

MONITORING BROAD ABSORPTION-LINE QUASAR VARIABILITY

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A DISSERTATION SUBMITTED TO
THE FACULTY OF GRADUATE STUDIES
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

Graduate Program in Physics and Astronomy
York University, Toronto, Ontario

April 2016

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Abstract

Winds generated by an accreting super massive black hole may provide feedback to the host galaxy and offer an explanation for the co-evolution of galaxies with their super massive black holes that has been reported in the literature. Some outflows are manifested as broad absorption line (BAL) troughs in quasar spectra, and are measured at velocities as high as $\sim 60,000 \text{ km s}^{-1}$ at ultra-violet wavelengths. These BAL troughs have been observed to vary on both long (years) and short (weeks) rest-frame time-scales and can emerge in a quasar that had none, or disappear completely. By monitoring the variability of absorption in BAL quasars, constraints can be placed on outflow models and the structure of quasars in general.

In this study, we isolate a set of quasars that exhibit emergent C IV BALs in their spectra, by comparing archival data in the SDSS Data Release 7 to the BOSS Data Release 9 and 10. After visually defining a set of emergent BALs, follow-up observations were obtained with the Gemini Observatory for 105 quasars. BALs were formally detected in all but two of the quasars in the dataset, and we report 219 absorption complexes in the entire set. After a BAL has emerged, we find it is equally likely to continue increasing as it is to start decreasing in a subsequent observation. Based on the range of time between our observations, this indicates the coherence time-scale of BALs is less than 100 days. There is a strong signal of coordinated variability among two troughs in the same quasar. Further, coordination is stronger if the velocity separation between the two troughs is smaller. We conclude the variability is likely due to changes in the ionizing flux incident on the absorbing cloud, which agrees with the results of Filiz Ak et al. (2013).

In this work we also test two competing models of BAL variability (bulk motion and ionization changes) in the context of a case study of the quasar SDSS J023011.28+005913.6, which had two high-velocity emergent troughs. Both models yield plausible results.

Acknowledgements

For me, it is a daunting task to sit down and write a set of acknowledgements. Those that know me could easily describe the rough time I have with remembering details both big and small; this is a personality flaw that manifests itself in many ways, but in the context of an acknowledgements section could lead to hurt feelings. Insofar, my goal to ‘know thyself’ has led to the collection of no data that correlates the amount a person may impact my life with my unfortunate ability to forget any given moment. No such correlation leads me to conclude that I have been unbelievably fortunate in my life; I would guess that it means I have had so many wonderful people in life to impact me greatly that it is difficult to remember properly, perhaps more people than I deserve. With that I hope the reader could, no doubt, take solace in knowing that should their name not appear here it does not make their impact less important than those that are named. There are many people and institutions that have helped build me into the person that wrote the dissertation in the coming pages. Here is my attempt to acknowledge them.

My journey has taken me from the YMCA of Greater Toronto, through to McMaster University, an unbelievable stint at the Ontario Science Centre, and finally to York University. Each institution has had its own character, values, and attitudes that I have absorbed and embodied in my own way. The YMCA taught me social values, McMaster taught me the world was bigger than I realized, the Ontario Science Centre gave me a voice, and York taught me how to turn my random interests and passions into a real career. It is surprising to look back down that path and see how much I’ve taken away from each place. There are lessons still resonating from my first job at the YMCA as a rockclimbing instructor, through to my time on the floor at the OSC. Though it was the people at these institutions that bear the bulk of the blame for the person I’ve become, so they should most certainly be named.

The luxury of having friendships strong enough to last from childhood to adulthood is not lost on me. I have known Brandon, Greg, and Ken for decades, and they remain three of my strongest and closest friends. That, in itself, is more than most could ask for. The three of them have consistently been a part of my life, shared in my greatest and weakest moments, and are three of the best drinking buddies I’ll ever have. Those that know them might wonder how I could possibly have gotten this far in life having those three as some of my best friends, and to them I answer... good question?

There are many people at York that I owe so much to, though one of the foremost is Marlene Caplan; she truly is the glue that keeps the professors and the graduate students of the Physics and Astronomy Department together. If I had an owl statue for every battle she fought for me, every detail she explained to me, every deadline she helped me with, and every fun conversation I had with her ... I might actually rival her massive collection of office owls and owl related paraphernalia.*

Paul Delaney is quite literally the person who began my science communication career. He and his observatory have played no small role in my life. The experience of working in the observatory and participating in its outreach activities, particularly *York Universe*, has shaped my career focus over the years. Paul, you are the best in Toronto when it comes to ‘waxing eloquently’ about all things space; I was fortunate enough to overlap with you at York. Thank you for sharing your knowledge! Grab another whiskey and go check out the score of the cricket game ... I hope the Aussies are winning.

I was asked once ‘why did you become a scientist?’ After a long-winded answer I summarized it with ‘... because I was interested.’ I can’t help but feel my supervisor could say the same. Patrick Hall’s genuine interest and excitement in astronomy is obvious and contagious, and made working with him over such a long time easy. In those years, Pat has somehow managed to turn me and my Bachelor’s Degree (with a total of 5 actual astronomy courses under my belt) into both a professional and expert in Astrophysics. I’ve told George and Lianne a hundred times that ‘I won the supervisor lottery,’ which is something I will always believe. Pat you are patient, accessible, and down-to-Earth. You created so many opportunities for me, and your encouragement was obvious. Thank you, this dissertation is both a testament to myself, but also your ability to supervise and mentor.

Petrie 328 was my home away from home for eight[†] years. As ready as I am to move on, I must admit it is actually hard to leave it behind. Hours and hours per day were poured into astronomical research from the quiet comfort but slight mess of 328. As far as I know, I was the first graduate student to use that office when I arrived in 2007, and I remained there alone for the first year or two of my graduate career. The room was eventually assigned two office mates: George and Lianne. ‘There is no other better’ two people for me to have shared that room with. We researched together, got coffee together, pulled long hours and bitched together, we drank beer together, and graduated together. Along the way, you two stopped being office mates and became friends. I look back on it, as I said above, and feel like it’s hard to leave my office behind, but what I’m really saying is it is hard to leave those memories behind. Thank you for somehow making the long hours in 328 a **good** memory.

If a doctoral dissertation is a marathon (and believe me ... it is), then the final year is the home stretch. To get that far is an achievement in itself. Congrats, you have done more than most. But the finish line can seem like an almost unbearably far distance still left to run. You can see it, but can you really make it? In many ways, this part of the marathon takes the most work, the largest

*That’s actually impossible... have you SEEN that collection?

[†]Yes ... eight.

push, the most dedication, and the biggest cheer from your sidelines. I was lucky enough to have Alex join my cheering section right at this moment. You came in at the hardest part, and you helped me push through that final stretch. You were nothing but a rock the whole time.

Of course, the most deserved acknowledgement I could possibly make is to my family. I could not ask for better than them. My parents have always supported myself and my siblings unconditionally, and I'm quite certain they are the primary reason the four of us turned out so awesome. Here's hoping a glowing thank you note in my doctoral dissertation is enough for them to forget all the money they've given me, not to mention the food I've taken.[‡] Speaking of taking from my parents, my siblings have always been a huge part of every thing I do in my life. I learn from them, and the examples they set, every single day. I would be surprised if that does not continue into our old age. Everyone on the Rogerson and Spencer side from Grandparents to Cousins, from sailors to steelers, from photographers to nurses, have always been supportive, excited, and genuinely interested in the lives we all lead. An extended family that feels like an immediate family must be rare, and I'm grateful for it.

Thank you to Jen & Krista (for giving me a roof when I had none), to Rob (for your sarcasm), to Ryan (for being you), to Shane (for your thoughtfulness), to Tanya (for the conversations), to Harrison (for your encouragement), to Chris (for the beers), to all the Hopscotch Scotch Swappers-Sasquatch Swatch (for swapping scrumptious scotch), to Christine (for constant understanding), to every host I ever worked with (for being hosts), to every volunteer at the observatory (for their undeniable enthusiasm), and to every person I could not remember (see first paragraph).[§]

[–‘get off the stage’ music starts to play–]

There are two quotes that best summarize these acknowledgements Sir Isaac Newton, one of the fathers of modern mathematics and physics, paraphrased a very famous and deeply truthful saying:

If I have seen further, it is by standing on the shoulders of giants.

Much earlier, Aristotle, one of the fathers of philosophy and science is known for saying:

The whole is greater than the sum of its parts.

Completing a dissertation is no small task to be sure, but the congrats need not, rather, should not, land solely with me. I truly feel I have been able to get this far because I have learned from so many others. I am the sum of a billion parts, a million interactions, a thousand learning opportunities, hundreds of people, and some of the best friends in the world. You have let me stand on your shoulders, thank you for that.

-Jesse Rogerson

25 April 2016

[‡]So, we're even now, ... right?

[§]Also, Titan ... for letting me name him after a moon.

*To past Jesse,
thanks for YOUR dedication.*

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Chapter 1

Introduction

1.1 The Big Picture

Quasars are the most energetic and distant subclass of a group of objects called active galactic nuclei (AGN). Observationally, quasars are characterized by large luminosities in most, if not all, wavelengths of the electromagnetic spectrum, a non-thermal spectral energy distribution, broad emission features, and unique variability. It is generally accepted that the origin of this massive energy output is the result of a super massive black hole (SMBH; $10^8 - 10^9 M_\odot$) that is actively consuming material from an accretion disk at the centre of the host galaxy (Netzer, 2013). As material in the accretion disk orbits the SMBH, friction occurs between the debris moving at different velocities. This creates an intrinsic viscosity of the disk that allows the material to slowly fall towards the SMBH, converting its gravitational potential energy to thermal energy as it moves inwards, which is radiated away in the form of black-body emission.

At the edge of the accretion disk where orbits are slower, the intrinsic viscosity is therefore also lower; this results in a black-body peaking in a lower energy band of the electromagnetic spectrum. Nearer to the SMBH orbits are much faster, creating a larger viscosity and a black-body radiator peaking in a higher-energy region of the spectrum. The resultant sum of black-body radiation results in an apparent non-thermal power-law distribution of energies in AGN spectra. In Figure 1.1, a composite of the ultra-violet portion of a quasar's spectrum is presented, which was derived in Vanden Berk et al. (2001) by averaging over 2200 quasar spectra. In that work it was found the underlying light in the region from about 1300–5000 Å can be modeled by a power-law with a frequency index of $\alpha_\nu = -0.46$ (note: $\alpha_\lambda = -(\alpha_\nu + 2)$). This light is referred to as the continuum. The SMBH and accretion disk together create an active galactic nucleus. Almost ubiquitous in quasars is the presence of broadened emission features on top of the continuum radiation. They are referred to as broad emission lines (BELs) and have widths of $\sim 5,000 \text{ km s}^{-1}$. As the Figure shows, there are many prominent emission features across the UV spectrum of a quasar, however, in this

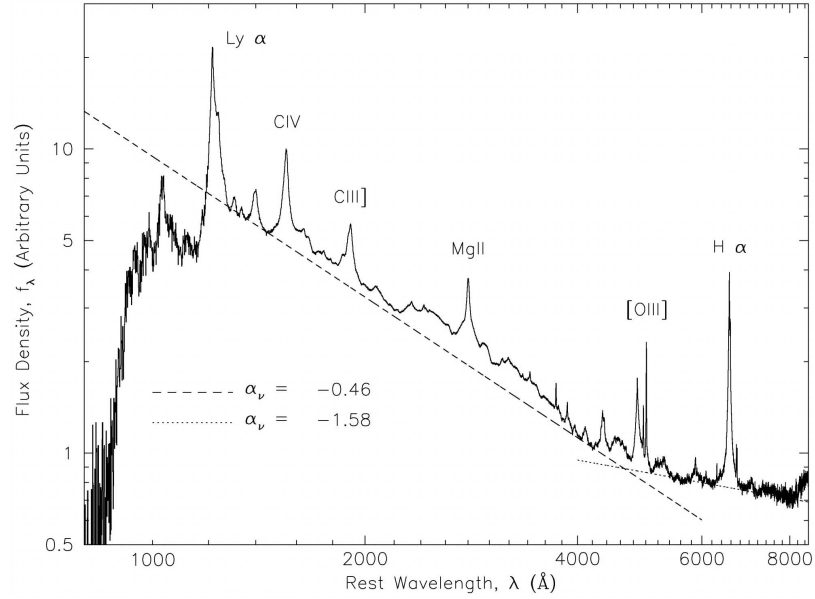


Figure 1.1: A composite quasar spectrum made by averaging over 2200 spectra from the Sloan Digital Sky Survey (Vanden Berk et al., 2001).

work we mainly focus on the region from 1200 – 1700 Å. In that region the most prominent emission features are Ly α at λ 1215.7 Å, which is usually blended with N V at λ 1240 Å; Si IV emission at $\lambda\lambda$ 1393.7, 1402.8 Å; C IV emission at $\lambda\lambda$ 1548.2, 1550.8 Å. Later in the work we also take advantage of the Mg II emission at λ 2800 Å; see Chapter 5.

Quasars are found only at very large distances from Earth, which has been determined by the large shifting of features in their observed-frame optical spectra. Due to the cosmological expansion of the Universe, as the radiation from a distant object travels through space, the light is shifted to longer wavelengths; this is known as redshift and is denoted z . Redshift is defined in the equation

$$1 + z \equiv \frac{\lambda_o}{\lambda_e}, \quad (1.1)$$

where λ_o is the wavelength of light observed in the telescope and λ_e is the emission wavelength of light before it was shifted. If $\lambda_o = \lambda_e$, then there has been no shift and $z = 0$. The larger the distance the light has to travel, the more the expansion of the Universe shifts the light towards longer wavelengths. This makes redshift a measure of cosmological distance (Hogg, 1999). The redshift distribution of quasars, shown in Figure 1.2, indicates that most quasars are found at distances large enough to shift the quasar’s ultra-violet (UV) light into the optical. As a result, the UV spectra of quasars have been studied extensively since their discovery, especially with the progress of large-scale optical surveys, such as the Sloan Digital Sky Survey (see § 2.1 herein for more information).

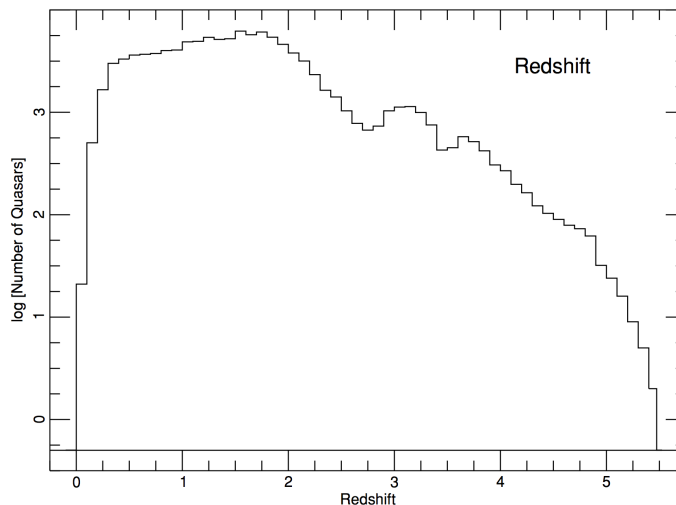


Figure 1.2: The redshift distribution of quasars in the observed 7500 Å flux-limited SDSS DR7 catalog (Schneider et al., 2010). In their catalog, they find a redshift range $0.065 < z < 5.46$, with a median value of 1.49.

1.2 Broad Absorption in Quasar Spectra

There are several types of absorption found in the spectra of quasars. Intervening absorption is always present for objects at large distances. These features are found across the spectrum and are a result of intergalactic gas between the quasar and the observer. There are two types of intrinsic absorption found in quasar spectra: narrow and broad. Narrow absorption lines (NALs) are narrow enough that the doublet lines from the species that create them (e.g., C IV, Si IV, etc.) are resolved. Broad absorption lines (BALs) occur in the same species, but over a large enough velocity regime that the doublets are blended together.

The first broad absorption troughs were identified by Lynds (1967) who noticed wide and strong absorption in C IV and Si IV blueward of their respective emission features. In Figure 1.3, an example of broad absorption is shown in the spectrum of SDSS J164646.69+355558.0, which is plotted centred on the 1100 – 1700 Å region (in the rest-frame of the quasar). The most prominent emission features are labeled, as well as two broad absorption lines that are shaded grey and labeled as due to absorption by C IV and Si IV gas. We are confident the absorption is due to these species because of the relative spacing between them. However, both troughs are noticeably shifted towards shorter wavelengths relative to their emission features. A shift in wavelength indicates there is a non-zero relative velocity between the quasar and Earth. As discussed earlier, the expansion of the Universe forces quasars to move away from us, shifting their entire spectra into longer wavelengths, or redshifting them. If the intrinsic BAL features of C IV and Si IV in J164646 are shifted towards shorter wavelengths, known as blueshift, the gas that is absorbing that light must be moving towards Earth, relative to the quasar.

Where useful, BAL troughs are plotted in velocity space using

$$\beta \equiv v/c = (R^2 - 1)/(R^2 + 1) \quad \text{where} \quad R \equiv (1 + z_{em})/(1 + z_{abs}), \quad (1.2)$$

where z_{em} is the redshift of the quasar, and z_{abs} is the redshift of the absorbing gas (Foltz et al. 1986, Hall et al. 2002). We define the zero velocity for each line using its laboratory vacuum rest wavelength. For the duration of this work, we use the shorter wavelength of the C IV doublet to define the zero velocity for all C IV BALs, which is λ 1548.202 Å. The top x-axis of the Figure provides velocities relative to that. In order for C IV gas to absorb light from the continuum at ~ 1450 Å it must be moving towards the observer at approximately $20,000 \text{ km s}^{-1}$. Thus, broad absorption shows quasars have highly accelerated gas moving outwards from the centre, absorbing large amounts of light.

It is not only the velocity of the absorbing gas that can be determined from this example of SDSS J164646.69+355558.0. Reading off the y-axis, we can see that least 50% of the ~ 1450 Å continuum has been absorbed; this indicates either the gas is completely opaque and is covering 50% of the continuum source at that wavelength, or the gas is completely covering the continuum source and is optically thin.

Historically, broad absorption Line (BAL) quasars have been defined as quasars that exhibit blueshifted absorption due to the C IV doublet at $\lambda\lambda$ 1548.203, 1550.770 Å that is at least $2,000 \text{ km s}^{-1}$ wide and can extend from $3,000 \text{ km s}^{-1}$ to $25,000 \text{ km s}^{-1}$, where 0 km s^{-1} is at the systemic redshift of the quasar (Weymann et al., 1991). Modifications to this definition have been used, e.g. Hall et al. (2002) and Trump et al. (2006), which were designed to include obvious absorption originally excluded by these guidelines. Indeed, in this work we have again modified this definition to account for new broad absorption troughs, see § 3.2. Regardless of individual definitions, broad absorption is rooted in a physically distinct origin compared to other features in quasar spectra.

In an optical survey, broad absorption occurs in about 10% of quasars, but modifying for selection and other effects, it is expected that around 23% of quasars exhibit blueshifted BAL troughs at ultra-violet wavelengths (see discussions in Rogerson et al. 2011 and Allen et al. 2011); the fraction increases if narrower ($500\text{--}2,000 \text{ km s}^{-1}$) ‘mini-BAL’ troughs are included (see Rodríguez Hidalgo et al. 2011 for a full discussion on mini-BAL quasars).

Looking at the entire picture, there are a number of features in the spectra of active galactic nuclei that require explanation in a proposed structure or model of AGN activity: broad emission, narrow absorption, broad absorption (and its prevalence only in 23% of quasars). There are also a number of other features not mentioned here, such as: radio loudness/quietness, jets, and more. In Figure 1.4, a schematic diagram of a quasar engine is proposed that would recreate all the observed qualities discussed so far (Elvis, 2000). It shows a thin accretion disk with a UV-emitting region close to the centre, and large winds moving outwards from the central source. In this disk-wind model of luminous AGN, BAL features are a result of material lifted off the accretion disk surrounding the central SMBH and accelerated by radiation line driving to high outflow velocities that we observe

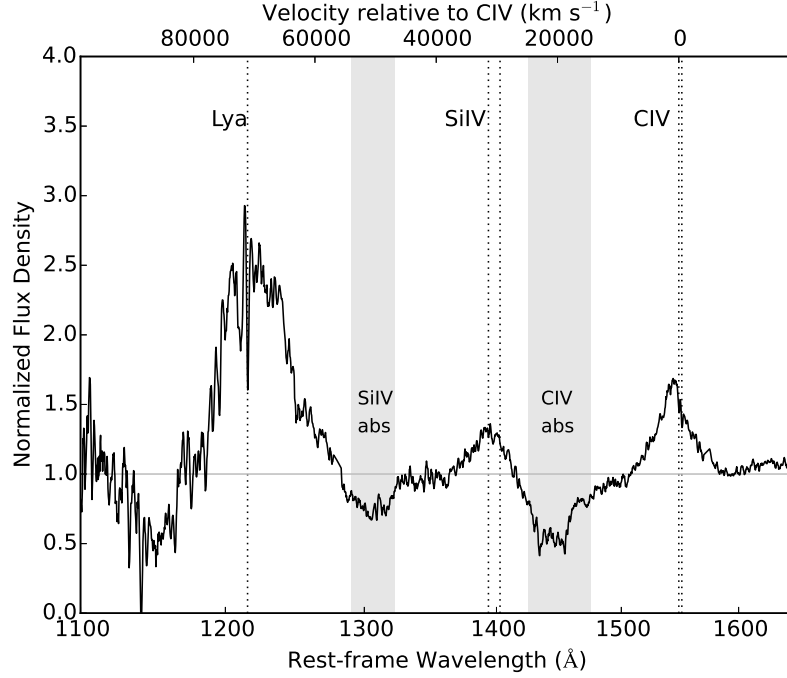


Figure 1.3: SDSS J164646.69+355558.0 is an example of a broad absorption-line quasar. The spectrum is normalized by a power-law fit to the continuum light such that the continuum is at a flux density level of 1.0. Emission features $\text{Ly}\alpha$ at ~ 1216 Å, Si IV at ~ 1400 Å, and C IV at ~ 1550 Å are labeled. There is a C IV broad absorption feature blueward of the C IV emission feature, and accompanying Si IV absorption blueward of its emission feature. In order for C IV to absorb the light at ~ 1450 Å, it must be moving towards the observer at approximately $20,000 \text{ km s}^{-1}$ (see top x-axis for velocities relative to the C IV emission). Spectrum is from this work.

as blueshifted absorption (e.g. Murray et al. 1995, Ostriker et al. 2010). In the schematic diagram provided, this would mean we are looking down the wind’s radial motion as it is accelerated away from the central source. It also means our line-of-sight affects whether we see a BAL or not. Thus, observing a quasar outflow provides insight into the structure of the central engine. Outflows of this magnitude may also represent a mechanism by which SMBHs provide feedback to their host galaxy (e.g., Leighly et al. 2014, Chamberlain et al. 2015, Moe et al. 2009, Arav et al. 2013).

1.3 Variability in the Literature

With outflow velocities at least as high as $25,000 \text{ km s}^{-1}$ it was recognized early on that BALs represent a window into a very dynamic engine. As models were being proposed attempting to explain the various observed phenomena in quasars, including BALs, it was also recognized that the variability of BALs will provide even more insight into the origin of the structure of the central engine.

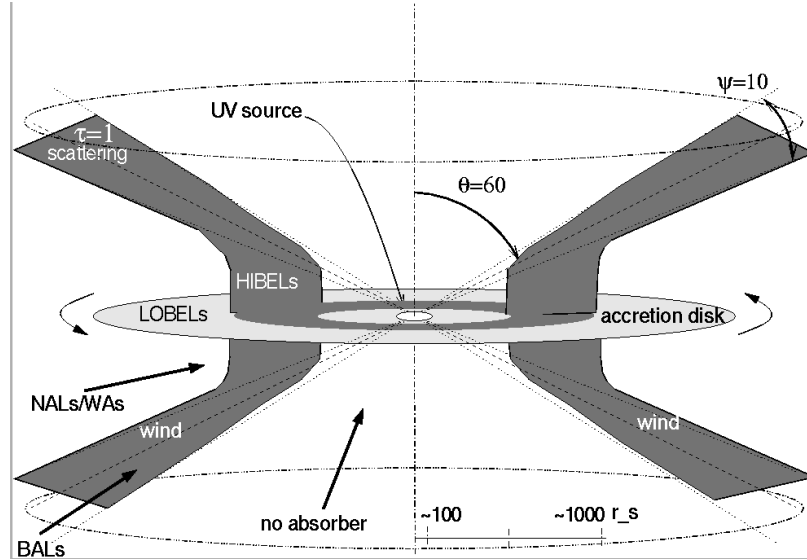


Figure 1.4: A schematic diagram of a quasar accretion disk and winds, from Elvis (2000). The high ionization (e.g., C IV) broad emission lines (HiBELs) originate mostly from the base of the wind, where as lower ionization emission features (LoBELs, such as Mg II) originate further out in the accretion disk. Narrow absorption features (NALs) are visible when there is a line of sight to the base of the wind, and broad absorption features (BALs) are visible when looking directly down the outflowing wind.

The first published attempts at this occurred in 1985: Bromage et al. (1985) observed the Seyfert 1 galaxy (a less luminous and less distant class of AGN) NGC 4151 multiple times, noticing significant changes in the absorption features therein. Two of the earliest works looking at variability of BALs in quasars (performed almost simultaneously) were Foltz et al. (1987) and Smith & Penston (1988). The former used data from between 1983-1985 to show that one of the broad troughs in Q1303+308 had slightly decreased in strength. The latter observed the broad troughs of Q1246 – 067 at three different times (or epochs) and noticed they had significantly changed over a 2.2 and 4.8 year period.

Shortly thereafter, the first multi-object sample of BAL variability was published by Barlow (1993), who collected a set of 23 BAL quasars and observed them at least twice. Variability in the strength (i.e., the depth, width, or outflow velocity profile) of BALs is now a well documented phenomenon both in individual quasars (e.g., Hall et al. 2011) and in large samples (e.g., Gibson et al. 2008, Capellupo et al. 2011). See Table 1.1 for a non-exhaustive list of multi-object C IV variability studies currently in the literature. There have been recent studies documenting the disappearance of BAL troughs (e.g., Filiz Ak et al. 2012), as well as emergence in quasars that were not classified as having BALs previously (e.g., Rodríguez Hidalgo et al., in preparation, Hamann et al. 2008, Leighly et al. 2009, Rogerson et al. 2016). This behaviour indicates broad absorption can occur, or is occurring, in all quasars but our ability to observe can depend on local factors as well as the viewing angle from Earth.

Table 1.1: Summary of C IV variability studies in the literature.

Reference	# of Quasars	ΔT Range (yr)	# of epochs
Barlow (1993)*	23	0.2–1.2	2–6
Lundgren et al. (2007)*	29	0.04–0.4	2–3
Gibson et al. (2008)*	13	3.5–6.1	2
Gibson et al. (2010)*	14	0.04–6.8	2–4
Capellupo et al. (2011)* ^A	24	0.02–8.7	2–13
Haggard et al. (2012)	17	0.001–0.9	6
Filiz Ak et al. (2012)	19	1.1–3.9	2–4
Filiz Ak et al. (2013)*	291	0.0006–3.7	2–12
Grier et al. (2015)*	1	0.003–0.3376	32
He et al. (2015)	188	0.001–3	2
This work	105	0.005–3.31	3–7

^A In Capellupo et al. (2011) are the same (plus one) as those in Barlow (1993); they were re-observed for a longer time baseline between observations. They were also the same quasars in two other studies by the same author: Capellupo et al. (2012) and Capellupo et al. (2013).

* Data was taken from these works to help create Figure 4.13

The cause of BAL-trough variability/emergence/disappearance is still largely debated in the literature, however, it is likely either due to transverse motion of absorbing clouds across our line of sight (e.g., Hall et al. 2011), or due to changes in the ionization of the absorbing gas (e.g., Hamann et al. 2008, Filiz Ak et al. 2013). Ultimately, it may be a complex mixture of these two scenarios. Full characterization of BAL variability events (either emergence, disappearance, or variability in general) would significantly increase our understanding of both the physics of the quasar’s central engine and the interaction of the quasar with its host galaxy.

1.4 Motivation and Outline

To date, variability studies with large samples typically focus on two epochs per target. Studies where more than one epoch is used per target are usually those with only one target in the study, and only consider the multi-epoch nature of the work as multiple sets of two-epoch studies. Typical motivating questions in these works are: how much has the absorption changed between two epochs? And what constraints can we place on quasar models based on these changes? Both of these questions are valid, and indeed questions we also look at here. In this work, we were primarily interested in analyzing the emergence of broad absorption in quasars. We define emergence to be any BAL that was previously not present in a quasar but appeared in a newer observation (this can occur both in BAL and non-BAL quasars). In contrast to previous studies, however, we were motivated to study how these emergent BAL troughs act in future observations. Our motivating questions are: Does the variability of a trough between two observations predict or otherwise inform how the trough will vary in a third observation? Further, we were also interested in how multiple troughs in a single

target behave: do troughs vary independently or in a coordinated fashion? In this study we track the variability of emergent broad absorption troughs in 105 quasars over at least 3 epochs and up to as many as 7 epochs per target.

This work is organized as follows: in Chapter 2 we explain where the quasar dataset came from, how it was selected, and the follow-up observations we performed to reach 3 or more epochs per quasar. In Chapter 3 the methodology is explained and preliminary characterization of the BALs in our dataset are discussed. Chapter 4, we analyze and discuss the nature of the variability we observe in our dataset, and offer some physical explanations for them. In Chapter 5, a case study on the object SDSS J023011.28+005913.6 is presented, unique for its record breaking high-velocity broad absorption trough, and highly-variable properties. Finally in Chapter 6, the results are summarized, and future work is outlined.

Chapter 2

Data Collection and Preparation

The dataset of emergent BAL troughs analyzed in this work was determined in a two-step data collection process. First, a candidate sample of emergent broad absorption lines in quasars was found by visual comparison of older spectra to newer spectra in publicly available archival data. Second, a subset of the candidate sample determined by the visual inspection was re-observed by applying for observing time on the twin Gemini Observatories. This resulted in at least three spectral observations for a large number of quasars with emerging broad absorption. In order to quantitatively compare all the spectra for a given quasar, the Gemini data were reduced, and all of the data were normalized such that the continuum light was equal to 1.0. We begin the chapter with an in-depth discussion of the target selection process.

2.1 Target Selection

The Sloan Digital Sky Survey (SDSS; York et al. 2000) operated from 2000–2008 under the two project titles SDSS-I and II (hereafter, referred to as SDSS). SDSS used a dedicated 2.5 meter f/5 Ritchey-Chrétien altitude-azimuth telescope located at Apache Point Observatory in New Mexico, USA (Gunn et al., 2006). The telescope was outfitted with a Photometric Camera, detailed in Gunn et al. (1998), and a multi-object, fiber-fed spectrograph. The latter had a wavelength coverage of 3900–9100 Å, with a resolving power ranging over 1500–3000. (see § 2 of Smee et al. 2013). During its operations, SDSS collected over 1.5 million spectra of galaxies, quasars, and stars covering approximately 10,000 deg² on the sky. The full catalog can be found in the SDSS Seventh Data Release (DR7; Abazajian et al. 2009), which was publicly available as of 2009. In DR7, there were 105,783 spectroscopically confirmed quasars; their redshifts range from 0.065 to 5.46, with a median value of 1.49 (Schneider et al., 2010). We obtained the DR7 quasar spectra from the free online database: CasJobs. The spectra were already reduced and calibrated by the SDSS team.

After SDSS-II concluded, the telescope was repurposed for a third iteration, SDSS-III,¹ which executed four different surveys, including the Baryon Oscillation Spectroscopic Survey (BOSS; Dawson et al. 2013). SDSS-III operated from 2008–2014, and was a dedicated spectroscopic project. BOSS’s primary scientific goal was to characterize the signal of Baryon Acoustic Oscillation (BAO) found in the Lyman- α forest by targeting high redshift ($z > 2.2$) quasars and Luminous Red Galaxies. To meet the science requirements, a new multi-object fiber-fed spectrograph was built with greater throughput, an increased wavelength coverage (to 3560–10400 Å), and similar resolving power as the original SDSS spectrograph (see § 3 of Smee et al. 2013). The most notable change to the spectrograph was a reduction in fiber diameter on the sky from 3 arcseconds to 2 arcseconds ($\sim 30\%$), which affected the overall throughput. We did not correct for this because we were only interested in comparing the normalized spectra.

On 31 July 2012, the SDSS-III collaboration made available to the public the SDSS Ninth Data Release (DR9), which consisted of data taken over December 2009 to July 2011 (Ahn et al., 2012). It expanded the original sky coverage of SDSS to approximately 15,000 deg², which partially overlaps with the observational footprint of SDSS, and obtained spectra for thousands of galaxies and quasars not originally part of the SDSS DR7 catalog. It also included all data available in previous data releases. In DR9 there were 78,086 new quasars discovered along with 9,736 quasars previously known (many of which in DR7); thus the DR9 quasar catalog has 87,822 quasars. The DR9 quasar catalog was released simultaneously, available through the SDSS website² and described in Pâris et al. (2012).

On 29 July 2013, the SDSS-III collaboration released the SDSS Tenth Data Release (DR10), which consisted of data taken over December 2009 to July 2012. This included all measurements taken up to and including DR9, and added on new measurements taken between 2011 and 2012 Ahn et al. 2014. DR10 made available new quasar spectra from the BOSS survey. A DR10 quasar catalog was released simultaneously, available through the SDSS website³ and described in Pâris et al. (2014), which contains 166,583 quasars in total, 74,454 of which were newly discovered since DR9. We obtained the DR9 and DR10 quasar spectra via the public database: CasJobs. As with the DR7 data, these spectra were already reduced and calibrated by the SDSS team.

We leveraged the multi-epoch nature of the DR7, DR9, and DR10 catalogs to search for a set of quasars that had been spectroscopically observed at least twice over all three data releases. The search was done using the online SDSS-III CasJobs SQL tool⁴ by matching the DR7 right ascension (RA) and declination (dec) to the DR9 and DR10 values to within 2 arcsec. This tolerance is required because the respective data reduction and astrometric calibration pipelines of all three data releases produce small differences in on-sky coordinates.

There were 8317 quasars matched between DR7 and DR9 some with multiple spectra totalling

¹<http://www.sdss3.org/collaboration/description.pdf>

²https://www.sdss3.org/dr9/algorithms/qso_catalog.php

³https://www.sdss3.org/dr10/algorithms/qso_catalog.php

⁴<http://skyserver.sdss.org/casjobs/>

9840 spectra for 8317 quasars. This is referred to as the DR7–DR9 parent sample. For each unique quasar, both the DR7 and DR9 spectra were visually compared by plotting both DR7 and DR9 spectra over top of each other centred on the region between $1200 - 1700 \text{ \AA}$ in the rest-frame, where we expect to find C IV broad absorption. Visual inspection over all 8317 quasar spectra yielded 111 candidates for the emergence of BAL troughs (76 were already classified as BAL quasars within which a 2nd candidate trough appeared, 35 were non-BAL quasars in DR7). All 111 objects were at $z > 1.68$ (noting there were 7417 quasars from the parent sample at $z > 1.68$).

There were 8940 quasars matched between DR7 and DR10 some with multiple spectra totalling 9652 spectra for 8940 quasars. This is known as the DR7–DR10 parent sample. As above, they were compared visually to look for emergence of BAL activity by plotting both DR7 and DR10 spectra over top of each other. Visual inspection yielded 178 candidates possibly exhibiting new BAL troughs in DR10 (91 were already BAL quasars based on DR7 data, 87 were non-BAL). All 178 of these were at $z > 1.68$ (noting there were 8239 quasars in the original DR10 sample $z > 1.68$). Together the DR7–DR9 and DR7–DR10 matches are referred to as the parent sample.

Comparing the numbers for only quasars with $z > 1.68$, the candidate emergent rate of DR7–DR9 was $111/7417 = 1.50 \pm 0.14\%$, and DR7–DR10 was $178/8239 = 1.99 \pm 0.15\%$. These rates differ by 3.1σ , likely in part due to the slightly longer average time baseline in the DR7-DR10 parent sample (see § 4.6).

There was a smaller group of quasars which were not in DR7, but were discovered in DR9 and were re-observed in DR10 (the DR9–DR10 parent sample). These were also visually inspected and 3 were found to exhibit candidate emergent BAL troughs.⁵ We included these in our emergent sample.

In total there were 306 quasars in our search that may be exhibiting the emergence of broad absorption; this is the candidate emergence sample. We refer to it as a ‘candidate’ sample because the emergent absorption was only found through visual detection and not quantitatively identified. Later we perform a more rigorous identification (see § 3.2).

In Figure 2.1 the distribution of redshifts (top) and the rest-frame time between the SDSS and BOSS epochs for each object (bottom) are plotted for both the parent sample (black) and the candidate emergent sample (red). The candidates are preferentially at smaller redshifts, and have a slightly broader range in time between observations than the parent sample they were chosen from.

The parent sample in Figure 2.1 includes data from both the DR7–DR9 and the DR7–DR10 searches. For DR7–DR9, the mean redshift is $\langle z_{7-9} \rangle = 2.8$ and mean time between observations is $\langle \Delta T_{7-9} \rangle = 695$ days. For DR7–DR10, the mean redshift $\langle z_{7-10} \rangle = 2.6$ and mean $\langle \Delta T_{7-10} \rangle = 730$ days. This indicates the two parent samples trace out slightly different regions of the available parameter space.

Follow-up observations of the candidate group was essential to answering the questions we posed

⁵SDSS J154718.70+341120.2, SDSS J094310.83+055632.8, SDSS J123149.92+064436.2. See Table 2.2

in the introduction. To that end, we applied for observing time with the Gemini Observatory. The resulting data would begin a monitoring campaign of the emergent sample, but also confirm the emergence is real.

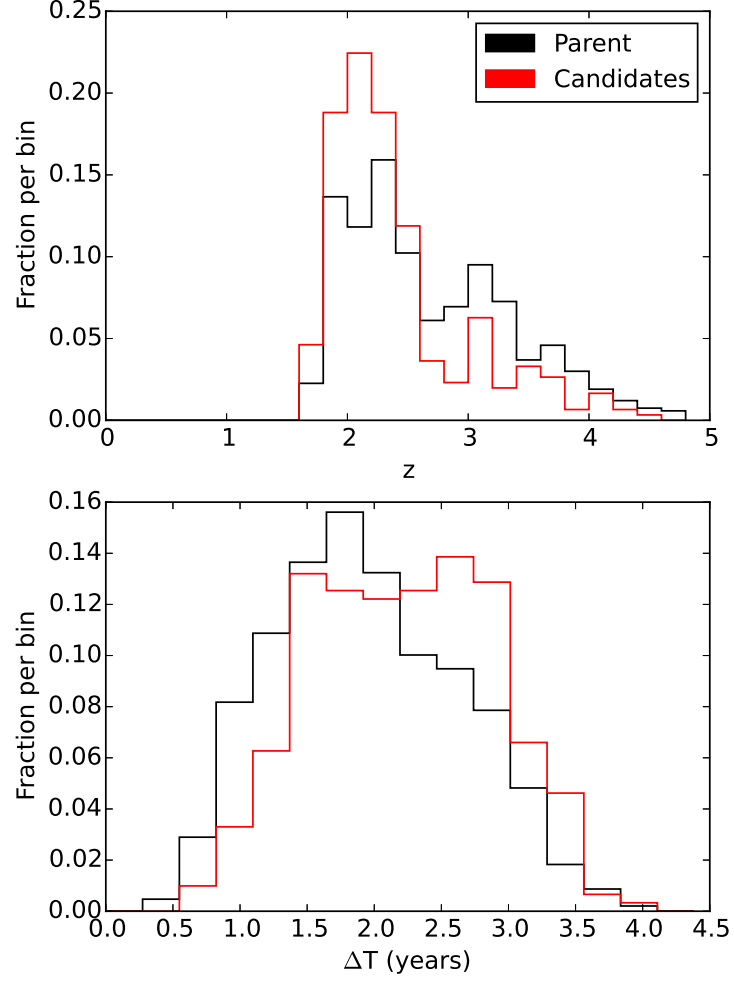


Figure 2.1: The distribution of redshifts (top) and rest-frame time between the spectra from SDSS and BOSS (bottom) for the parent sample (black) and the visually determined candidate emergent absorbers (red).

2.2 Following Up: Gemini Observations and Reductions

2.2.1 Gemini Observations

We successfully proposed to the twin Gemini Observatories for follow up observations, and obtained data on 105 targets from the candidate emergence sample. These 105 targets were chosen based on brightness, ease of observing the 1200–1600 rest-frame continuum, and shortest rest-frame time between the BOSS epoch and the proposed Gemini observations. For example, lower redshift targets push the wavelength region of interest closer to the atmospheric cut-off and also yield longer rest-frame time separations for a given time separation in the observed-frame.

Gemini North is an 8.1 meter Cassegrain telescope located at the summit of Mauna Kea, Hawai'i; its twin, Gemini South, is located at the summit of Cerro Pachón, Chile. We used the Gemini Multi-Object Spectrograph (GMOS) (one on each telescope) outfitted with a 1.0'' wide longslit to individually observe each target in our sample. GMOS provides gratings that cover the entire optical spectrum (3600–9400 Å) at a variety of spectral resolutions. For the majority of our observations, we employed the use of the B600 grating with 600 lines mm⁻¹, a blaze wavelength of 461 nm, simultaneous wavelength coverage of ~300 nm, and $R \sim 1688$. For some high-redshift targets, we used the R400 grating with 400 lines mm⁻¹, a blaze wavelength of 764 nm, a simultaneous wavelength coverage of ~400 nm, and $R \sim 1918$. These settings were chosen such that the resulting data had similar spectral resolution as the SDSS/BOSS spectra. We calculated exposure times, using the online Integration Time Calculator (ITC)⁶ provided by the Gemini Observatory, that resulted in a signal-to-noise ratio of ~15 in the region between rest-frame 1200–1600 Å. This was chosen to be roughly close to the signal-to-noise ratio found in SDSS and BOSS quasar spectra.

Our Gemini follow-up of the 105 targets was spread over three observing semesters: 2013A, 2013B, and 2014A.⁷ In total, we ran three different observing campaigns, each with multiple programs on either Gemini North or South. In Table 2.1, all observing program reference numbers are listed, the number of quasars observed in that program, and some other notes. The main campaign was the initial follow-up observations, targeting all 105 quasars. A smaller, more specific program was initiated targeting BALs from the main campaign that exhibited variability in troughs at high-velocity (specifically, BALs blueward of Si IV, see § 1.2). Finally, we were able to utilize an unrelated observing campaign (PhotoVariability) to gather more data on one target.

In the top portion of Figure 2.2, the distribution of redshift is plotted for the original visually determined candidate sample (green) and those that were observed on Gemini (red). The latter is a subset of the former. In the bottom portion of this plot the distributions of time between observations have been plotted. The red histogram is the ΔT values for the objects traced out by the red histogram in the top plot. The blue histogram is the rest-frame time between the most

⁶<https://www.gemini.edu/sciops/instruments/gmos/itc-sensitivity-and-overheads>

⁷Observing seasons are typically split into two semesters. 'A' is from 1 February through 31 July, 'B' is from 1 August through 31 January.

Table 2.1: A summary of all observing programs on Gemini.

Program Reference	Objects	Notes - Telescope, semester, standard star
Main Campaign ^A		
GN-2013A-Q-104	14	North, 2013A, std. HZ44
GS-2013A-Q-86	19	South, 2013A, std. LTT6248
GN-2013B-Q-59	15	North, 2013B, std. G191B2B
GS-2013B-Q-50	7	South, 2013B, std. LTT7379
GN-2014A-Q-67	24	North, 2014A, std. HZ44,
GS-2014A-Q-24	27	South, 2014A, std. EG274
High Velocity Campaign ^B		
GN-2014B-Q-75	3	North, 2014B, std. G191B2B
PhotoVariability Campaign ^C		
GN-2013B-Q-39	1	North, 2013B, std. HZ44
GS-2013B-Q-21	1	South, 2013B, std. LTT7379

^A The main observing campaign targeted all 105 targets. There are actually a total of 106 numbered above because object J161336 was observed both in GS-2013A-Q-86 and GN-2014A-Q-67.

^B The high-velocity campaign gathered multiple spectra of 3 targets that were already observed in the main campaign: J073232, J083017, J083546.

^C The purpose of this campaign was unrelated to the science of this work, however, we were able to use the Standard Target of Opportunity feature of Gemini to observe J023011 twice.

recent BOSS observation, and our Gemini follow-up observations. The cyan histogram represents a number of data sets, as follows: while our target selection was predicated on just one epoch from each of DR7, DR9, and DR10, there are many cases where there are multiple epochs from each data release for each target. Further, a small subset of our targets from the Main Campaign were observed again in other campaigns. The cyan histogram captures all rest-frame time between all successive spectral epochs available for a given target from DR7, DR9, DR10, and Gemini. See § 2.4 for a full summary of our observational data.

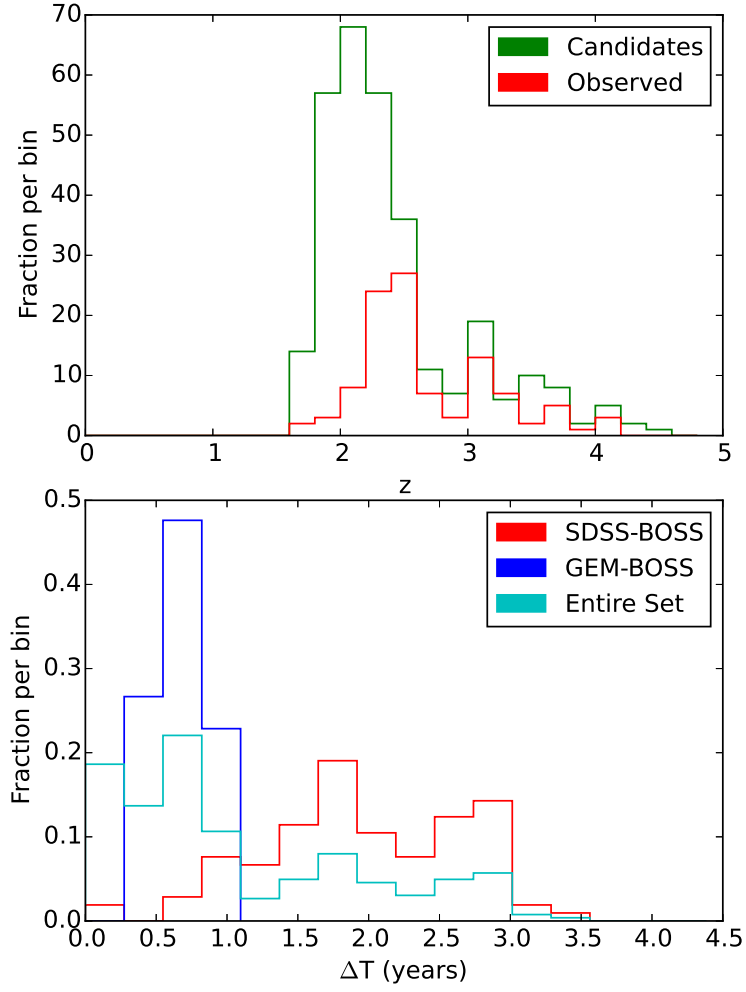


Figure 2.2: **top** The redshift distribution of the visually determined candidate sample (green), and the subset of those that received follow-up Gemini observations (red). **bottom** This histogram contains only information for target that received follow-up observations on Gemini. The SDSS-BOSS histogram indicates the time frames probed by existing archival data. The GEM-BOSS histogram shows how our follow up observations compare with SDSS-BOSS. The Entire Set represents all possible archival epochs and any possible extra Gemini observations that were done. See Table 2.2, for more clarification on this.

2.2.2 Gemini Reductions

The Gemini spectra were reduced using the Gemini IRAF⁸ package created by the observatory and the following standard techniques.

All science data were run through a cosmic ray rejection task to remove large spikes at locations cosmic rays impacted the CCD. Any spikes that were not rejected by the task were removed later using a linear interpolation algorithm. The systematic underlying bias in the CCDs was determined by taking at least 10 individual zero-second images and averaging them together. This may have been provided by the Gemini observing team, depending on the program. If it was not provided, an average bias image was built using the publicly available biases found via the Canadian Astronomy Data Centre (CADC).⁹ This average bias was referred to as the ‘master bias’ and was subtracted from the science data. Flat field calibration images were created with a 5W Quartz Tungsten Halogen lamp and divided out of the science data. Wavelength calibration spectra were created using a Copper-Argon (CuAr) Hollow cathode lamp, and used to scale the science data to a linear wavelength scale.

The quasar spectra were extracted using different extraction window sizes, depending on the signal-to-noise of the data. The underlying background noise was removed at this step by extracting and averaging two windows on either side of the signal and removing from the data. Spectrophotometric calibration was calculated using the standard star observations. Finally, as each quasar had at least two extracted spectra (see below), the science data were combined into a final spectrum.

Only one set of standard star spectra was taken over the course of each observing program (one for each GMOS wavelength setting used in the program). Each star is listed in Table 2.1 and was taken from Landolt (1992). Due to the queue nature of our observations, this meant the calibration stars were not measured on the same night as the quasars themselves and could be separated in time by as much as 5 months. Thus, while we can use the standard stars to correct the shape of the quasar spectrum, they cannot be spectrophotometrically calibrated. This is not a problem as the science herein does not require such a calibration (see our section on normalizing the continuum flux density below).

The CCDs that are used within the GMOS instruments have two chip gaps measuring approximately 2.8 arcsec in width (or about 39 unbinned pixels in width in the dispersion direction). In order to avoid any loss of light to the gaps, Gemini advises users to split their observations into two separate observations wherein the grating central wavelength is dithered by some small amount. To account for this, our Gemini observations have (at least) two separate spectra shifted by 10 nm.

All SDSS and BOSS spectra have wavelength scales based on vacuum wavelengths.¹⁰ The Gemini wavelength calibrations are based on atomic transitions measured in air. In order to properly compare all data in this work, it was necessary to shift the Gemini spectra wavelength scale into the

⁸<https://www.gemini.edu/node/10795>

⁹<http://www.gemini.edu/sciops/data-and-results/gemini-observatory-archive>

¹⁰https://www.sdss3.org/dr9/spectro/spectro_basics.php

vacuum frame. The standard for this conversion is given in equation (3) of Morton (1991).

2.3 Normalizing the Spectra

Our data consist of at least three spectra from three different instruments attached to multiple telescopes. Moreover, for each quasar, observations could be separated by as much as a decade in the observed-frame. In order to properly compare one spectral epoch to another across these multiple observations, the spectra were normalized. This is done via the following approach.

In the rest-frame, the ultra-violet-optical continuum of a typical quasar can be modeled as a power law (see the Figure 1.1 in the Introduction). Assuming all quasars are represented by this model, a power law can then be fit to the continuum of each quasar and divided out. The resulting normalized spectrum would then have the continuum resting at a unit-less normalized flux density of 1.0, any emission features would be greater than 1.0, and any absorption features would be less than 1.0. An example of this process is shown in Figure 2.3. We have three spectra in our data set for object J105207, one from each of DR7, DR9, and Gemini. The top portion of Figure 2.3 shows the three unnormalized spectra, SDSS in black, BOSS in red, and Gemini in cyan. The BOSS and Gemini spectra have been shifted artificially to roughly match the flux density of the SDSS spectrum. This was done mainly to aid in the visual identification of normalization windows (see below). Also, both the BOSS and Gemini spectra are not necessarily perfectly spectrophotometrically calibrated. As mentioned above, the BOSS spectra carry with them a systematic calibration error as a result of instrument set-up and the Gemini spectra were calibrated using standard stars not taken on the same night. As this work only studies the normalized flux density of the quasars, this is not an issue.

In order to fit a power-law to the continuum, we chose regions on the spectra that were relatively free of emission or absorption thus making these regions a clean sample of the continuum, hereafter: the normalization windows. All normalization windows for all 105 targets were chosen by eye with the goals of 1, avoiding all major emission features, 2, avoiding as many minor emission features as possible, 3, regions must be covered by all spectra available for the target. In Filiz Ak et al. (2012), six relatively line-free regions were identified and used for normalization purposes: 1250–1350, 1700–1800, 1950–2200, 2650–2710, 2950–3700, and 3950–4050 Å. These regions were also identified in Vanden Berk et al. (2001) as being relatively clear of any emission features. Unfortunately, while most of the SDSS and BOSS observations we collected have large enough UV coverage in their spectra to be accessible to these line-free regions, the wavelength coverage of the Gemini data was much smaller. Most of the Gemini spectra typically cut-off around of ~ 1750 Å.

It is important that all chosen normalization windows are the same for all epochs in a given quasar, so that we can be sure the continuum has been weighted the same in all data. As a result of this requirement, we are unable to use most of the line-free regions from other works mentioned above. A further result of the smaller wavelength coverage of the Gemini data is that we were forced

to use normalization windows in the region where we are searching for absorption (i.e., between 1200–1550 Å). This is why each normalization window was chosen by eye, though, as much as possible we chose normalization windows from the list above. In the case of J105207, the windows used were 1320–1330, 1440–1450, 1590–1620, and 1750–1800 Å, and are highlighted as the greyed out regions in Figure 2.3. Using a least-squares fitting routine, a power-law function is fit to the continuum inside the normalization windows of the form $y = Ax^{\alpha_\lambda}$, where α_λ is the wavelength index and A is a constant. For J105207, best-fit spectral indexes were $\alpha_\lambda = -1.38$, -1.50 , and -1.33 for the SDSS, BOSS, and Gemini spectra, respectively. Power-laws with these fits are plotted as dashed lines in Figure 2.3 with corresponding colours. We divide each of J105207’s spectra by their respective power-law fit to remove the underlying quasar continuum. In the bottom portion of Figure 2.3, the normalized spectra for J105207 are shown, with the continuum sitting at a value of 1.0.

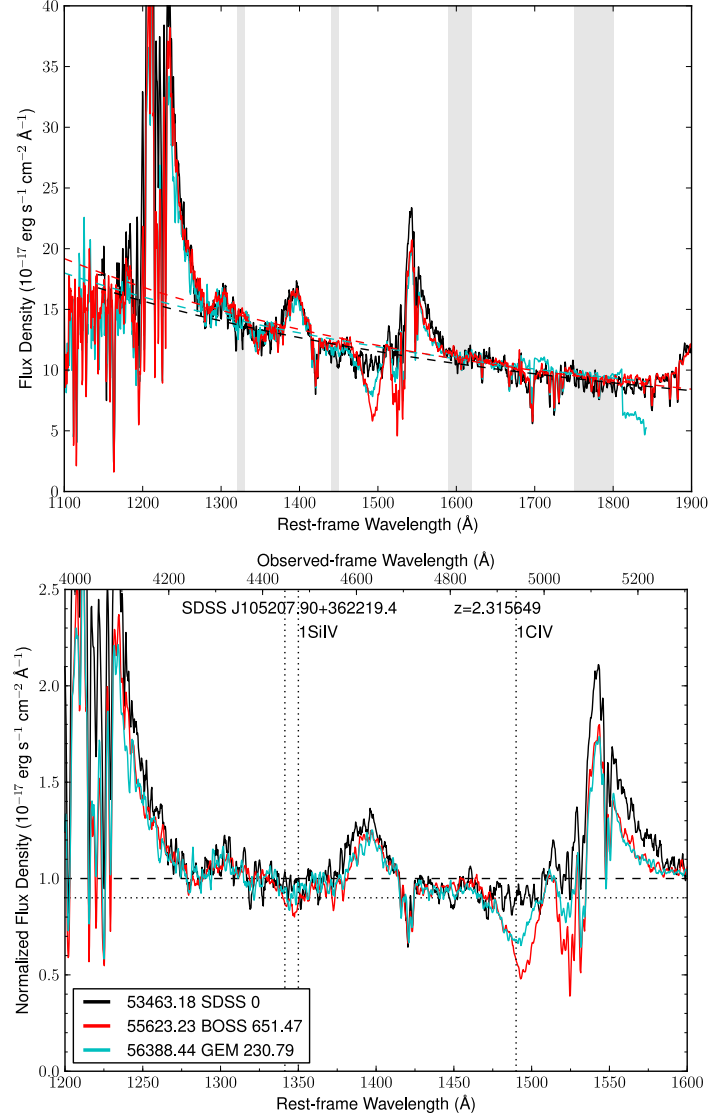


Figure 2.3: **top:** The unnormalized spectra for object J105207. The grey regions represent the normalization windows fit for the continuum removal. Dashed lines are the power-law fit to the normalization windows. **bottom:** The resulting normalized spectra. The horizontal dashed line is the continuum level. The horizontal dotted line is 90% the continuum, which is used in broad absorption identification later. The emergent C IV absorbing trough is labeled, along with where we expect accompanying Si IV absorption to occur. The legend gives the MJD of observation, and the rest-frame time between successive absorption.

2.4 Tabular Summary of Observations

This section provides the complete list of 105 quasars that were observed in the Gemini Campaigns. Each quasar is labeled by its SDSS DR7 name, in the form of SDSS Jhhmmss.ss±ddmmss.ss, where hhmmss.ss is the right ascension and ddmss.ss is the declination of the target on the sky in J2000.0 format. Though the reader should note that in this work we typically refer to each object by just the first half of that name: Jhhmmss. Each quasar’s apparent magnitude, as measured in the g filter by SDSS, and observational redshift are in columns 2 and 3, respectively; both of these values are used in preparing observing plans (i.e., integration times, instruments, grating, etc.). The redshifts in column 3 are taken from Hewett & Wild (2010), which are more accurate than the original SDSS redshift values. There are a few exceptions to this, in the cases of quasars discovered in DR9 or DR10; they are denoted with a ‘b’ next to their redshifts in the table. Columns 4, 5, and 6 tally the total observations culled from SDSS, BOSS, and Gemini, respectively, with the 7th column giving the total number of spectral epochs for each target. In the 8th column is the number of absorption complexes identified in the quasar (see § 3.4). In the last column, the smallest and largest rest-frame time between observations per target is given.

Table 2.2: The Full List of Targets in the Sample

Object	g_{mag}	z	SDSS	BOSS	GEM	Total	# Abs	ΔT
SDSS J000330.19+000813.2	19.18	2.59	1	1	1	3	3	271.4–824.1
SDSS J001641.17+010045.2	19.74	3.05	2	1	1	4	6	178.9–731.7
SDSS J002845.77+010648.3	20.01	2.47	1	2	1	4	1	76.6–648.8
SDSS J004041.63–010235.7	20.48	3.12	2	1	1	4	3	22.5–359.6
SDSS J004047.76+073310.3	19.32	2.8	1	1	1	3	3	186.6–573.8
SDSS J012700.69–004559.2	19.73	4.1	2	1	1	4	1	2.8–643.0
SDSS J015017.71+002902.4	19.2	3.0	2	2	1	5	3	0.9–744.6
SDSS J021045.01–074715.5	19.89	2.61	1	1	1	3	2	214.4–1014.4
SDSS J022143.19–001803.8	19.07	2.65	2	1	1	4	1	1.9–505.6
SDSS J022559.78–073938.8	19.73	3.02	1	1	1	3	3	191.7–975.7
SDSS J023011.28+005913.6 ^a	19.52	2.47	2	2	3	7	2	10.3–652.5
SDSS J073232.80+435500.4	19.53	3.46	1	1	5	7	1	5.8–418.2
SDSS J074711.14+273903.3	19.91	4.13	2	1	1	4	1	5.0–569.0
SDSS J081114.66+172057.4	18.23	2.33	1	1	1	3	3	224.7–667.4
SDSS J081811.49+053713.9	18.23	2.52	2	1	1	4	3	63.9–830.5
SDSS J082313.06+535024.0	19.3	2.56	2	2	1	5	2	23.1–506.1
SDSS J082801.67+411937.2	19.22	2.55	2	1	1	4	2	229.3–636.1
SDSS J083017.31+413521.5	19.49	2.21	2	1	4	7	1	10.2–703.4

Continued on next page...

Table 2.2 – continued from previous page

Object	g_{mag}	z	SDSS	BOSS	GEM	Total	# Abs	ΔT
SDSS J083546.51+351300.8	19.11	3.31	1	1	4	6	1	4.5–664.9
SDSS J083925.61+045420.2	20.22	2.47	2	2	1	5	3	16.7–813.6
SDSS J085825.71+005006.7	18.89	2.86	1	1	1	3	2	290.2–938.2
SDSS J090215.06+202026.3	20.49	3.33	1	2	1	4	4	2.8–533.2
SDSS J090410.43+211531.0	19.35	2.11	1	2	1	4	1	1.9–737.1
SDSS J090556.79+462727.6	18.52	2.51	1	2	1	4	2	18.7–961.0
SDSS J090842.27+081949.8	20.04	3.12	1	1	1	3	2	186.1–717.8
SDSS J091301.01+422344.7	17.54	2.32	1	1	1	3	1	85.7–1001.4
SDSS J091415.53+113820.9	19.38	3.01	1	1	1	3	1	178.2–472.6
SDSS J091621.46+010015.4	18.97	2.18	1	1	1	3	3	252.1–1135.9
SDSS J092303.05+173324.2	19.41	2.78	1	1	1	3	4	204.3–582.7
SDSS J094017.62+445431.4	19.25	1.72	1	1	1	3	3	301.9–1208.0
SDSS J094310.83+055632.8 ^b	19.42	2.69	0	2	1	3	1	73.7–203.6
SDSS J095254.10+021932.8	18.43	2.15	1	1	1	3	2	218.2–1185.3
SDSS J100945.47+120927.0	18.98	2.25	1	1	1	3	4	228.3–903.7
SDSS J103821.23+094322.9	21.42	3.65	1	1	1	3	2	176.4–692.3
SDSS J103842.14+350906.9	19.06	2.2	1	1	1	3	3	235.0–665.0
SDSS J104101.36+104251.7	17.88	2.17	1	1	1	3	1	249.4–903.7
SDSS J105207.90+362219.4	18.88	2.32	1	1	1	3	3	230.8–651.5
SDSS J105210.67+073805.6	20.74	3.21	1	1	1	3	3	187.1–773.4
SDSS J105454.51+015008.4	18.51	2.24	1	1	1	3	1	339.2–1018.2
SDSS J105632.75+373910.0	17.08	1.86	2	1	1	4	3	9.4–751.7
SDSS J111231.00+032040.9	19.15	3.29	1	1	1	3	3	197.6–827.0
SDSS J111337.46+030053.9	18.01	2.49	1	1	1	3	2	312.2–937.0
SDSS J113536.40+084219.0	19.4	3.85	1	1	1	3	2	170.8–656.1
SDSS J114440.30+012143.8	18.54	2.43	1	1	1	3	2	208.4–1059.0
SDSS J114832.37+074923.4	19.04	2.54	1	1	1	3	1	200.7–734.8
SDSS J115122.14+020426.3	19.05	2.41	1	1	1	3	4	214.1–1051.1
SDSS J115831.61+131917.6	21.37	3.73	1	1	1	3	2	144.9–605.3
SDSS J120206.80+370919.5	19.09	2.48	1	1	1	3	3	211.2–619.3
SDSS J120315.72–011123.6	19.09	2.61	1	1	1	3	1	288.5–920.7
SDSS J120729.75+042910.0	18.18	2.43	1	1	1	3	2	318.9–950.3
SDSS J121314.03+080703.6	18.22	2.37	1	1	1	3	0	232.1–759.3
SDSS J122646.01+010235.0	19.57	2.39	1	2	1	4	2	20.9–1060.9
SDSS J123149.92+064436.2 ^b	20.39	2.22	0	2	1	3	4	77.5–247.6
SDSS J123404.81+041512.7	19.01	2.36	1	1	1	3	1	205.0–980.9

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Table 2.2 – continued from previous page

Object	g_{mag}	z	SDSS	BOSS	GEM	Total	# Abs	ΔT
SDSS J123641.01+195043.9	19.34	1.87	1	1	1	3	1	272.6–544.5
SDSS J123720.85–011314.9	19.19	2.16	1	1	1	3	4	363.3–1034.8
SDSS J124720.26–011343.1	19.43	2.28	1	2	1	4	3	2.4–1100.0
SDSS J124829.45+341231.3	18.44	2.23	1	1	1	3	2	320.2–482.3
SDSS J125145.10+083635.5	20.94	3.78	1	1	1	3	5	167.0–357.6
SDSS J130600.56+220826.7	18.96	2.12	1	1	1	3	1	244.1–499.9
SDSS J130931.03+051745.3	19.42	3.08	1	2	1	4	2	7.3–812.6
SDSS J131026.78+033230.1	19.22	2.29	2	1	1	4	1	80.4–1022.5
SDSS J131425.55+245926.6	20.15	3.0	1	1	1	3	2	161.3–465.5
SDSS J131433.83+032321.9	18.61	2.26	2	1	1	4	4	81.1–1031.9
SDSS J131542.17+074753.7	19.04	2.47	1	1	1	3	3	217.9–418.4
SDSS J132508.81+122314.2	18.22	1.77	1	1	1	3	2	260.0–1032.2
SDSS J132700.20+245009.2	19.15	2.5	1	1	1	3	1	184.8–449.3
SDSS J132758.83–023025.4	19.23	2.36	1	1	1	3	2	226.5–944.3
SDSS J132846.06+114007.3	21.16	3.7	1	1	1	3	2	153.5–608.8
SDSS J132938.94+401708.5	20.07	3.74	1	2	1	4	2	10.7–540.4
SDSS J134605.45+142920.7	18.58	2.58	1	1	1	3	3	217.1–603.1
SDSS J135203.25+024643.5	19.85	2.55	1	1	1	3	1	292.5–931.1
SDSS J135448.57+103610.8	18.63	3.14	1	1	1	3	2	178.3–687.0
SDSS J135711.25+250000.4	18.69	1.99	1	1	1	3	2	246.6–767.7
SDSS J140224.15+003002.2	18.94	2.42	2	1	1	4	2	88.1–1079.1
SDSS J140815.58+060023.2	19.16	2.58	1	1	1	3	3	189.5–612.3
SDSS J140837.24+164503.0	20.71	4.05	1	1	1	3	6	144.1–296.5
SDSS J142054.41+160333.3	19.21	2.02	1	1	1	3	1	234.5–597.8
SDSS J142110.21+392137.8	18.29	2.31	1	2	1	4	1	89.0–802.8
SDSS J142903.03–014519.3	18.74	3.42	1	1	1	3	0	250.1–726.7
SDSS J143046.29+261204.9	18.27	2.42	1	1	1	3	1	189.2–659.2
SDSS J143308.08+223758.5	20.3	2.97	1	1	1	3	1	190.4–649.2
SDSS J143406.28+440741.8	19.25	3.06	1	1	1	3	2	179.4–828.8
SDSS J143711.31+131533.3	20.42	2.94	1	1	1	3	1	193.8–636.9
SDSS J145230.38+130227.3	17.97	2.51	1	1	1	3	1	211.5–510.1
SDSS J145952.05+321320.3	19.2	3.02	1	1	1	3	1	269.4–522.5
SDSS J150935.13+284154.4	19.79	3.26	1	1	1	3	2	289.4–342.6
SDSS J151128.77+265133.1	19.21	2.43	1	2	1	4	3	80.0–330.2
SDSS J153439.53+054229.4	20.22	3.08	1	2	1	4	1	5.1–369.1
SDSS J154718.70+341120.2 ^b	19.91	2.71	0	2	1	3	2	78.9–197.6

Continued on next page...

Table 2.2 – continued from previous page

Object	g_{mag}	z	SDSS	BOSS	GEM	Total	# Abs	ΔT
SDSS J154844.60+045907.6	19.15	2.39	1	1	1	3	2	201.6–329.7
SDSS J155506.40+365356.1	18.47	2.57	1	1	1	3	1	221.0–804.8
SDSS J160008.42+120724.3	19.28	2.24	1	1	1	3	1	310.0–355.0
SDSS J160216.74+293038.8	18.98	2.27	1	1	1	3	1	198.8–677.3
SDSS J161336.81+054701.7	19.17	2.49	1	1	2	4	2	144.3–522.7
SDSS J163112.06+273141.1	19.16	3.3	1	1	1	3	1	252.1–681.5
SDSS J164646.69+355558.0	19.19	2.26	1	1	1	3	1	308.2–1048.4
SDSS J165044.78+390045.6	18.32	3.16	1	1	1	3	2	157.8–967.5
SDSS J165642.32+401358.0	20.19	2.52	1	1	1	3	2	124.9–530.8
SDSS J213231.09+101254.1	19.21	2.19	1	1	1	3	1	306.1–942.5
SDSS J220813.99+125046.3	19.3	2.26	1	1	1	3	3	206.9–1024.8
SDSS J221019.53+144723.0	20.18	2.59	1	1	1	3	4	22.5–214.2
SDSS J221631.48+130731.6	19.56	2.27	2	1	1	4	2	3.8–1077.8
SDSS J222838.05+023202.5	19.11	3.27	1	1	1	3	1	89.2–167.1
SDSS J230638.25–010700.2	19.23	2.31	1	1	1	3	2	313.3–782.2

^a The redshift for J023011 was determined separately. See Chapter 5.

^b These targets were not discovered until BOSS, and thus they were not part of the Hewett & Wild (2010) analysis. We use the redshifts as determined by the BOSS DR9 pipeline.

2.5 Individual Target Notes

While all of the above data preparation was automated, there were some targets that required special attention. This section summarizes any approaches that deviated from the automatic data preparation above.

J145952. Only one of the two dithered Gemini spectra were used for this target due to data corruption in one of them. See § 2.2.2.

J083017. In the GEM3 epoch, only one of the two dithered Gemini spectra were used for this target due to data corruption in one of them. See § 2.2.2.

J083925. This quasar had multiple C IV absorbers, each with accompanying Si IV. In some cases, Si IV accompanying one C IV absorber merged with a C IV absorber at different velocities. In order to measure physical parameters of these troughs individually later on, we adjust the spectra by hand at this stage to artificially separate troughs; this occurred at 4850 Å in the SDSS2 epoch and 4580 Å in the BOSS1 epoch.

J105210. In the Gemini epoch of this target, we manually adjusted the smoothed spectrum in

order to ensure the emergent Si IV absorption feature was measured properly. In all epoch before the Gemini one, an intervening system had been measured along with any broad absorption. Adjusting the Gemini epoch made sure the same intervening system was captured in all three epochs.

J111337. There is an emission feature at 1325 Å in the Gemini spectrum that is not real.

J113536. The Gemini data in this quasar was manually smoothed with a window of 7 pixels in order to pull out a high-velocity absorber.

122646. The emergent absorption this quasar was selected for did not measure to be significant absorption, however, other BALs in this quasar lead to it still being a BAL quasar.

J132508. For the SDSS epoch on this target, we manually split an intervening system out of a broad trough to ensure proper comparison to later epochs.

J142054. We manually smoothed the BOSS spectrum by a window of 7 to make absorption features much clearer. Originally, the BOSS spectrum was the best SNR in this quasar's data set.

J155506. The Gemini epoch, which was the best SNR, was manually smoothed by a boxcar window of 3 pixels to pull out some absorption. Only one of the Gemini settings was used; the other was bad data.

J164646. Only one of the two dithered Gemini spectra were used for this target due to data corruption in one of them. See § 2.2.2.

2.6 Summary of the Dataset

In this section, it is described how the data was collected. This began by first using the archival quasar data of the SDSS and BOSS collaborations. Visual inspections yielded over 300 quasars that exhibited emergent absorption in their spectra. This means there was broad absorption features that had appeared sometime between an SDSS observation and a later BOSS spectrum. We successfully proposed for follow up observations on 105 of the 300 quasars identified visually, yielding a dataset of 105 quasars with at least 3 spectral observations. All data was normalized and prepared for analysis in the following chapters.

Chapter 3

Identification and Quantification of Absorption

In this chapter we present a quantitative method by which to identify broad absorption in quasar spectra: the BALnicity Index, described below. This method is based on historical considerations but has been modified herein to more appropriately encompass all absorption in our dataset that is rooted in the same physical origin (i.e., eliminating narrow or intervening systems). The process begins by first smoothing the multiple spectra of each quasar such that the signal-to-noise ratios are as similar as possible. After smoothing, the absorption in all data is identified. A thorough visual inspection of the identified absorption is performed in order to remove any further contaminants. Also in this chapter, we introduce the parameters we measure to determine the strength of the absorption (e.g., depth, width, etc.).

3.1 Signal-to-Noise and Smoothing

The Signal-to-Noise Ratio (SNR) of a spectrum is found by taking the ratio of the signal to the noise level in the data. A common approach to measuring this in BAL quasars is to measure SN_{1700} : the median of the flux density divided by the noise for all spectral bins between $1650 - 1750 \text{ \AA}$ in the rest-frame (e.g., Gibson et al. 2009). This wavelength region has been commonly used because it is typically free from any absorption or emission features. While this region could be used to measure the SNR in the SDSS or BOSS data, our Gemini data does not necessarily cover redward of $1750 \text{ \AA}$. Thus, we measure SN_{1500} : the median of the flux density/noise for all bins between $1400 - 1600 \text{ \AA}$. We recognize this region contains both emission (Si IV and C IV) as well as the variable broad absorption we analyze in this work, but we do not believe this will greatly impact the SNR measurement.

An unfortunate side effect of our data being collected with different telescopes and instruments is the resulting wide range of SNR for each spectral epoch. For example, in the case of SDSS

J21045.01 – 074715.5 we have three spectral epochs that measure SNRs of 5.1 (SDSS), 12.8 (BOSS), and 33.2 (GEM). In order to compare these spectra properly, we applied a variable smoothing routine. We do not need to re-bin each spectrum to create identical spectral resolution before smoothing because the resolutions of SDSS, BOSS, and Gemini data are already similar.

Spectral smoothing is the act of approximating an underlying pattern while reducing any statistical noise that may make the pattern difficult to see. A common smoothing approach is the boxcar averaging routine, which we use in this work. If one is smoothing out statistical white noise where the amplitude of the noise will be similar regardless of where on the spectrum you measure, boxcar is the best method. Boxcar smoothing is where the input signal $y(x)$ is smoothed to $y'(x)$, where each value in $y'(x)$ is the average of the n pixels adjacent to it. The user is required to set the averaging window n , where n is an odd number. A boxcar smoothing algorithm can be written as,

$$y'(x) = \frac{1}{n} \sum_{i=-n/2}^{n/2} y[x+i]. \quad (3.1)$$

The averaging window is set to an odd number because the average is centred on the value at x and thus an odd number would sample an equal amount of values either side of the value at x . For our purposes, we are smoothing the normalized flux density of each spectrum. The value at each pixel is set to the average normalized flux density of all pixels within the averaging window (centred on the original pixel) and the same is done for the noise variance at each pixel. By smoothing a spectrum, we increase its SNR. This is done at the expense of the underlying shape and amplitude of the spectrum. For example, smoothing would make emission features slightly smaller, and absorption features not as deep. The impact smoothing has on the shape/amplitude is related to the width of the averaging window. In order to be sure we do not affect the overall shape of the spectrum we instituted a smoothing limit.

As in the example of SDSS J21045.01 – 074715.5 above, a given quasar’s SNR can range from epoch to epoch. To bring their SNRs values closer to each other, thus making variability comparisons more meaningful, we apply the following routine. First we determine which spectrum has the highest SN_{1500} for the quasar. All other spectra for this quasar are iteratively smoothed and their SN_{1500} is re-calculated until a value is reached that is at least equal to highest SN_{1500} found in any spectrum for the quasar.

For some quasars, the disparity in SNR between epochs requires boxcar windows much higher than would be reasonable. As a result, we capped the window size at 9 pixels, leaving many spectra with improved SNR but not necessarily equal to the best SNR spectrum for the quasar. The raw spectra used from SDSS, BOSS, and Gemini all had similar spectral resolutions, resulting in the wavelength separation between pixels to be $\sim 2 \text{ \AA}$. Thus, a window of 9 pixels would equal roughly $18 \text{ \AA}$. In the next section, we set a lower limit of 1000 km s^{-1} , or $\sim 5 \text{ \AA}$, on the width of an absorption trough below which the absorption would not be considered broad. A window of 9 pixels would be larger than the width of some troughs. We do not consider this to be an issue.

In Figure 3.1, an example of the spectra for object J083017 before smoothing (top) and after smoothing (bottom) is given. The spectra have already been normalized and have been separated artificially for ease of viewing. The continuum for each is the dotted line. In the before figure, it is clear there is a wide range in SN_{1500} for the three spectra available for J083017. In the after figure, we attempted to match the SN_{1500} value for the SDSS and BOSS observations to that of the Gemini observation.

3.2 Identification of Broad Absorption Lines

The targets selected in § 2.1 were found by visual identification of emergent broad absorption (see § 2.1 for more details on this process). This was a satisfactory approach to determine an initial set of quasars to study, but we did not apply a formal definition of absorption that confirmed the visual emergence as statistically significant absorption (i.e., within the noise). Some broad absorption is very obvious, but there are cases where it can be difficult to tell whether or not absorption is present. Multiple factors contribute to this, such as: absorption overlapping with emission features, data with low signal-to-noise ratio, or simply weak/shallow absorption. A formal definition that would cleanly separate quasars into those with broad absorption lines (BAL quasars), and those without (non-BAL quasars), was required in order to remove any subjectivity related to the above factors. Further, it was important to create a definition that would allow comparison of the trough strength in BAL quasars. In response to this need, Weymann et al. (1991) defined the BALnicity Index (BI). Here we reproduce that definition, point out its shortcomings, and redefine it for our use in this work.

The original definition of BI from the above work measured the amount of absorption (in units of km s^{-1}) of C IV by integrating over the absorption trough from the lower velocity limit of the trough to the higher velocity limit. Thus, the integration begins at the point the absorption is closest to the C IV emission-line and continues to the furthest point. Also, in order to be counted towards the integration, the absorption must meet the following criteria. Firstly, any absorption that is included in the index must be at least $2,000 \text{ km s}^{-1}$ wide. It is important to note that only the absorption after this condition is satisfied is counted towards BI. Thus, any absorption in the first $2,000 \text{ km s}^{-1}$ is not included in the actual BI. This was introduced to exclude any narrow intervening systems that are physically distinct from the BAL troughs created in outflowing gas. Secondly, any absorption found within the first $3,000 \text{ km s}^{-1}$ blueward of the C IV emission peak (at $\sim 1550 \text{ \AA}$) is ignored, which was introduced as a way of ignoring ‘associated’¹ absorption systems. Thirdly, no absorption after $25,000 \text{ km s}^{-1}$ blueward of the C IV emission peak is included, such absorption begins to overlap with the Si IV emission at $\sim 1400 \text{ \AA}$. Finally, the flux density in the trough must be below 90% of the normalized flux density at the continuum. This was introduced to account for possible errors in fitting the quasar’s continuum.

¹Associated systems are defined as absorption occurring on top of its own emission feature; e.g., C IV absorption on the C IV emission feature.

The above rules can be written into the following equation:

$$\text{BI} = \int_{3000}^{25000} \left(1 - \frac{f(v)}{0.9} \right) C dv, \quad (3.2)$$

where 0 km s^{-1} is at the systemic redshift of the quasar, positive velocities represent blueshift, and $f(v)$ is the flux density at a given velocity. The quantity C is equal to 1 only when the quantity in parentheses has been greater than zero for more than $2,000 \text{ km s}^{-1}$, otherwise it is set to 0. Under this original definition, the maximum value of BI would be $\text{BI} = 20,000 \text{ km s}^{-1}$.

As research into BAL quasars progressed, it was realized that this original definition of BALnicity erred on the conservative side; it does not fully encompass all intrinsic broad absorption observed in quasar spectra. For example, a trough narrower than the $2,000 \text{ km s}^{-1}$ criterion can be still rooted in the same physical origin as broader troughs and should be included. These are known as ‘mini-BAL’ troughs in the literature and range in width from $500\text{--}2,000 \text{ km s}^{-1}$ (see Rodríguez Hidalgo et al. 2011 for a full discussion on mini-BAL quasars). Modifications of the BALnicity Index have been proposed, e.g. Hall et al. 2002, Trump et al. 2006, to include absorption over wider velocity ranges.

For this work we measure BALnicity using a modification of the index proposed in Trump et al. (2006), which we define as:

$$\text{BI}^* = \int_{v_{low}}^{v_{high}} \left(1 - \frac{f(v)}{0.9} \right) C dv, \quad (3.3)$$

using the asterisk to distinguish it from the original definition of BI. Included in our target selection was a search for C IV absorption occurring blueward of the Si IV feature at $\sim 1400 \text{ \AA}$. This places the outflow velocity of the winds generating the absorption at $>25,000 \text{ km s}^{-1}$. As all previous modifications of the BI only focussed on the region between C IV and Si IV emission, this absorption is left out. In the above equation, v_{low} and v_{high} are purposefully not defined to indicate there is no formal limit on the minimum and maximum absorbing velocities. This accounts for our interest in high-velocity absorption. We also relaxed the trough width requirement; troughs must be at least $1,000 \text{ km s}^{-1}$ wide, and we include all absorption in that first $1,000 \text{ km s}^{-1}$ (this is similar to Trump et al. 2006, for example). Therefore, C is equal to 1 only in regions more than $1,000 \text{ km s}^{-1}$ wide in which the quantity in parentheses is everywhere greater than zero, otherwise it is set to 0. If $\text{BI}^* > 0$ we consider there to be statistically significant absorption present; a $\text{BI}^* = 0$ indicates no absorption is present.

In § 2.1, targets with possible absorption anywhere between the Ly α emission and C IV emission were chosen. Thus, while no formal limits on the BALnicity were required for this work, in practice the bounds on BI^* were set to $0 < v \text{ (km s}^{-1}\text{)} < 65,000$.

3.3 Visual Inspection

All normalized spectra were run through an automatic BALnicity measurement routine developed by the author. As part of this routine, each spectrum was automatically smoothed by an additional

3-pixel-wide boxcar average on top of the variable smoothing from § 3.1. The compounded effects of boxcar-smoothing an already boxcar-smoothed spectrum results in what is commonly known as Savitsky-Golay smoothing; this is a form of smoothing that weights pixels closer to the centre pixel higher than those at the edge of the smoothing window (see Savitzky & Golay 1964). All absorption meeting the BI* requirements identified by the measurement routine was visually inspected for any contamination. There are a number of possible contaminants that required visual confirmation or elimination. Intervening absorption or narrow C IV systems are, by design, meant to be ignored by BI*. However, a spectrum that was heavily smoothed with our technique may smooth out narrow systems into wider ones even though they were quite clearly not BAL troughs. They were removed by hand. There were also a number of accompanying Si IV BAL troughs that were removed.

After all non-C IV-BAL related detections were removed, there were a total of 653 individual C IV absorption troughs across 360 normalized spectra. To quantify the strength of the absorption in this sample of absorption troughs, we measure each trough’s centroid velocity (in km s^{-1}), width (in km s^{-1}), and depth (distance from normalized continuum in normalized flux density units). Thus a measured depth of 0.3, is 0.3 normalized flux density units below the continuum at 1.0. The centroid velocity, v_{cent} , of a trough was measured following the definition in Filiz Ak et al. (2013): the mean of the velocity in a trough where each pixel is weighted by its distance from the normalized continuum. The width of a trough is the velocity range over which the trough met the BI* criteria.

The mean depth of the trough was calculated in two ways. First, we measured d_{BAL} as in Filiz Ak et al. (2013), which is the mean depth of the trough relative to the normalized continuum of 1.0 for each data point in the trough. Second, we measured d_{max7} , which is calculated by sliding a 7-pixel-wide window across the trough and measuring the average depth over each window relative to the normalized continuum at 1.0. We take the largest depth over all these windows as d_{max7} . The uncertainty on the depth is calculated as the uncertainty in the mean of the 7 pixels in the average. We note that since the observations were taken with different telescopes and instrument set ups, 7 pixels correspond to slightly different resolutions; however, the differences do not substantially affect the results.

The distribution of trough width versus trough centroid velocity is plotted in Figure 3.2. The mean centroid velocity in the plot is $19,500 \text{ km s}^{-1}$, and the mean trough width is $3,600 \text{ km s}^{-1}$. The widest troughs appear to cluster between $15,000 < v \text{ (km s}^{-1}) < 25,000$. There are noticeable gaps in the distribution at $30,000 \text{ km s}^{-1}$ due to Si IV emission at $\sim 1400 \text{ \AA}$, at $43,000 \text{ km s}^{-1}$ due to C II emission at $\sim 1335 \text{ \AA}$, and at $50,000 \text{ km s}^{-1}$ due to O I emission at $\sim 1304 \text{ \AA}$. Since emission is present, it raises the flux density level at which absorption starts at, while the amount of absorption stays the same. There is likely absorption present at these velocities but would require a very massive absorber to be detected. The widest trough, at $22,200 \text{ km s}^{-1}$, was observed in J083546; its spectra are plotted in Figure 4.10.

The distribution of trough depth (both d_{BAL} and d_{max7}) versus trough centroid velocity is

plotted in Figure 3.3. d_{max7} is more sensitive to narrow features as it is an average of the deepest 7 contiguous pixels, d_{BAL} is more representative of the entire trough; thus, d_{max7} measures on average larger depths. In black is d_{BAL} , with a mean value of 0.24, and in red is d_{max7} with mean 0.32. The d_{max7} value at 0.6 and approximately $57,000 \text{ km s}^{-1}$ is from object J105210, and is the result of an intervening absorber sitting on top of a BAL at high velocity.

In Figure 3.4, the trough width is plotted against the BI^* of each trough. The mean BI^* is 678 km s^{-1} . The largest value of BI^* is found in J130600. In its BOSS spectrum, the absorption spans the entire region between C IV and Si IV emission, reaches $d_{BAL} = 0.4$, and width of $17,600 \text{ km s}^{-1}$. It is the second-widest trough, next to J083546 above.

Finally, the trough depth (both d_{BAL} and d_{max7}) is plotted against trough width in Figure 3.5. The two data points at very high trough width are a result of J083546. Again, in this case d_{max7} is not the best measure of the depth of the trough because it is biased by a narrow feature sitting on top of the broad absorption.

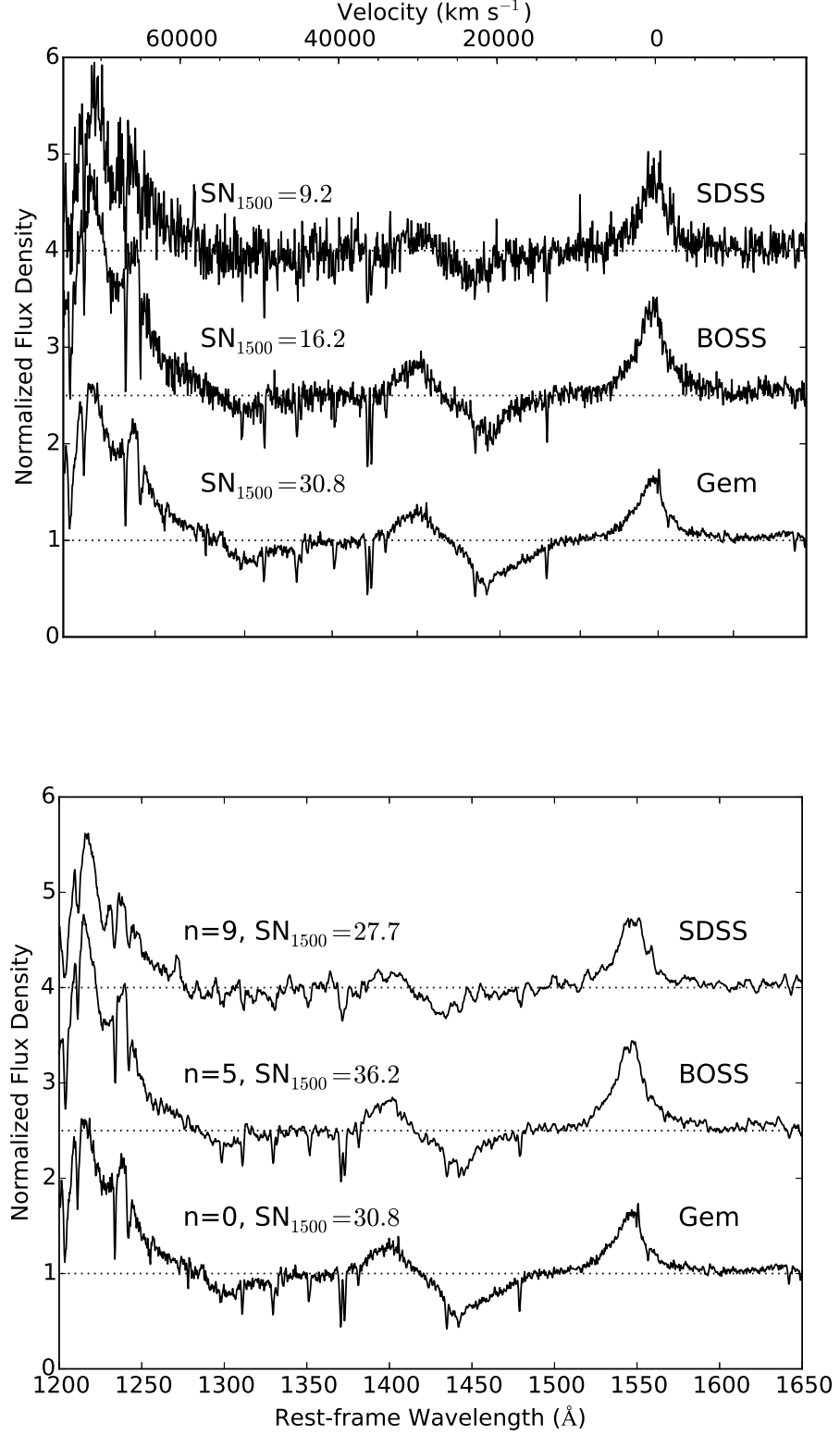


Figure 3.1: Each spectrum in this work was smoothed so that it had a signal-to-noise (SNR) measurement that was as close as possible to the highest SNR in a given quasar. **top** The unsmoothed spectra for object J083017 are plotted with their SNRs. The spectra are already normalized and are artificially separated (the dotted line represents the continuum for each spectrum). **bottom** The smoothed spectra and their new SNRs. The window size used in boxcar smoothing is labeled.

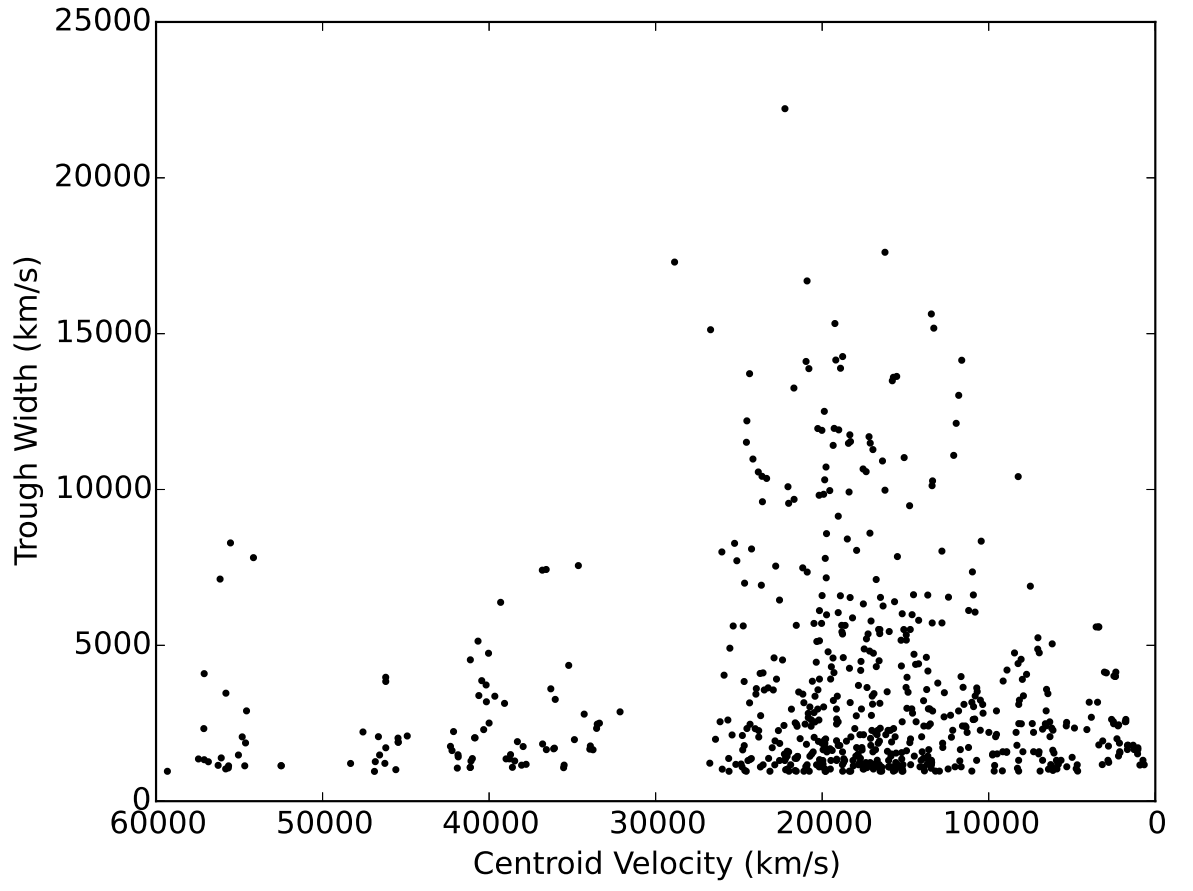


Figure 3.2: The distribution of trough widths and trough centroid velocities for all absorption identified by the BI* criteria. There are a total of 653 absorption features in 360 spectra.

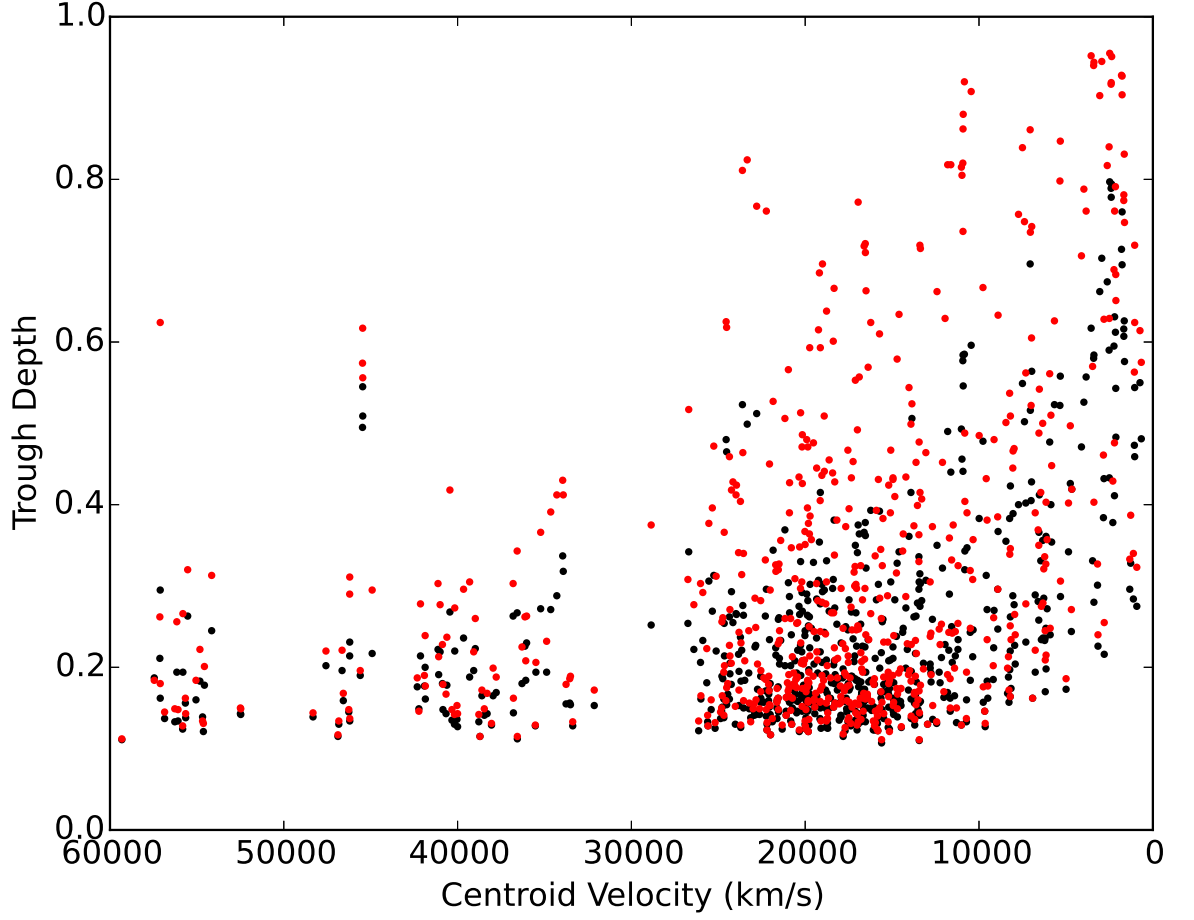


Figure 3.3: Comparing the depth of troughs relative to the normalized continuum at 1.0, versus their centroid velocities for all absorption identified by the BI* criteria. There are a total of 653 absorption features in 360 spectra. The black points are d_{BAL} , and the red points are d_{max7} .

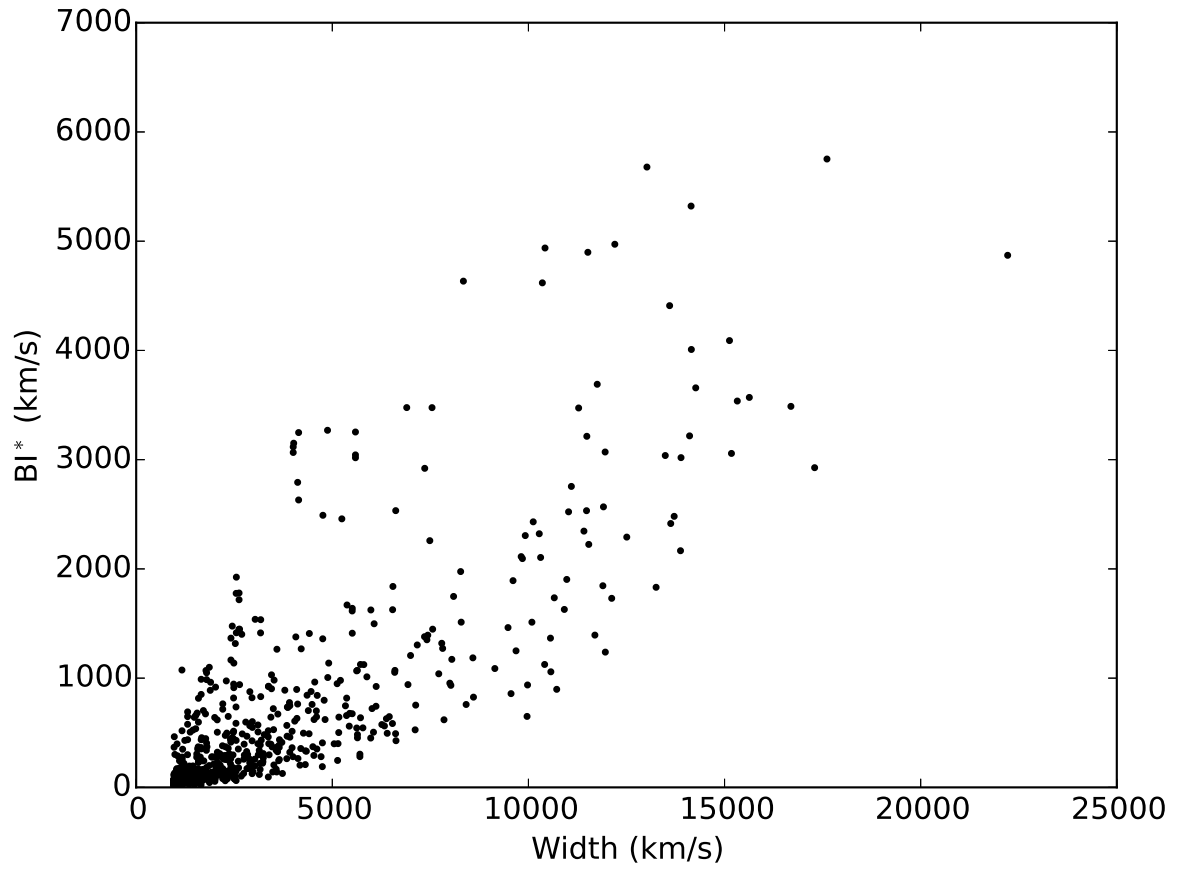


Figure 3.4: The BI^* plotted against the width of the troughs identified by BI^* .

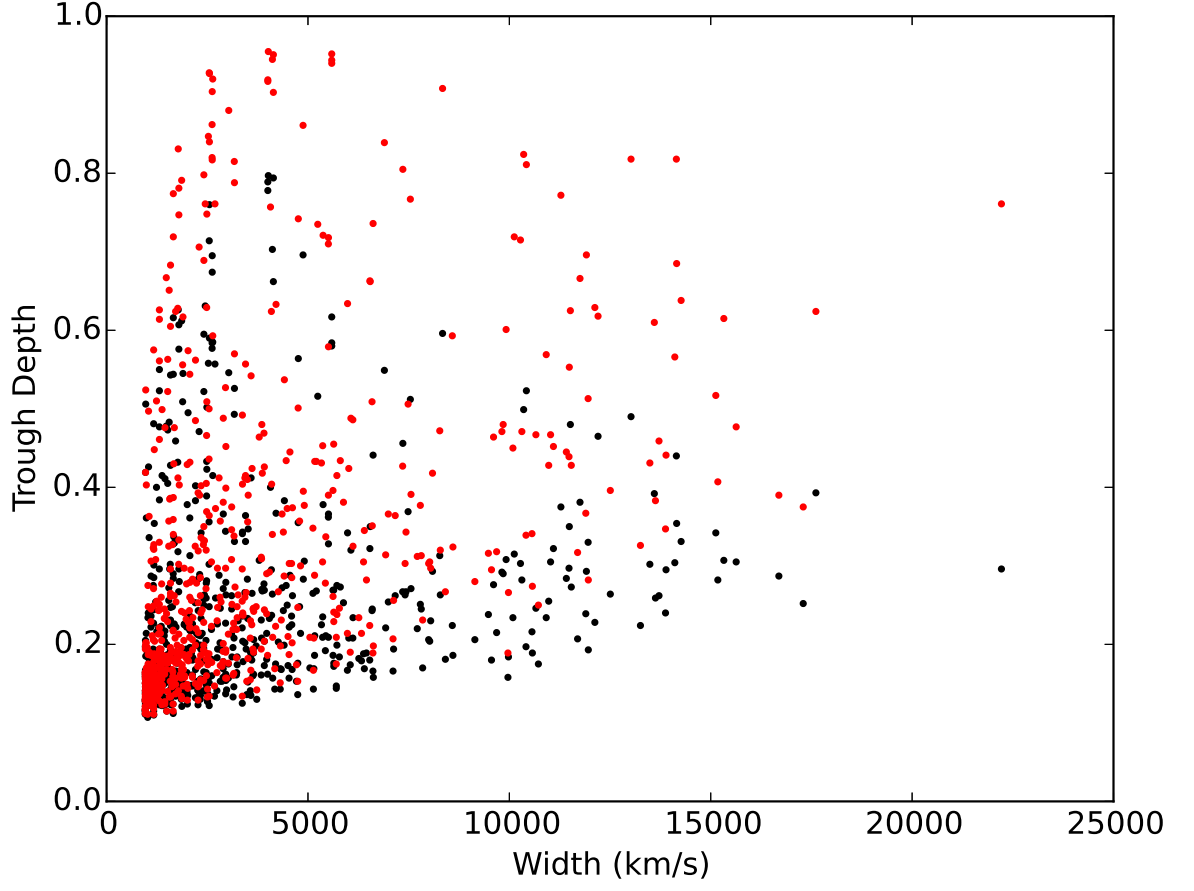


Figure 3.5: The depth d_{max7} (red) and d_{BAL} (black), relative to the continuum at 1.0, plotted against the velocity width of the trough.

3.4 Absorption Complexes

From epoch to epoch, a given trough may split into multiple smaller troughs as it decreases in absorption strength, or two adjacent smaller troughs may merge into one large trough as the absorption of one or both of the troughs widens, or the depth increases. In order to properly characterize the variability of broad absorption between epochs, we identify BAL complexes. We have mimicked the approach of Filiz Ak et al. (2013) in identifying complexes. In Figure 3.6, we have an example of how this identification is done for the quasar J082313. In the earliest epoch, no absorption feature is observed at all. In the following epoch a large trough emerges, spanning the region $1411.2 - 1475.3 \text{ \AA}$. In the final epoch, that large trough has split into two separate troughs spanning $1420.4 - 1426.0 \text{ \AA}$ and $1439.4 - 1466.9 \text{ \AA}$. We consider this all to be one complex of CIV absorption. To identify complexes, we following these steps:

1. Sort all troughs identified by the BALnicity code above in order from highest velocity to lowest. They are also sorted into spectral epoch order, from oldest to newest observations.
2. Begin with the highest velocity trough in the oldest spectrum, setting the v_{max} and v_{min} of the absorption complex to this trough's velocity range values.
3. Loop through all absorption features in the following epochs. If the complex's v_{max} intersects a trough in a later epoch, reset v_{max} to that trough's v_{max} . The same is done for v_{min} .
4. This is repeated for all absorption features identified by the BALnicity measurements above.
5. Repeat the entire process starting with the most recent epoch and moving towards the oldest.

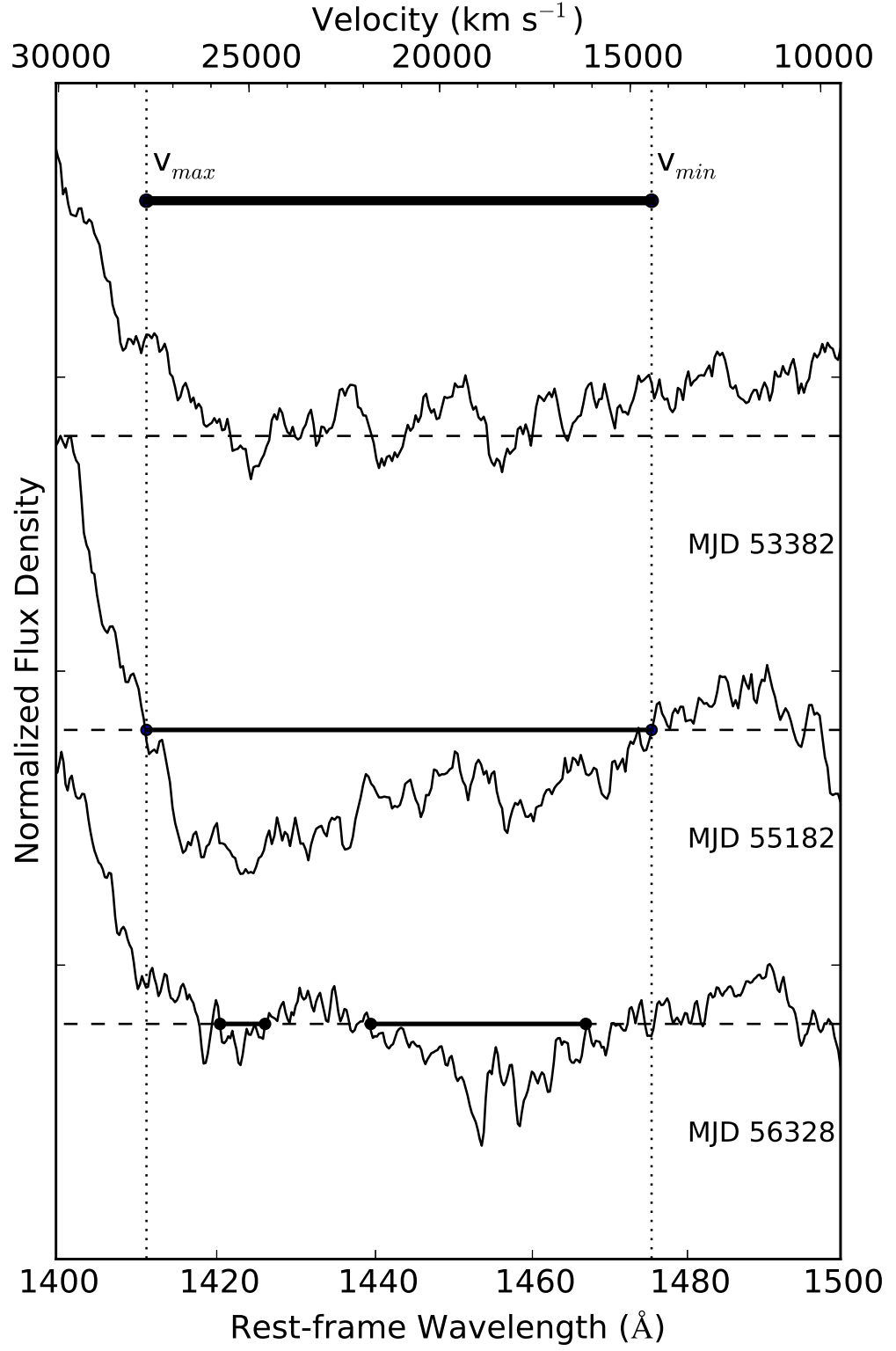


Figure 3.6: From quasar 082313.06+535024: The oldest spectral epoch is at the top, and each epoch is in chronological order after that (see the MJD label beside each spectrum). In the first epoch, there is no absorption, in the second a broad absorption trough appears, and in the final epoch, that trough splits into two. The thick horizontal lines indicate the individual trough(s), and the total absorption complex velocity width is labeled at the top from $v_{\max}$ to $v_{\min}$.

As is evident in Figure 3.6, this procedure results in a maximum and minimum velocity, v_{max} and v_{min} , respectively, range that encompasses all absorption in that region for all epochs; we define the difference between these two values as the velocity width of the absorption complex. Thus each individual CIV absorber is associated with one complex. Taking the 653 absorbers identified via BI* and running them through this routine results in 219 individual absorption complexes across all quasars in our sample.

3.5 Quantifying the Absorption

In order to quantify the variability in the absorption complexes identified in the previous section, we must measure some of their absorption parameters. After absorption complexes have been identified in the spectra, we measured the equivalent width (EW; in Å, defined below), the weighted centroid velocity v_{cent} , and the average trough depth (d_{BAL} and d_{max7}) over that region for all epochs of a quasar's spectrum. This is regardless of whether or not absorption is actually identified in the spectrum. For example, in Figure 3.6, the earliest spectral epoch at MJD 53382 exhibits no absorption, however, we still measure the EW, v_{cent} , and depth of the trough over the complex's range in this epoch. This provides us with a baseline from which to measure changes.

To measure the EW in Å and its uncertainty from the normalized spectra we followed equations 1 and 2 in Kaspi et al. (2002), which are,

$$EW = \sum_i \left(1 - \frac{F_i}{F_c} \right) B_i, \quad (3.4)$$

and,

$$\sigma_{EW} = \sqrt{\left[\frac{\Delta F_c}{F_c} \sum_i \left(\frac{B_i F_i}{F_c} \right) \right]^2 + \sum_i \left(\frac{B_i \Delta F_i}{F_c} \right)^2}. \quad (3.5)$$

F_i and ΔF_i are the normalized flux density and its error in the i th bin. F_c and ΔF_c are the mean and the uncertainty on the mean of the continuum normalized flux density measured in the normalization windows. B_i is the bin width in units of Å. In our normalized spectra, $F_c = 1$ and ΔF_c are calculated using the normalization windows determined by the normalization procedure in § 2.3. Thus σ_{EW} represents the statistical uncertainty inherent in spectra. It does not quantify the systemic uncertainty, which is governed by the placement of the continuum by normalization. The wavelength range over which the sums in equations (3.4) and (3.5) are measured is set by the identification of v_{max} and v_{min} in the previous section. The BI* is measured only when the normalized flux density is below 90% of total continuum for more than 1000 km s⁻¹. The beginning and ending wavelengths where this criterion is satisfied are carried over to the absorption complexes, and the EW is measured between them. Thus, while the range over which equations (3.4) and (3.5) are measured is set by this criterion, we still use $F_c = 1$ as the normalized continuum level (and not 0.9 as might have been expected).

As mentioned in § 3.3, we use the centroid velocities and mean depths as tool to compare troughs. We now apply the same measurements to the velocity range of the absorption complexes with a caveat in the case of measuring the centroid velocity. If in the absorption complex, the normalized flux density is above 1.0, the velocity of that bin is not counted towards the weighted mean v_{cent} . If *all* of the normalized flux density is above 1.0 for the absorption complex, which can happen in cases where absorption has disappeared on top of an emission feature, then all bins are weighted equally. This results in a centroid velocity being in the mean of the absorption complex's maximum and minimum velocities. Calculating the mean depths, d_{BAL} and d_{max7} , in the absorption complex is the same as before, i.e., the normalized flux density values above 1.0 are not ignored.

3.6 Measuring Variability

There are several ways to compare one epoch to the next for any of the absorption complexes. For example, we can measure the change in EW,

$$\Delta EW = EW_2 - EW_1 \quad \sigma_{\Delta EW} = \sqrt{\sigma_{EW_2}^2 + \sigma_{EW_1}^2}. \quad (3.6)$$

We can also measure the fractional change in EW, which is the change in EW from one epoch to the next divided by the average EW over both epochs (e.g, Gibson et al. 2008, Filiz Ak et al. 2013). This measurement indicates how significant a change in absorption is compared to the size of the feature that is changing.

$$\frac{\Delta EW}{\langle EW \rangle} = \frac{EW_2 - EW_1}{(EW_2 + EW_1) \times 0.5}, \quad (3.7)$$

$$\frac{\sigma_{\Delta EW}}{\langle EW \rangle} = \frac{4 \times (EW_2 \sigma_{EW_1} + EW_1 \sigma_{EW_2})}{(EW_2 + EW_1)^2}$$

Similarly, we can measure the change in depth from one epoch to the next, and those corresponding uncertainties:

$$\Delta d_{BAL} = d_{BAL,2} - d_{BAL,1} \quad \sigma_{\Delta d_{BAL}} = \sqrt{\sigma_{d_{BAL,2}}^2 + \sigma_{d_{BAL,1}}^2}. \quad (3.8)$$

$$\Delta d_{max7} = d_{max7,2} - d_{max7,1} \quad \sigma_{\Delta d_{max7}} = \sqrt{\sigma_{d_{max7,2}}^2 + \sigma_{d_{max7,1}}^2}.$$

These diagnostics of variability are calculated between all epochs for all 105 quasars in the dataset. The analysis is presented in the next chapter.

3.7 Summary of the Investigative Approach

In this section we have described the BALnicity Index: a standardized parameter, which the literature has used identify broad absorption amongst any other absorption in quasar spectra. We augmented the Index from its historical definition, while still keeping the overall spirit of the parameter, in order to identify and study a more complete set of broad absorption present in our dataset. Using the index, we identified all true broad absorption, and presented their physical parameters in multiple plots. The troughs were then organized into absorption complexes, defined as regions in quasar spectra that encompasses a discrete amount of absorption that varies from epoch to epoch. Absorption complexes provide a more physically meaningful region over which to study variability.

In this chapter we also introduced multiple physical parameters by which to study both the strength of absorption in a given complex, but also the variability in a given complex from epoch to epoch. In the following chapter we will present the results of our variability measurements and offer physical interpretation where applicable.

Chapter 4

Results and Discussion

In this chapter we present an analysis of the absorption complexes identified in the previous chapter. First, we fully characterize the complexes by plotting their various physical parameters. The number of quasars that transition from non-BAL to BAL, or from BAL to non-BAL is determined. Given the multi-epoch nature of our dataset, we also determine what happens to a trough, statistically, after it emerges in a quasar. Many of the quasars in our dataset have multiple absorption troughs in their spectra. As a result, we were able to calculate the prevalence of coordinated variability in BAL quasars. Coordination between troughs is defined as two troughs either increasing or decreasing their absorption strength in synchronization. Where appropriate or possible, a discussion of the physical implications of the results we present is given, in the context of understanding broad absorption line outflows.

We begin the chapter, however, with specific notes on individual quasars.

4.1 Individual Notes

J004041. This target had very noisy spectra in all SDSS and BOSS data. Maximal boxcar smoothing was used for all data, except for the data in Gemini epoch. We elected to drop the BOSS1 spectrum; it was too noisy to be of any use.

J021045. The associated absorption system at the systemic redshift has a Si IV accompanying component that likely contributes to the BI of the major absorption feature.

J074711. There is a large absorption feature at $\sim 1480 \text{ \AA}$ in the quasar rest-frame which is actually atmospheric absorption at $7600 \text{ \AA}$.

J121314 and *J142903*. Of the 105 quasars in the set, these two quasars did not end up meeting the BI* criteria for absorption (see § 3.2) Their spectra are plotted in Figure 4.1. In both cases, there is a small absorption feature emerging in the BOSS spectrum (red) just blueward of the Si IV emission at $\sim 1400 \text{ \AA}$. In both quasars, this drop in flux density was the basis of the visual assertion

that they contained emergent broad absorption. However, the emergent absorption features do not reach below a normalized flux density of 0.9, making them not register on the BI* measurement. Thus they are not considered BAL quasars in our sample.

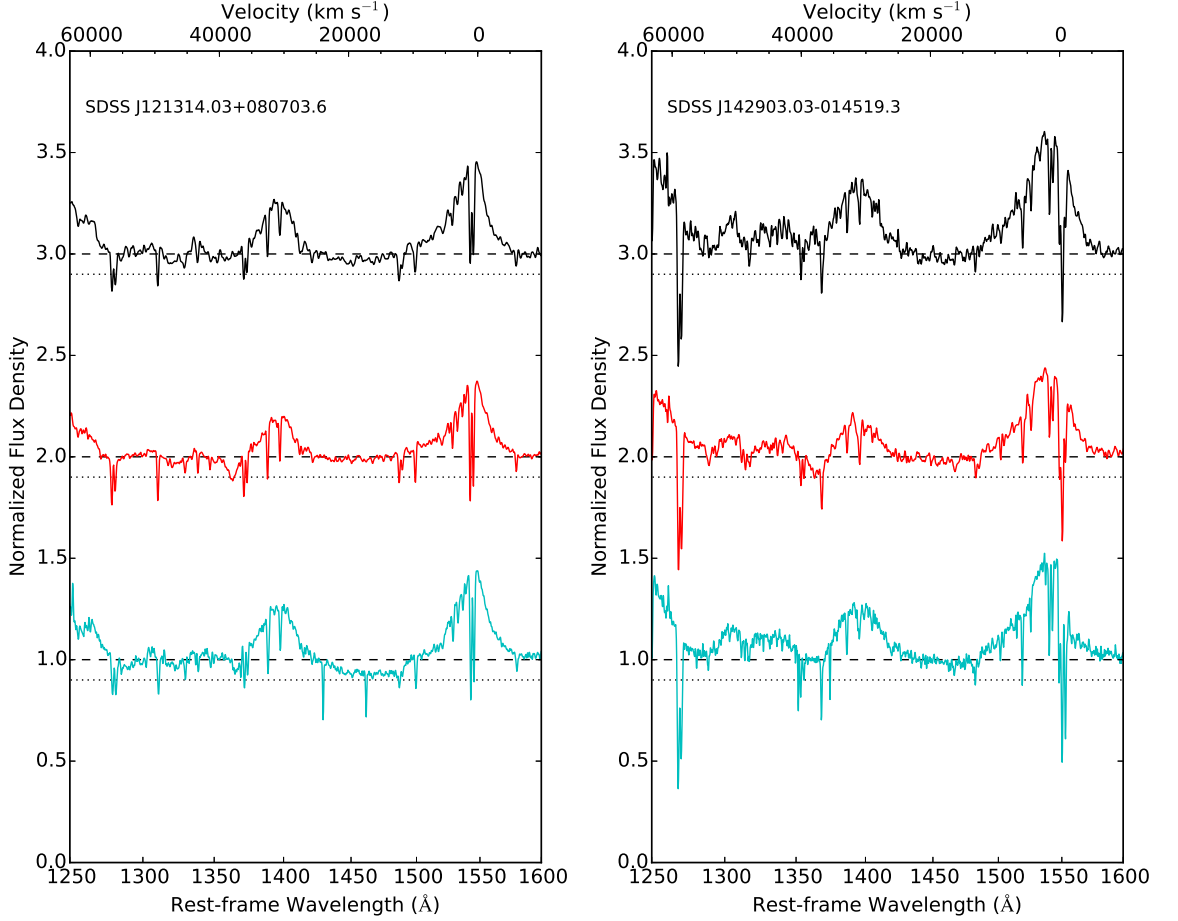


Figure 4.1: Quasars 121314.03+080703.6 and 142903.03–014519.3 did not meet the criterion for BI* to be considered BAL quasars. Plotted here is their multi-epoch spectra with the oldest at the top and each successive epoch in chronological order below it. For both candidates, absorption is clearly visible near 1360 Å. The dashed lines represent the normalized continuum levels for each spectrum, the dotted lines are at 90% of the continuum: the minimum threshold for BI*. Different colours represent different datasets: black is SDSS, red is BOSS, and cyan is Gemini. See Appendix A for more information on these figures.

4.2 Summary of Absorption Complex Characteristics

Combining BI* with complex identification resulted in 219 individual C IV absorption complexes in 103 quasars. There are a total of 354 spectra for these 103 quasars, as each quasar is observed between 3-7 times (see Table 2.2). In Figure 4.2, the distribution of rest-frame times between successive spectral epochs in a target is plotted. The longer times are mostly a result of the time between SDSS and BOSS epochs, which has been studied before (e.g., Filiz Ak et al. 2013). The unique parameter space explored here is the time separations near ~ 200 days, which is mostly due to the timing of our Gemini follow-up observations. More detail on this is found in Figure 4.13.

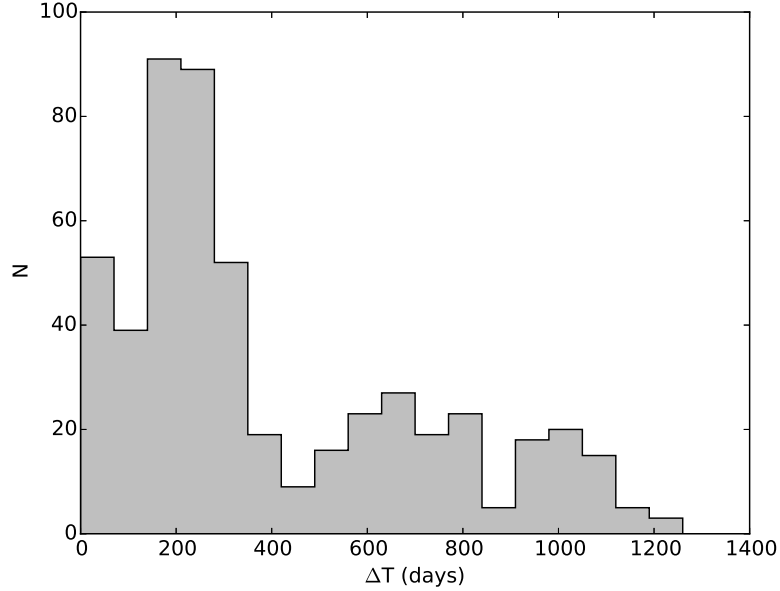


Figure 4.2: A quasar in the sample has anywhere from 3-7 spectral observations. This distribution represents the rest-frame time, in days, between successive epoch of a given quasar. The total number of data points in this histogram is 526.

The distribution of maximum and minimum velocities, v_{max} and v_{min} , respectively, in the 219 absorption complexes is plotted in Figure 4.3. The quasar with the largest v_{max} was J023011 with $59,800 \text{ km s}^{-1}$. The smallest v_{max} was found in J091621 at $1,400 \text{ km s}^{-1}$, which also had the smallest v_{min} at just 30 km s^{-1} . The largest v_{min} is at $58,800 \text{ km s}^{-1}$ in quasar J113536.

We plot the distribution of absorption complex velocity widths, which was defined in § 3.4, in Figure 4.4. There are more complexes with smaller widths than with large widths. The widest absorption complex is found in J165642; it contains a complex $24,600 \text{ km s}^{-1}$ wide. The smallest absorption complex width in our sample is $1,000 \text{ km s}^{-1}$, which is the lower limit imposed by the BI*. It is of note that the widths presented in Figure 4.4 are not the true widths of individual troughs, but the widths of the complexes.

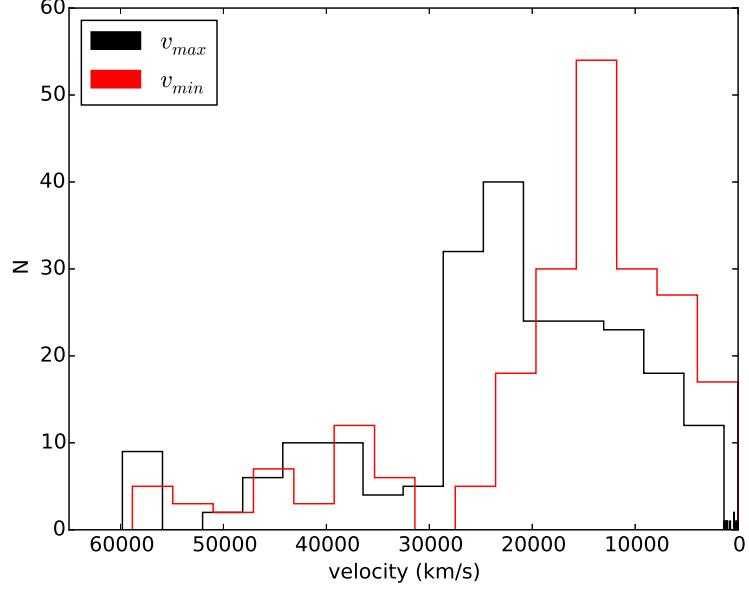


Figure 4.3: The distribution of absorption complex maximum and minimum velocities, v_{max} and v_{min} , respectively. The majority of the values are between 0 and 30,000 km s⁻¹, the region between C IV and Si IV. Yet there are still a large number at high velocity.

The distribution of absorption complex centroid velocities, v_{cent} , is plotted in Figure 4.5. There are 219 absorption complexes, each complex having at least 3 epochs of observations; this results in 748 data points.

In Figure 4.6, the centroid velocity of every complex is plotted against their widths. There is an obvious trend: as a centroid velocity gets larger, so does the width of the complex.

4.3 BAL/non-BAL Transitions

An emergent BAL quasar is when a quasar initially is measured to have $BI^* = 0$ in one spectral epoch, and in the next it has $BI^* > 0$. This indicates a significant trough appeared in a quasar previously considered non-BAL. Of course, the opposite can happen: all troughs in a BAL quasar can disappear converting the quasar from BAL to non-BAL, which was studied extensively in Filiz Ak et al. (2012). Of the 103 targets with significant absorption in our dataset, there were 36 instances of transition from non-BAL to BAL: emergent BAL quasars. All of these instances occurred in different quasars. In all but 3 of these instances the transition occurred between the SDSS and BOSS observations, which is expected given the full sample was chosen due to visual identification of new absorption between those epochs. The remaining 3 occurred in J113536, J145230, and J222838 between their BOSS and Gemini observations; their spectra are plotted in Figure 4.7. In these quasars, emergent

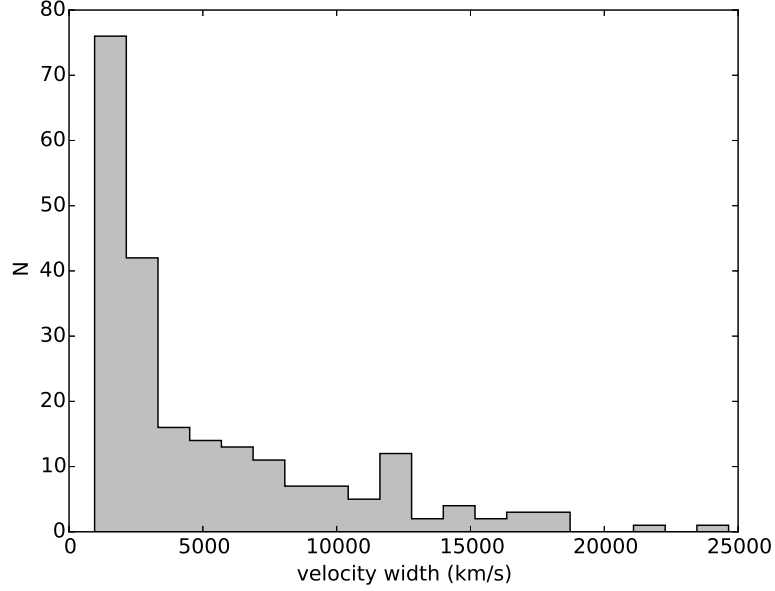


Figure 4.4: The distribution of absorption complex velocity width. There are 219 data points in the histogram. The figure exhibits that most of the troughs have small widths, peaking well below the $5,000 \text{ km s}^{-1}$ value. It is of note that the smallest allowable width was $1,000 \text{ km s}^{-1}$.

absorption is visible in the SDSS-BOSS transition but it did not meet the BI^* criterion. However, the visually identified emergence continued to increase into the Gemini observation, where it became strong enough (in all three quasars) to be considered a BAL.

There were 11 cases where a quasar went from BAL to non-BAL, occurring in 10 different quasars (one quasar, J015017, made this transition twice, see below), the majority of which occurred in the BOSS-Gem transition. There were 2 cases of disappearance that occurred in the SDSS1-SDSS2 transition, as well as 2 cases that occurred in the SDSS-BOSS transition. The 2 that occurred in the SDSS-BOSS transition were in J132508 and J150935. The former is plotted in Figure 4.10, and was targeted for possible absorption at high velocities; the large absorber at small velocities happened to disappear in our follow-up.

There were 5 quasars that exhibited both emergence and disappearance over the course of our observations: J015017, J022143, J081811, J095254, and J142054. Of particular interest was quasar J015017; its spectra are plotted in Figure 4.8. In the 101.25 days between SDSS1 and SDSS2 observations, all BALs disappeared in J015017. The troughs reappeared with a much stronger absorption 745.54 days later in the BOSS1 observation. Then between BOSS1 and BOSS2 (66.41 days) the trough weakened substantially. Finally the troughs disappeared again in the Gemini observation, 303.05 days after the last BOSS observation.

It is also interesting to determine the BAL/non-BAL transition rate for individual absorption

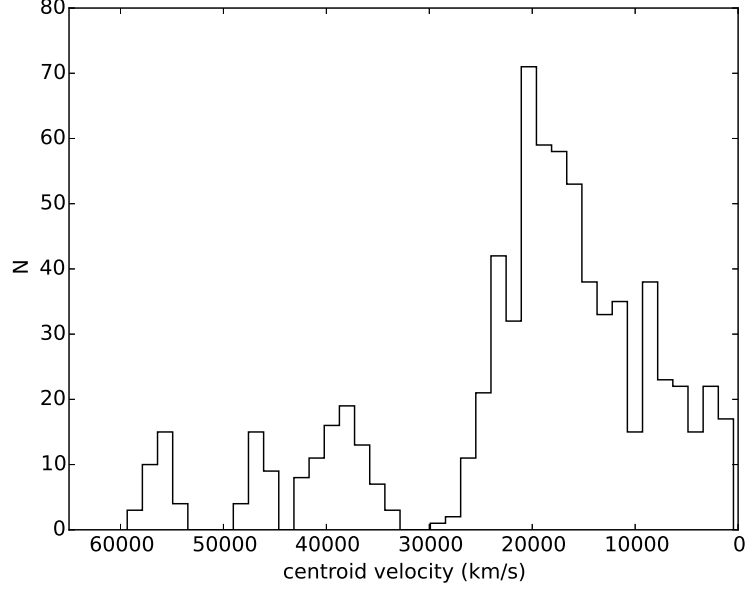


Figure 4.5: The distribution of absorption complex centroid velocities, v_{cent} . There are 748 data points in the histogram. The majority of the centroid values occurred between 0 and 30,000 km s^{-1} , the region between C IV and Si IV. However, there are still a large number of troughs occurring at high-velocity. Also of note in the figure, is the gaps due to various emission features, such as Si IV at ~ 1400 ($\sim 30,000 \text{ km s}^{-1}$).

complexes. A quasar could already have had a BAL in its spectrum, but have a new trough appear elsewhere in its spectrum. With 219 absorption complexes observed at least 3 times each, we found 526 transitions between epochs. In those 526 transitions, there are 123 cases of an emergent complex, 56 cases of disappearance, and 347 cases where absorption in the complex remained present.

In Filiz Ak et al. (2012), 21 C IV broad absorption features were observed to disappear in 19 quasars. The 19 quasars were selected from a parent sample of 582 BAL quasars in SDSS and BOSS. They conclude that the disappearance rate is $\sim 1 - 2\%$ on the timescales in their dataset. This rate is comparable to the emergence rate measured in this work of $\sim 1 - 2\%$. Also in Filiz Ak et al. (2012), it was noted that 10 of the 19 quasars made a full transition from BAL to non-BAL, a phenomenon that happened in 10 of the quasars in our dataset.

4.4 What Happens to the Absorption After it Emerges?

Our original candidate sample was targeted for visual identification of emergent absorption. This indicates our sample is biased towards an increase in EW when comparing an SDSS observation to a BOSS observation. In Figure 4.9, the change in EW (ΔEW) measured between SDSS and BOSS observations is compared to the change in the same absorption complex between the BOSS

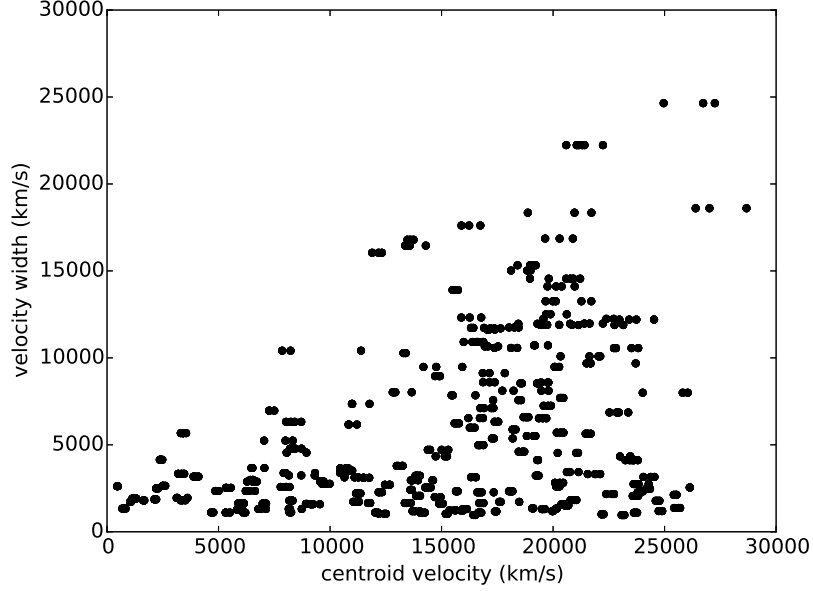


Figure 4.6: The width of the absorption complexes versus the individual centroid velocities measured for each epoch. There are 748 data points in the histogram. The further away the absorption complex is away from the C IV emission feature, the wider it can be.

observation and our Gemini observation. Note that there are some quasars with multiple SDSS and/or BOSS observations, but the figure only plots the two with the shortest separation in time (i.e., SDSS2-BOSS1); in target selection, these were the spectra that were visually compared. Thus, for each absorption complex, we have one x,y pair for the figure. There are 3 exceptions: the quasars that were not discovered until the BOSS survey released SDSS Data Release 9 (see § 2.4); they are not included in the plot.

As expected, most of the data points are found to the right of $\Delta EW = 0$ on the x-axis, indicating almost always an absorption feature's EW got larger between SDSS and BOSS observations. Though, there are exceptions to this trend. This is because in building the visually identified emergent sample in § 2.1, we only searched for new troughs, not new BAL quasars. Thus, a trough could have already existed in the quasar, and a new trough had appeared between SDSS and BOSS observations. Figure 4.9 also suggests that, more often than not, the change in EW got smaller between BOSS and Gemini observations, though, there is large scatter on the graph. The weighted-mean ΔEW from SDSS to BOSS observations was $4.16 \pm 0.10 \text{ \AA}$, and $-0.93 \pm 0.09 \text{ \AA}$ from BOSS to Gemini observations. This is the cyan point in the figure. Also in Figure 4.9, there are four red points which are highlighted because they exhibit extreme changes in EW for both SDSS to BOSS observations and BOSS to Gemini observations. Their spectra have been plotted in Figure 4.10. For example, object J132508 exhibits a massive decrease in EW from SDSS to BOSS observations. The spectra indicate

a large absorber at small velocities completely disappeared between the two observations. J132508 was originally targeted for a large absorber emerging with an outflow velocity of $40,000 \text{ km s}^{-1}$, but turned out to be spurious with the larger wavelength coverage of the Gemini observation. Object J130600 exhibits some of the largest absorption seen in our entire data set. Another object of interest that is highlighted in Figure 4.9 is J083546, which in its BOSS spectrum exhibits massive absorption on top of the Si IV emission. While it is difficult to know just how much absorption occurred, because we do not know what size the Si IV emission was in advance, that it pushed the region below 90% of the continuum at all indicates a large depth of absorbing gas. Finally, J004041 exhibits a large change to its associated system, representing a very large drop in the BOSS-GEM observations.

The type of comparison we perform here with Figure 4.9 is a good initial look at how an absorption complex behaves after emergence, but we wanted to do a more targeted analysis of how a previous change in equivalent width could predict the change in EW between the next two epochs. We are interested in how troughs behave after a change has been observed. If a trough changes its EW, what is it most likely to do next? Will it continue to change in the same way? Or will it reverse its change? And on what time-scales?

Utilizing the full suite of epochs for each quasar, ranging from 3-7 epochs, we were interested in learning what an absorption complex is likely to do after it emerges. For a given quasar, we first determine the change in EW from its first observation to its second; this is the reference point, and it can either be increasing, decreasing, or within the uncertainties (i.e., there was no statistically significant change). Now we compare the second observation to the third observation, and determine if that change in EW was increasing, decreasing, or within the uncertainties. If both changes in EW were increasing, we call this ‘staying the same,’ if the first change in EW is increasing while the second is decreasing (or vice versa), then we call this ‘changed,’ and if the changes are within the uncertainties we refer to this as ‘uncertain.’ The goal was to determine if a quasar’s history of increasing (or decreasing) in absorption could predict what it would do next.

There were, however, some caveats to the above prescription. Below is an itemized list of how we built this analysis, assuming a quasar has been observed n times (i.e., epoch₁...epoch _{n}).

1. Determine the reference point. The reference point is the first change of EW from one epoch to another that is significant at $3\sigma_{EW}$. Starting with the first observation, epoch₁, and search for a reference point in this order: epoch₁-epoch₂, epoch₂-epoch₃, epoch₁-epoch₃, epoch₃-epoch₄.
2. If epoch₁-epoch₂ is SDSS1-SDSS2, ignore it, unless epoch₂-epoch₃ showed no statistically significant change in EW. As our visual sample was built around searching for emergence between SDSS-BOSS, we set that to be the first reference used as much as possible.
3. Determine the sign of the change in EW from the reference point, either positive for increasing absorption or negative for decreasing absorption.
4. Compare the reference point to the next epoch change. For example, if the reference point

was epoch_n-epoch_{n+1}, determine whether the change in EW over epoch_{n+1}-epoch_{n+2} is in the same direction or opposite ('flipped') to the reference point. Record the ΔT between epoch_{n+1}-epoch_{n+2}. However, if no statistically significant change in EW occurred between epoch_{n+1}-epoch_{n+2}, then compare the reference point to epoch_{n+1}-epoch_{n+3}, epoch_{n+1}-epoch_{n+m}, etc. until a significant change is found.

5. Reset the reference point to epoch_m-epoch_{m+1}.
6. Go back to 3 and repeat until there are no more epochs.

The result of the above analysis is plotted in Figure 4.11. The plot has three histograms on it: cyan is the number of troughs that continued to increase after an increase was already observed, red is the number of troughs that switched their direction of variability, and grey are the instances we could not determine due to uncertainties inside the errors. The ΔT on the x-axis is the time frame between the second and third epochs in the analysis (see Step 4 above). The histogram has variable bin widths such that 50 ΔT measurements, with uncertainties, are in each bin.

Within the uncertainties, we are unable to tell the difference between red and cyan histograms. This indicates that on the time-scales between our 2nd and 3rd epoch, quasars are equally likely to continue increasing/decreasing or stay the same. Thus, the coherence time-scale of BAL EW variations must be less than ~ 100 days in the rest-frame.

4.5 Coordinated Variability

Many of the quasars in our dataset have more than one trough varying in their spectra. Comparing how the troughs vary with respect to one another can help distinguish models of outflows. For example, if two troughs in the same quasar both increase their EW at the same time, or decrease their EW at the same time, it indicates the source of the variability is affecting differing outflowing clouds equally. This is called coordinated variability. Two troughs could also vary opposite to each other: when one increases in EW, the other decreases. This is called anticoordinated variability. It would be difficult to explain coordinated variability in the context of the transverse motion of clouds across the line of sight to the quasar. A more natural explanation is the total ionizing light incident upon the various individual troughs (from the central source) has increased or decreased and is there responsible for global changes in the absorption, regardless of outflow velocity of the trough. Coordinated variability has been observed in Filiz Ak et al. (2013) as well as in the recent work by Wang et al. (2015).

To determine whether coordinated variability was occurring in our dataset, we set aside all quasars with more than one absorption complex, then calculated the change in EW between successive epochs. A complex would be considered increasing/decreasing in absorption if the change in EW was larger than 3 times the statistical noise propagated from the EW uncertainties. If the change in

EW was smaller than 3 times the statistical noise it was considered to have not changed. If we have estimated the uncertainties in the EWs properly, and the errors follow a Gaussian distribution, then 3 times the propagated noise would represent a 99.7% confidence that the change in EW is real. We then compared each complex's direction of change of EW to all other absorption complexes in the quasar, one at a time. In Table 4.1, the conditional probabilities of how a complex changed given the condition set by another complex in the quasar are given. For example we can ask the question: if a given complex 1 increased in EW from SDSS to BOSS observations, what were the probabilities that complex n did the same, did nothing, or decreased over the same ΔT . From the table, if an absorption complex EW was measured to be increasing, then each other absorption complex EW in that quasar has a 69.8% chance of increasing over the same time frame; this happened 300 out of 430. If an absorption complex EW was observed to be decreasing, each other absorption complex EW in that quasar has a 65.9% chance to also be decreasing; this happened 182 out of 276 times). Both of these situations are considered coordinated variability. If we add them together (300 coordinated increase, 182 coordinated decrease), there is a $(300 + 182)/(276 + 430) = 68.3\%$ rate of coordinated variability in our data. Conversely, there is a $(70 + 70)/(430 + 276) = 19.8\%$ rate of anticoordinated variability. The remaining percentage points are the cases where any change in the absorption complex EW is within statistical noise. Note that because each absorption complex is compared to every other complex, there is double counting in this approach. For example, two absorption complexes, 1 and 2 were compared both 1-versus-2 as well as 2-versus-1. While the numbers suggest variability is coordinated, below we remove this potential bias.

However, with such a strong signal of coordinated variability, we first investigated whether velocity separation between absorption complexes had an impact on the conditional probabilities of the other complexes. In the top portion of Figure 4.12, the cumulative distribution function (CDF) of coordinated (black) versus anticoordinated (red) variability are plotted as a function of difference in centroid velocity. Also plotted is the distribution of cases where no significant change happened (cyan). Applying a two sample Kuiper Variant to the Kolmogorov-Smirnov test to the coordinated/anticoordinated distributions results in a probability of 1.7% that the two distributions are the same. Thus, the two distributions of velocities for coordinated and anticoordinated variability are statistically different. There is a greater fraction of coordinated variability at smaller velocity separations than anticoordinated. This leads us to believe that the closer troughs are in velocity to each other the more likely they have coordinated variability. Applying the Kuiper test to the coordinated versus unknown histograms results in probability of $\sim 10^{-4}$, meaning the coordinated histogram is significantly different from the unknown histogram. Finally, the Kuiper test comparing the anticoordination versus unknown gives a probability the two distributions are the same of 15%. We cannot reject the hypothesis that the anticoordination and the unknown histograms are drawn from the same sample.

It is clear there is coordinated variability happening in the dataset. To be sure the double counting

Table 4.1: The conditional probability that, given a change in EW for one complex in a quasar, of what were the other troughs in the same quasar doing. The first column indicates the condition set by some complex, and the following columns indicate the probabilities of other complexes in a quasar varying in specific ways. Increase is a complex increased in EW between two observations, same is a complex has not changed within the statistical noise of the data, and decrease means the complex has decreased in EW between two observations.

condition	increase	same	decrease	total
increase	69.8% (300)	13.9% (60)	16.3% (70)	430
same	60% (60)	16% (16)	24% (24)	100
decrease	25.4% (70)	8.69% (24)	65.9% (182)	276

did not create a bias, and to also investigate whether the direction of coordination/anticoordination matters, we performed the a more detailed analysis. To avoid the double counting, absorption complexes were only compared to other complexes at higher velocities. In this analysis we also retained the information on velocity separation, ΔT between observations, and the differing directions (e.g., increasing/decreasing) of the variability. The above can be written into following logical steps:

1. For a given quasar, collect all absorption info for each complex for all spectra available. e.g., for a quasar with SDSS, BOSS, and Gemini observations and two absorption complexes, collect the 6 centroid velocity measurements and the 4 different changes in EW from SDSS to BOSS observations, and BOSS to Gemini Observations. We removed any comparisons between SDSS1 and SDSS2 observations.
2. Sort the complexes in ascending velocity order (i.e., closest to C IV emission to furthest).
3. Compare first complex to second, third, to n th. Record direction of coordination (see below), separation in centroid velocity, and ΔT between observations.
4. Compare second complex to third, to n th. Record direction of coordination (see below), separation in centroid velocity, and ΔT between observations.
5. Compare third to n th. Record direction of coordination (see below), separation in centroid velocity, and ΔT between observations.
6. Repeat until no more absorption complexes.

The results of this analysis are in Table 4.2, which indicates there is a $(150 + 91)/(216 + 146) = 66.6\%$ rate of coordinated variability and a $(27 + 43)/(216 + 146) = 19.3\%$ rate of anticoordinated variability. The remaining $\sim 14\%$ of trough pairs have no coordination either way or any signal is within our statistical uncertainties. As was argued in Filiz Ak et al. (2013), if we assume that all comparisons between two troughs will give a mixture of both coordinated and anticoordinated variability, then some apparently coordinated variations will actually be anticoordinated variations that appear coordinated by chance. To correct for this, we can take the rate of anticoordinated

(19.3%) and remove it from the rate of coordinated (66.6%) giving a 47% rate of coordinated variability motivated solely by some mechanism (and not chance).

In the bottom portion of Figure 4.12 is the cumulative distribution functions for the data in Table 4.2. In the Figure, we have separated out the differing possibilities troughs can respond with respect to one another. The symbol ‘++’ indicates the case where two troughs have increased in absorption at the same time, while ‘--’ indicates the opposite. The two antcoordination cases are ‘-+’ and ‘+-’; the former is when the first absorption complex EW is decreasing, and the one compared to it (at higher velocity) is increasing, the latter is the opposite. For all the cases where no change could be measured in one or both troughs, it is labeled ‘0’.

It is clear that both cases of coordinated variability are similar to each other; the Kuiper test yields a 42% probability they are the same, meaning there is a good chance the two distributions are drawn from the same sample, therefore there is no favoured direction of coordinated variability. A surprising result in the figure is the obvious difference between the ‘-+’ and ‘+-’ cases. The Kuiper test between these two cases, with a probability of 56%, indicates a good chance those two are actually drawn from the same sample. Small-number statistics mean that the apparent difference between the ‘+-’ and ‘-+’ histograms, while intriguing, cannot be interpreted as real until better statistics are obtained.

One last test was done: we removed all absorption complexes that were less than $10,000 \text{ km s}^{-1}$ in outflow velocity and redid the analysis. Absorption complexes at these lower velocities may be overlapping or otherwise influenced by the C IV broad emission feature. Variability in associated systems (i.e., absorption complexes overlapping or on top of their emission features) might be difficult to disentangle from changes to the emission feature. Thus, by removing the lower-velocity absorption complexes, we can see if any of the coordinated variability we have observed this far was related to the emission feature. After re-doing the analysis, the probabilities increased to 7.3% in comparing coordinated to antcoordinated groups; this indicates a reduced significance and a higher chance they were selected from the same sample. There is still a significant difference between the coordinated group and the unknown group (top panel). A Kuiper test found a probability 1.8% they were drawn from the same sample.

Coordinated variability among troughs in a quasar has been observed before (e.g., Filiz Ak et al. 2013). This result suggests that the cause of variability in BAL troughs is likely due to changes in ionizing light incident upon the cloud. It is difficult to explain two troughs of differing velocities varying in the same fashion in the context of clouds moving across the line of sight to the UV continuum. Instead, if the light that is ionizing the BAL gas to its current state suddenly changes, all troughs in a quasar would respond equally, but over a time-scale that is shorter at higher densities.

The origin of antcoordinated variability could be self-shielding of clouds. If two troughs at differing velocities are along the same line-of-sight (one closer to the emitting region and one further away) then the closer trough would respond to changes in the ionizing source faster.

Table 4.2: The conditional probability that, given a change in EW for one complex in a quasar, of what all other complexes at higher velocities than the complex that set the condition were doing. By enforcing a comparison to only higher velocity troughs, the double counting from Table 4.1 was removed. The first column indicates the condition set by some complex, and the following columns indicate the probabilities of other complexes in a quasar varying in specific ways. Increase is a complex increased in EW between two observations, same is a complex has not changed within the statistical noise of the data, and decrease means the complex has decreased in EW between two observations.

condition	increase	same	decrease	total
increase	69.4% (150)	18.1% (39)	12.5% (27)	216
same	51.2% (21)	19.5% (8)	29.3% (12)	41
decrease	29.4% (43)	8.2% (12)	62.3% (91)	146

However, our data does also suggest that troughs that are closer together in velocity are more likely to vary in a coordinated way. We cannot assume outright that because they are at similar velocities, they are at similar distances from the ionizing source. This result is likely due to density considerations. Higher velocity outflows will have lower densities (see Fig. 4 in Murray et al. 1995). Since the ionization state of an absorbing cloud is related to its density, it is conceivable that two outflows in the same quasar with a large separation in velocity would be less likely to vary in unison.

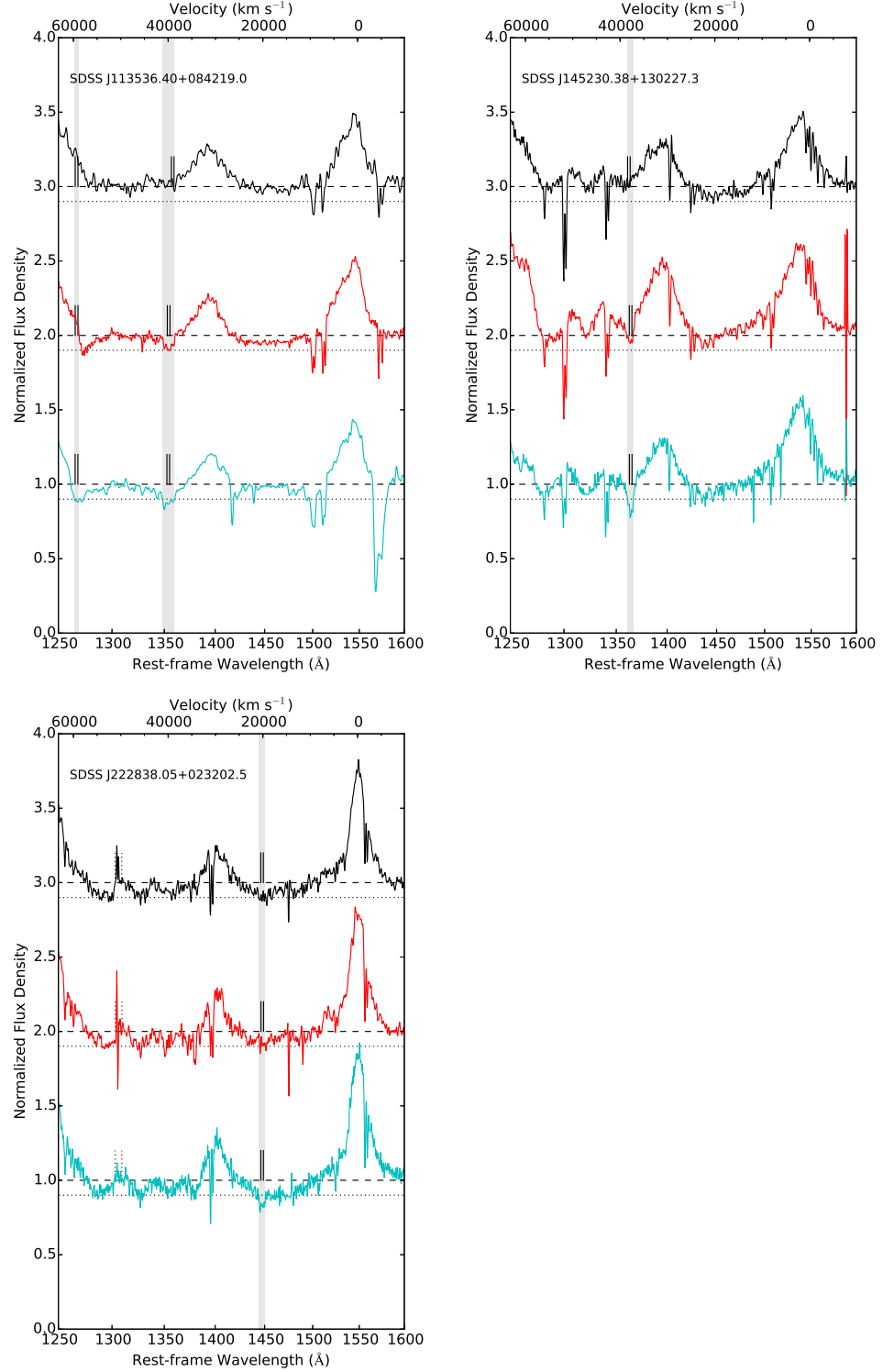


Figure 4.7: Quasars J113536, J145230, and J222838 were visually identified as emergent BALs but did not meet the BI* criteria in their SDSS (black) or BOSS (red) spectra but did meet the BI* criteria in their Gemini (cyan) spectra. For object J113536, there are features redward of the C IV emission. For SDSS/BOSS, they are intervening systems. For the Gemini observation it is an atmospheric absorption feature at 7600 Å. See Appendix A for more information on these figures.

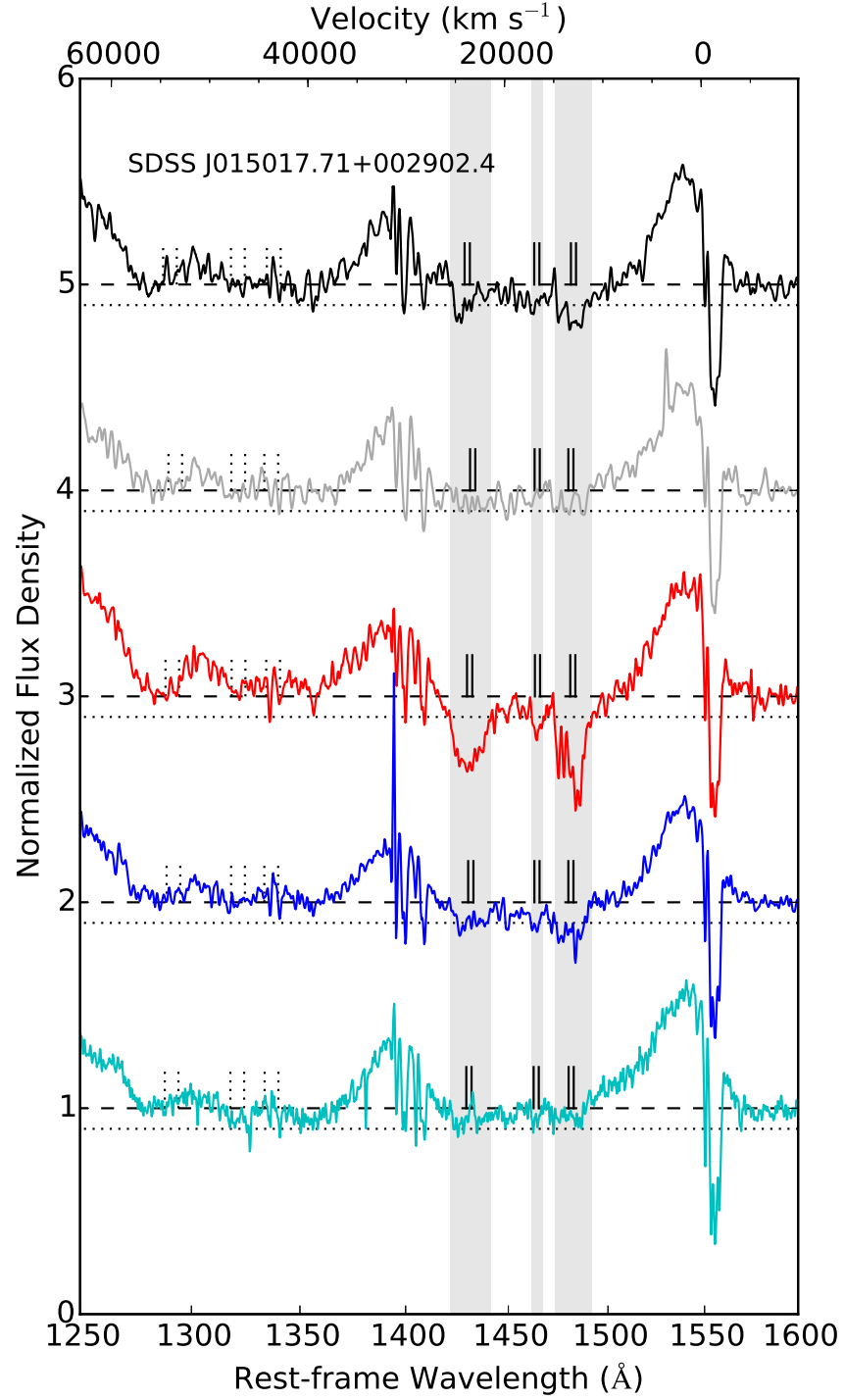


Figure 4.8: A plot of spectra taken at five different epochs for the quasar J015017. Note the changes in the three absorption complexes between the wavelength range 1400 Å and 1500 Å. With the first spectrum at the top, and each successive observation in chronological order below, we can observe these complexes emerge between the 2nd and 3rd observation, then disappear again between the 4th and 5th.

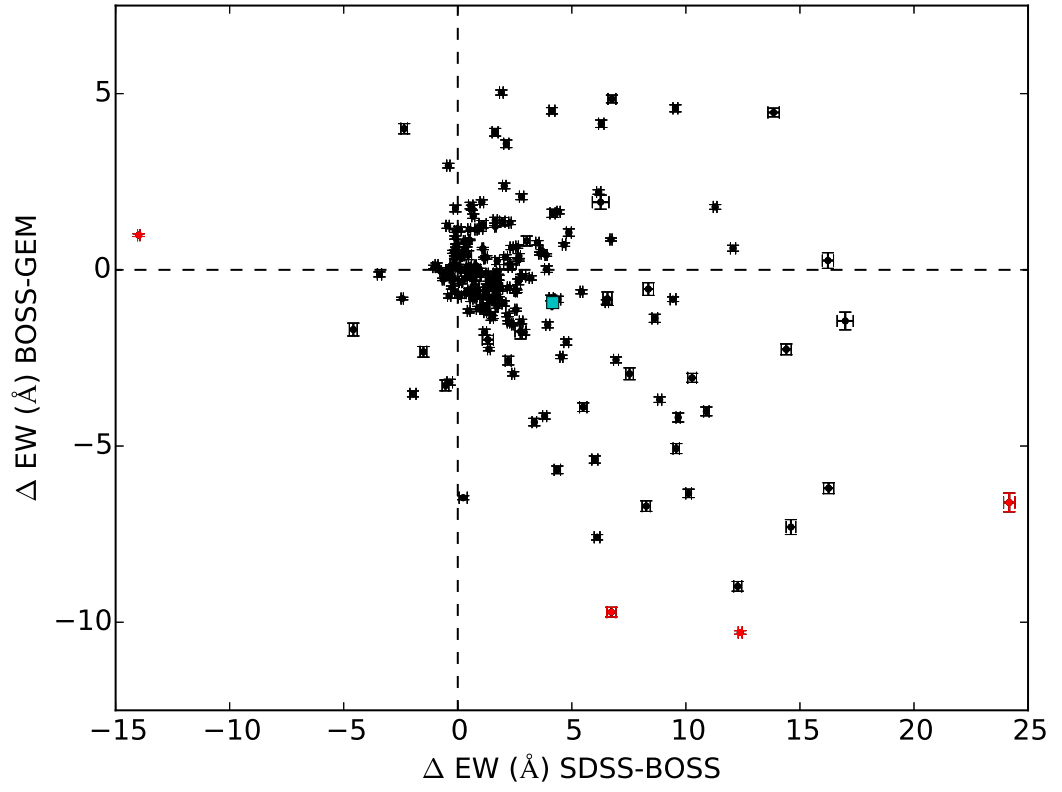


Figure 4.9: Comparing the change in EW between the SDSS and BOSS observations to the same quasar’s change in EW between the BOSS and GEM observations. The 4 red points are highlighted for being interesting cases worthy of further investigation in Fig. 4.10. The cyan point is the weighted-mean value of all the points in the plot.

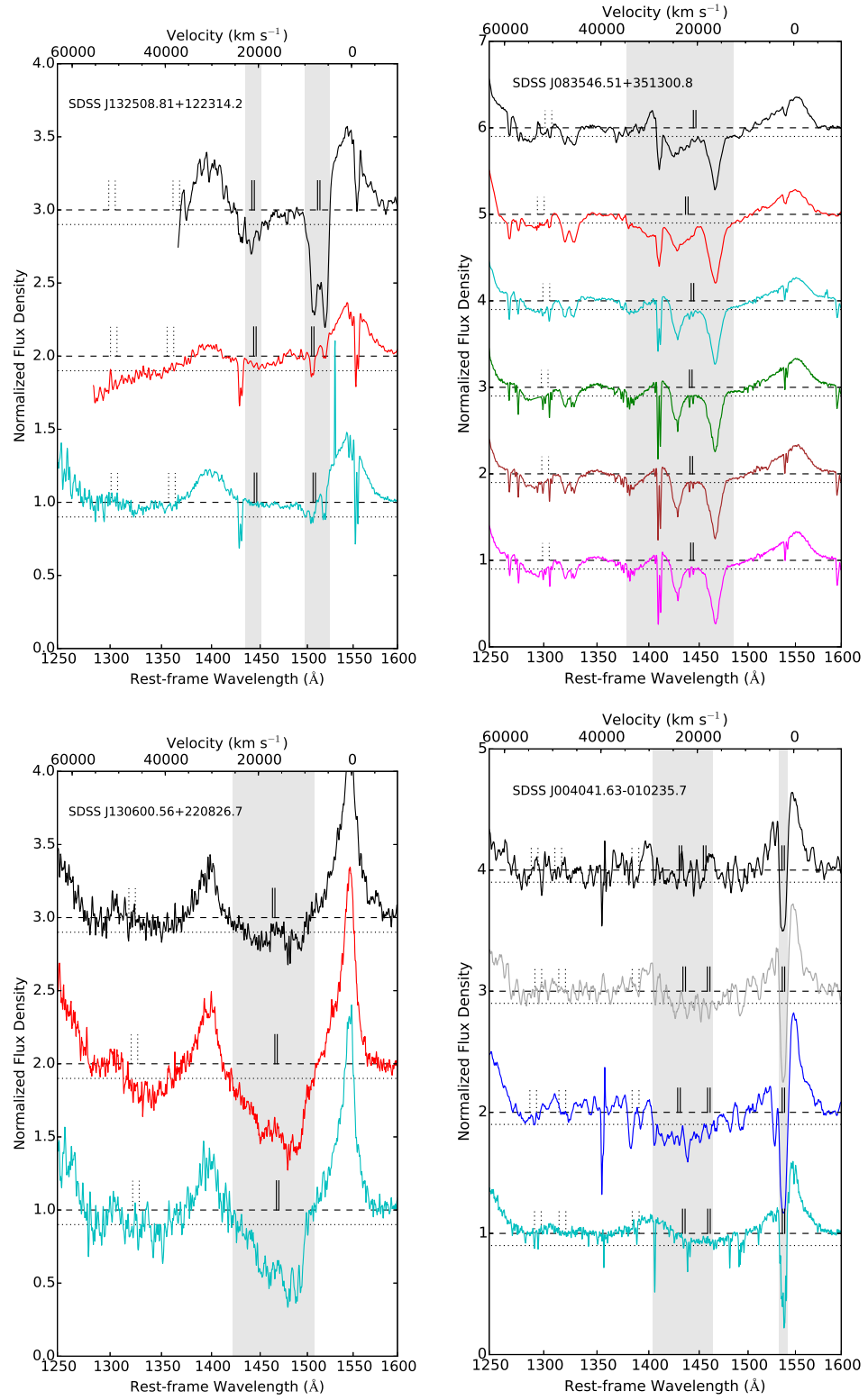


Figure 4.10: The 4 quasars highlighted as red points in Fig. 4.9 represent some of the most extreme changes in absorption measured in this dataset. Each quasar's spectra are plotted, with the oldest spectrum is at the top with each successive spectrum in chronological order below it. Colours represent the differing observational origins of each spectrum. See Appendix A for more information on these figures.

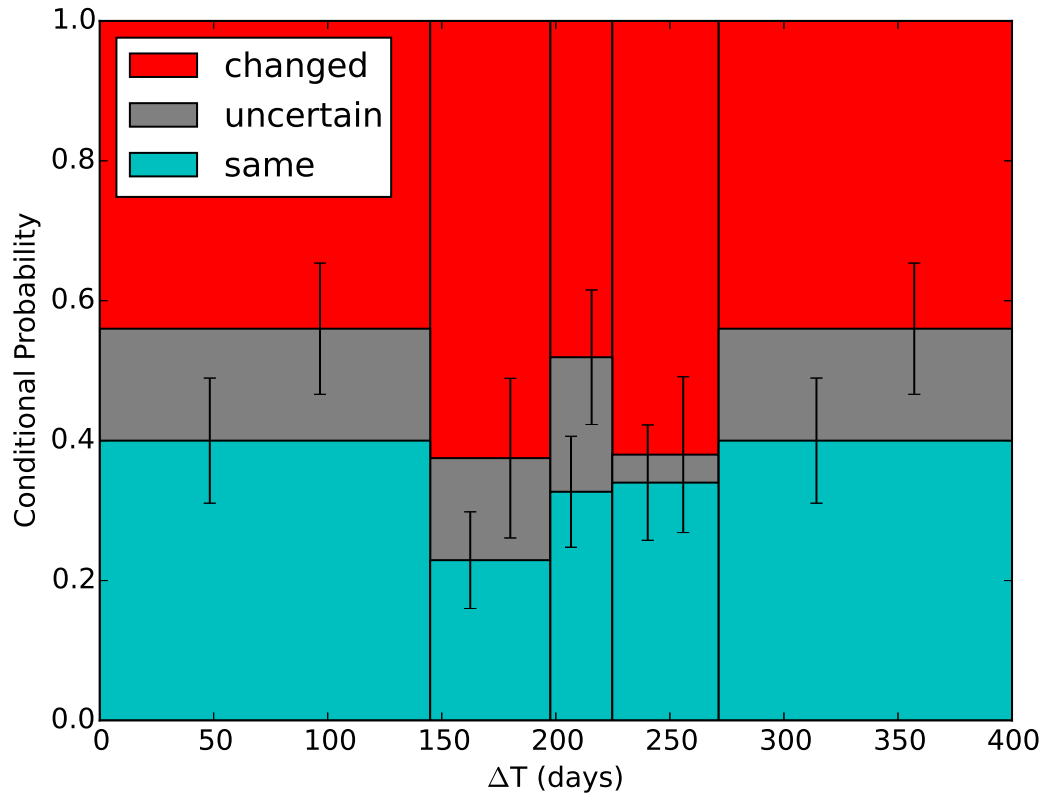


Figure 4.11: Conditional probability of increasing or decreasing absorption after the first epoch. In cyan is the time between the 2nd and 3rd observation for troughs that continued to increase after they had been observed to increase between their 1st and 2nd observation. In red is the time frame between 2nd and 3rd observations for troughs that flipped their direction of variability. Grey represents the cases that could not be determined due to measurement error.

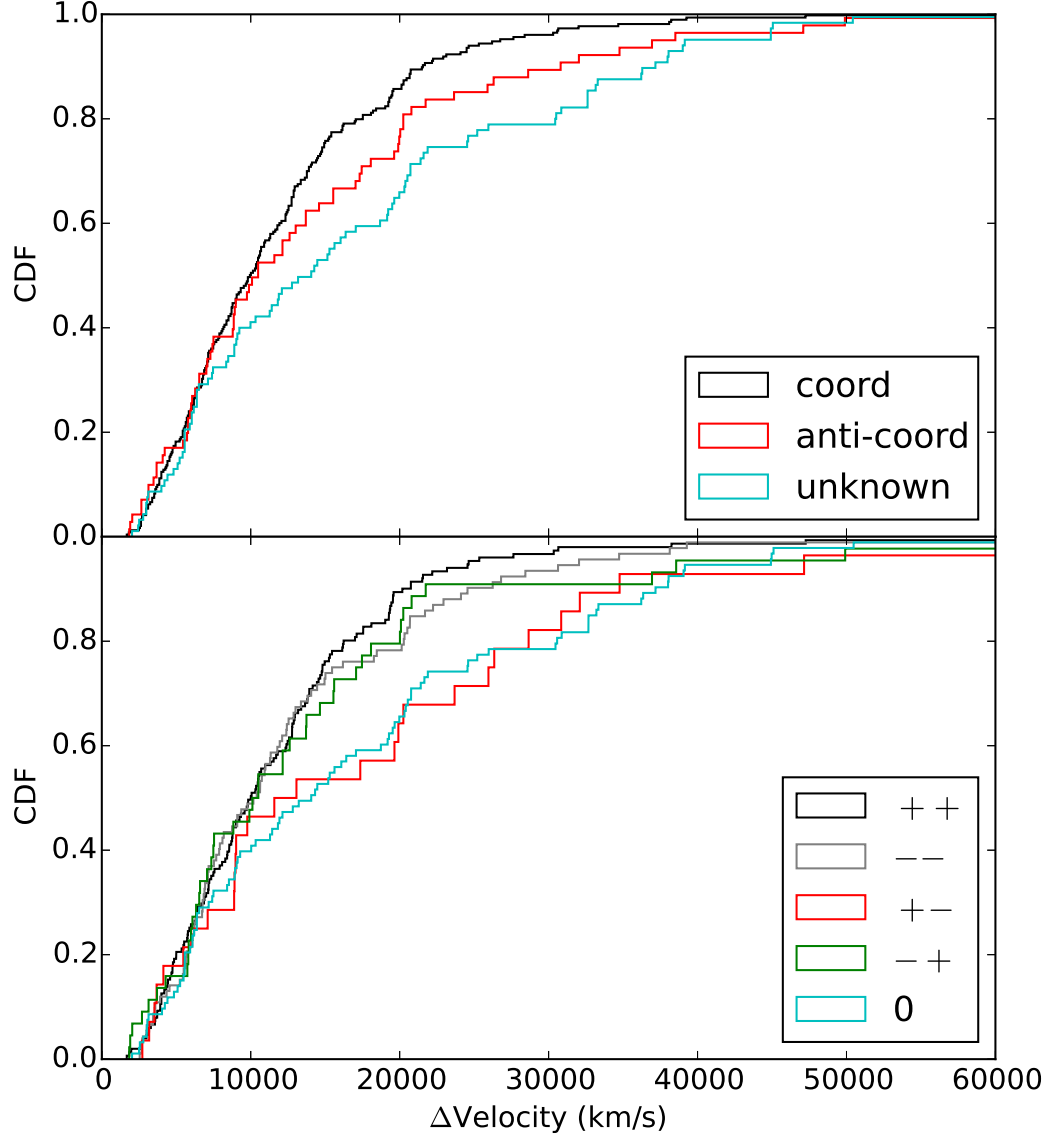


Figure 4.12: **top:** The cumulative distribution functions (CDFs) of coordinated variability (black) versus anticoordinated variability (red). For the data in this figure, each absorption complex from a given quasar was compared to every other complex. This is considered double counting. **bottom:** This plot removes double counting, as well as separates out the different cases of coordination/anticoordination. Cases are indicated by: ‘++’ when two troughs increased in EW together, ‘--’ when two troughs decreased in EW together, ‘-+’ when the lowest-velocity trough decrease in EW while the other increased, ‘+-’ when the lowest-velocity trough increased in EW while the other decreased, and finally ‘0’ for all cases that involved a change that was below the 3σ statistical noise limit.

4.6 Changes in Equivalent Width

With 103 quasars with 219 absorption complexes, and at least 3 observations per quasar, there are 526 epoch-to-epoch changes in EW, depth, and centroid velocity. In that set of data, 462 of the changes were statistically significant at greater than $3\sigma_{EW}$, while the other 64 were within the noise. Thus, the fraction of absorption complexes that exhibited a statistically significant change in EW was $462/526=88\pm4\%$, and no change was $64/526=12\pm1\%$. Of course, this is biased because we specifically chose quasars to observe that showed some obvious changes in their spectra between the first two observations.

We plot the change in EW between successive epochs of all absorption complexes in the top portion of Figure 4.13 (see equation 3.6), and the fractional change in the bottom portion (see equation 3.7). All of the grey points in both figures are values taken from the literature (see Table 1.1). The coloured points are from this work: black points represent changes between two SDSS observations, red points are changes from SDSS to BOSS observations, blue are changes between two BOSS observations, cyan are changes from BOSS to Gemini observations, and all other colours are changes between two Gemini observations. We note that our data largely traces the results of other works: on longer time-scales, large changes in EW are possible. There are no large changes in EW on short time-scales. Figure 4.13 also shows how our dataset has filled in the region on medium time-scales of 0.5 – 1.0 years in the rest-frame, a region of parameter space that has been largely unexplored.

In Figure 4.14, the change in depth of trough is plotted against the time between successive observations as measured by d_{BAL} (top) and by d_{max7} . Both figures display a similar trend to how EW changes with time; that on longer time-scales, larger changes are possible.

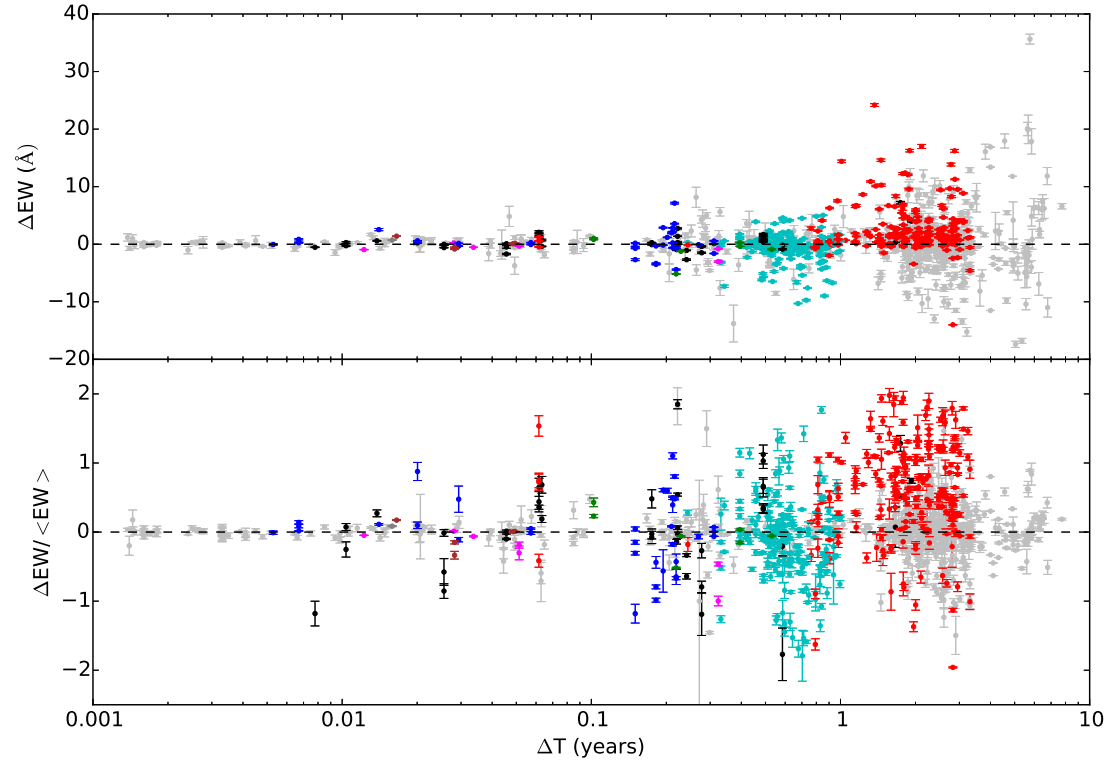


Figure 4.13: The change in equivalent width, ΔEW , (top) and change in fractional equivalent width, $\Delta EW / \langle EW \rangle$, between successive epochs in a quasar as a function of rest-frame time between them. The grey points are taken from the literature (see Table 1.1). All other points are from this work. Black points represent changes between two SDSS observations, red points are changes from SDSS to BOSS observations, blue are changes between two BOSS observations, cyan are changes from BOSS to Gemini observations, and all other colours are changes between two Gemini observations.

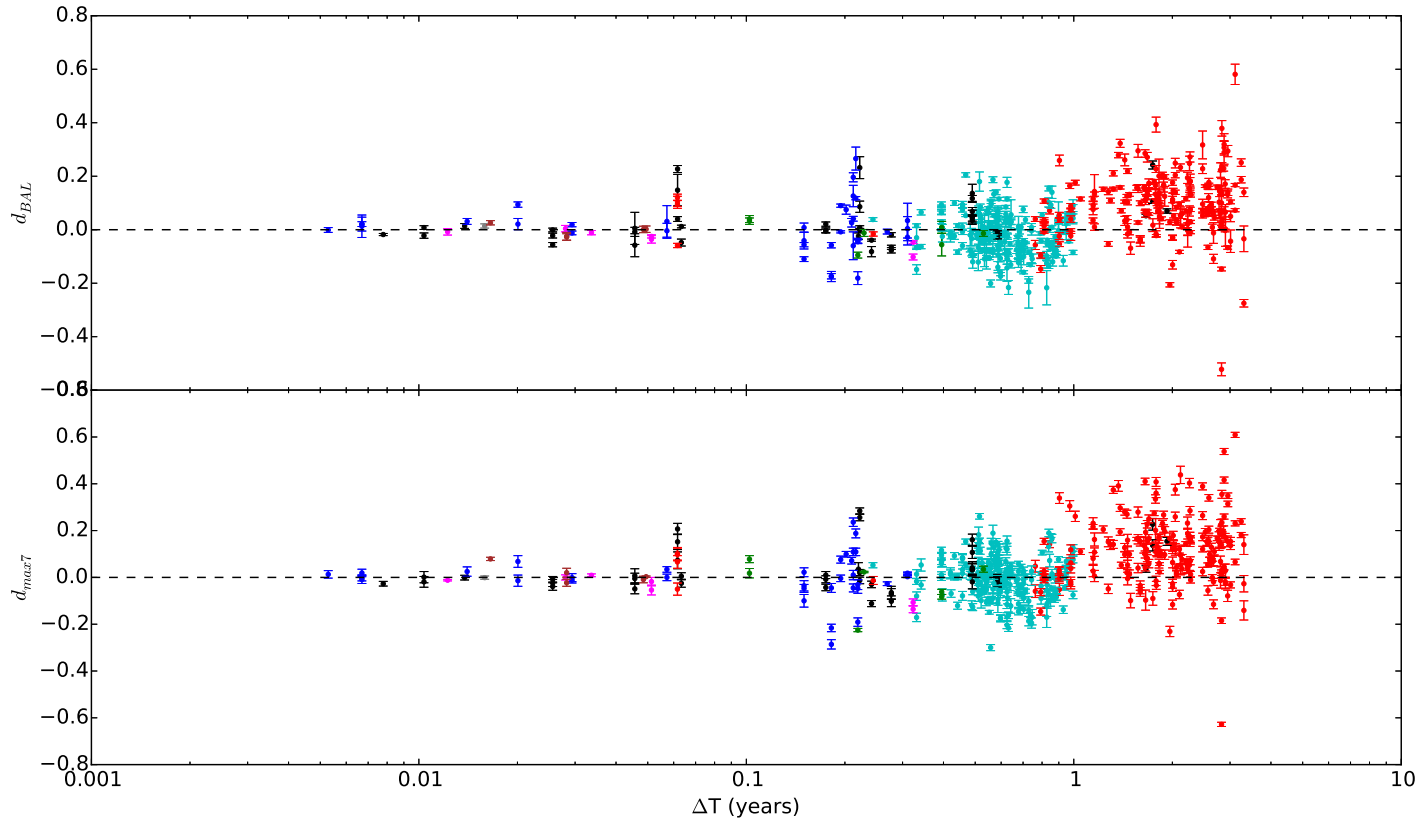


Figure 4.14: The change in d_{BAL} (top) and d_{max7} (bottom) between successive epochs in a quasar as a function of rest-frame time between observations. Black points represent changes between two SDSS observations, red points are changes from SDSS to BOSS observations, blue are changes between two BOSS observations, cyan are changes from BOSS to Gemini observations, and all other colours are changes between two Gemini observations.

4.7 Summary of the Results

In this chapter we have studied the variability of absorption complexes over at least 3, and as much as 7 spectral epochs. Our specific goal was to track how the past variability of an absorption complex can inform the future variability. There was no statistically significant signal that suggest the past variability can inform its future variability; thus, BAL variability remains stochastic in nature, and any coherence time-scale is less than at least 100 days in the rest-frame.

We also detected a strong signal of coordinated variability, which suggests variability seen in absorption troughs is mostly due to changes to the ionization state of the gas, a result also seen in other recent variability studies, such as Filiz Ak et al. (2013).

In the following chapter, we present a case study of the quasar SDSS J023011.28+005913.6, which contains the highest velocity outflow observed in our dataset. In this single object, much more detailed probing of differing models of variability can be performed.

Chapter 5

A Very High-Velocity Case Study

We present the discovery of the highest velocity C IV broad absorption line to date in the $z=2.47$ quasar SDSS J023011.28+005913.6, hereafter J0230. In comparing the public DR7 and DR9 spectra of J0230, we discovered an emerging broad absorption trough outflowing at $\sim 60,000 \text{ km s}^{-1}$, which we refer to as trough A. In pursuing follow up observations of trough A, we discovered a second emergent C IV broad absorption trough outflowing at $\sim 40,000 \text{ km s}^{-1}$, namely trough B. In total, we collected seven spectral epochs of J0230 that demonstrate emergent and rapidly (~ 10 days in the rest-frame) varying broad absorption. We investigate two possible scenarios that could cause these rapid changes: bulk motion and ionization variability. Given our multi-epoch data, we were able to rule out some simple models of bulk motion, but have proposed two more realistic models to explain the variability of both troughs. Trough A is likely an augmented ‘crossing disk’ scenario with the absorber moving at $10,000 < v \text{ (km s}^{-1}\text{)} < 18,000$. Trough B can be explained by a flow-tube feature travelling across the emitting region at $8,000 < v \text{ (km s}^{-1}\text{)} < 56,000$. If ionization variability is the cause for the changes observed, trough A’s absorber has $n_e \geq 724 \text{ cm}^{-3}$ and is at $r_{\text{equal}} \geq 2.00 \text{ kpc}$, or is at $r < 2.00 \text{ kpc}$ with no constraint on the density; trough B’s absorber either has $n_e \geq 1540 \text{ cm}^{-3}$ and is at $r_{\text{equal}} \geq 1.37 \text{ kpc}$, or is at $r < 1.37 \text{ kpc}$ with no constraint on the density. The work in this chapter has been published in Rogerson et al. (2016).

5.1 Introduction, Identification, and Follow-Up

The previous highest-velocity absorption identified at ultraviolet wavelengths in a BAL quasar was at $56,000 \text{ km s}^{-1}$ in PG 2302+029 (Jannuzi et al., 1996), with the next highest being at $50,000 \text{ km s}^{-1}$ in PG 0935+417 (Rodríguez Hidalgo et al., 2011).¹ Outflows at these extremely high velocities have

¹We have determined the features claimed by Foltz et al. (1983) to be O VI at up to $70,000 \text{ km s}^{-1}$ in the BAL quasar H 1414+089 are actually Si IV $\lambda 1062$ and Si IV* $\lambda \lambda 1072, 1073$ absorption in a lower-velocity trough reaching only $28,000 \text{ km s}^{-1}$. That identification is secure because the object’s Si IV+Si IV* trough shares the same distinctive ‘double-dip’ velocity structure as its C IV and N V troughs reaching $28,000 \text{ km s}^{-1}$; see Figure 2 of Foltz et al. (1983).

been previously observed in X-rays (e.g., Chartas et al. 2002, Pounds et al. 2003, but see Zoghbi et al. 2015) and might pose problems for theoretical acceleration models.

Due to the irregular nature of the J0230 spectrum (i.e., weak emission features, discussed below), the SDSS pipeline, as well as Hewett & Wild (2010), were unable to determine a suitable redshift for this object. We adopt a redshift of $z = 2.473 \pm 0.001$ for J0230 based on visual inspection of the Ly α , C III], and Mg II emission lines and the onset of the Ly α forest. Our redshift is identical within the errors to the value of $z = 2.4721 \pm 0.0005$ given for this quasar in Pâris et al. (2014). We adopt a systematic uncertainty on the redshift of ± 0.0044 , or 380 km s^{-1} . This uncertainty is the difference between the C III] emission-line redshift and the principal component analysis-based ‘pipeline’ redshift presented in Pâris et al. (2014); see that reference for details. If our adopted redshift is a slight underestimate due to blueshifting of the emission lines in our spectrum, it is conservative in the sense that it errs in the direction of minimizing the observed trough outflow velocities.

J0230 has an apparent magnitude of $g = 19.52$ and an absolute magnitude of $M_g = -27$. Because it is undetected in FIRST with an apparent magnitude of $i = 18.76$, it is not radio-loud ($R_i < 1$; see Figure 19 of Ivezić et al. 2002).

In Figure 5.1 we plot the visual comparison of the mean SDSS spectrum (black; see § 5.1.1) and the BOSS2 spectrum (blue) that led to the identification of an emergent absorbing trough. The locations of the C IV and Si IV emission are given, though noted to be very weak (see § 5.1.3 for further discussion regarding Weak Line Quasars). The absorbing trough, which we refer to as trough A for the remainder of the chapter, emerged at some point between the two spectral epochs and spans roughly 1260–1300 Å. We attribute this trough to C IV absorption by highly blueshifted gas outflowing along our line-of-sight to the quasar at approximately $\sim 56,000 \text{ km s}^{-1}$. We are confident trough A is not due to blueshifted Si IV absorption due to the lack of accompanying C IV expected at $\sim 1425 \text{ Å}$. Further, there is some evidence that trough A has accompanying N V absorption, which we discuss in § 5.1.3. We note there is a significant change in J0230’s spectrum shortward of trough A, which is attributed to changes in the Ly α +N V complex in that region. Note that those changes do not affect our measurements on trough A throughout this work. Based on this visual identification of the absorption, and the extreme nature of the outflow causing it, a total of 3 Gemini observations were obtained to study it. In Table 5.1 a more detailed description of the observations and the nomenclature used for duration of the work is given.

5.1.1 Notes on Normalization and Emergent troughs

The normalization approach is, in general, the same as that described in § 2.3, there are some specific deviations taken for J0230, explained below.

The windows used for the normalization of J0230’s spectra in Chapter 2 were 1305–1330,

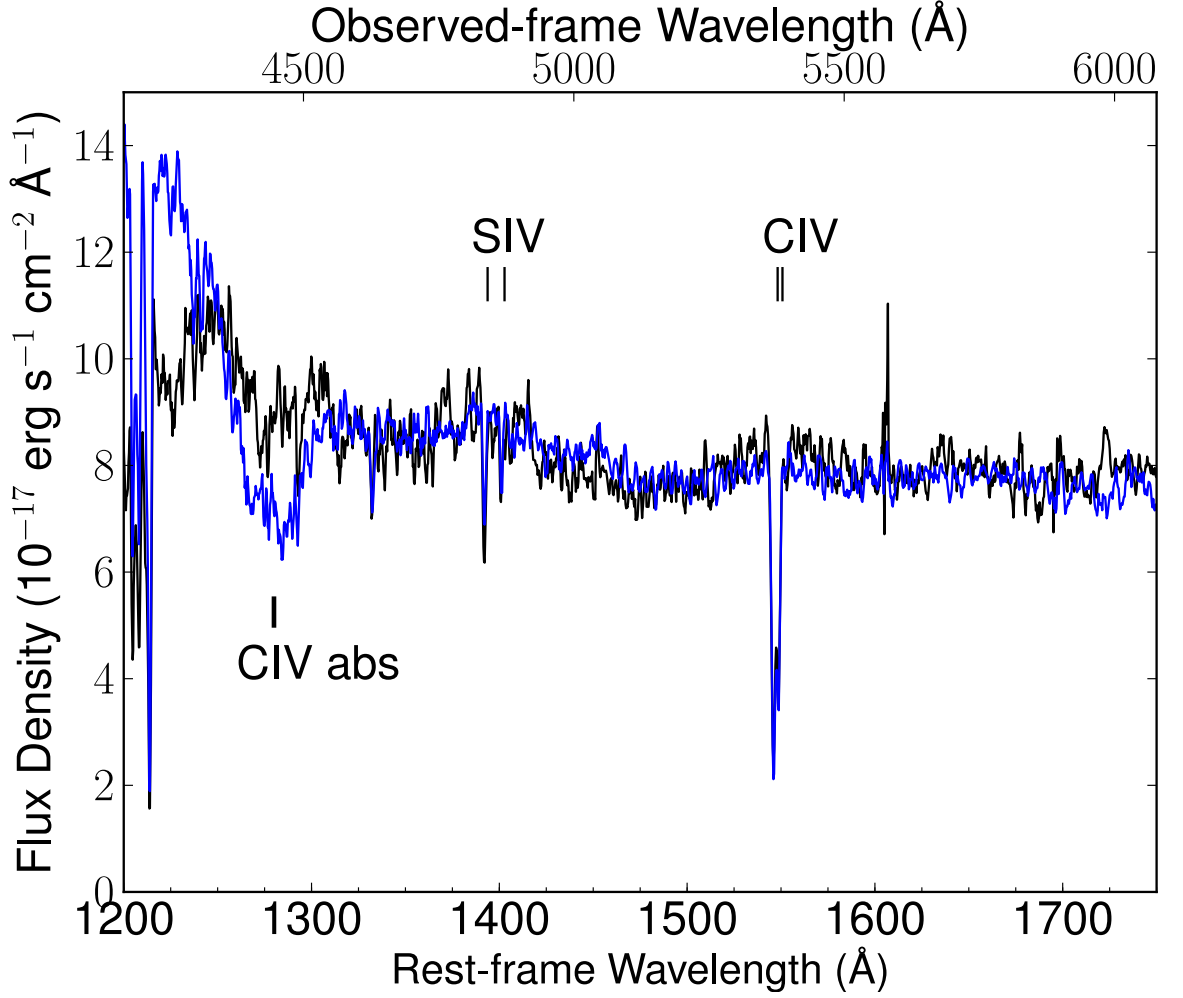


Figure 5.1: Spectra of J0230 at rest-frame wavelengths (bottom scale) and observed (top scale). The black spectrum is the mean of the two SDSS spectra (see § 5.1.1). The blue spectrum was taken by BOSS on MJD 55455. The locations of the C IV and Si IV emission are labeled (though are weak). In comparing the spectra, a broad and deep trough was identified at roughly 1262–1302 Å. This trough was identified as highly blueshifted C IV absorption. This trough is referred to as trough A for the remainder of the paper. The Flux Density of the BOSS spectrum is artificially scaled up to match the continuum level of the SDSS spectrum for the purposes of visual comparison.

MJD_{Obs}	Rest ΔT	Rest Day	Plate	Fiber	Origin	SN_{1675}	Name
52200.39	000.00	−866.02	705	407	SDSS-I	7.50	SDSS1
52942.34	213.63	−652.39	1509	365	SDSS-I	7.57	SDSS2
55208.10	652.39	000.00	3744	634	SDSS-III/BOSS	12.3	BOSS1
55454.46	71.93	71.93	4238	800	SDSS-III/BOSS	16.4	BOSS2
56519.53	306.67	378.06	...	...	Gemini-North	22.1	GEM1
56649.21	37.33	415.39	...	...	Gemini-North	23.2	GEM2
56685.07	10.32	425.71	...	...	Gemini-South	18.0	GEM3

Table 5.1: Spectroscopic observations of J0230. Rest ΔT is the rest-frame time in days elapsed since the previous observation. Rest Day is cumulative rest days relative to the first BOSS observation. SN_{1675} is the median value of the normalized flux density divided by the error in the flux density over the spectral range 1650–1700 Å. The final column indicates how we will refer to each epoch for the duration of the paper.

1410–1420, 1590–1620, and 1650–1675 Å. The size of the final window 1650–1675 Å was chosen because GEM3’s wavelength coverage drops off severely after 1675 Å (see Figure 5.4). In this Chapter, we were able to perform a more detailed study, and thus chose the final normalization window to be 1650–1700 Å for all spectra except GEM3, which retained the 1650–1675 Å sized; this does not largely affect the results of the work.

Two spectra of J0230 were taken on MJD 52200 and 52942, as part of the SDSS-I survey. In Figure 5.2 we present the normalized SDSS spectra; the gray regions indicated the normalization windows. The normalized error spectra are plotted along the bottom. Visual comparison shows little difference between the two, with the small exception of apparent absorption at 1225–1235 Å present in the spectrum taken on MJD 52942, but not present in the previous epoch, taken on MJD 52200. This feature vanished by the time BOSS2 was observed and never re-appeared, it is present only in our noisiest spectrum, and, most importantly, is not related to the two broad troughs that are the focus of this work. As a result, we do not consider it in this study. Other than this feature, there are little differences between the two SDSS spectra; we combined them into one (hereafter, ‘the SDSS spectrum’) in order to increase our signal to noise. We adopt an observation date for this combined spectrum of MJD 52942, that of the latter SDSS observation. Since no broad absorption is present in either of the SDSS spectra, we can confidently indicate this date to be the last time we observed no absorption present.

The BOSS survey observed J0230 two more times on MJD 55209 and 55455. We normalized these two spectra using the same normalization windows as were used for the SDSS spectra. In Figure 5.3 we plot the normalized BOSS spectra. In both BOSS epochs, trough A is present at ~ 1280 Å. The absorption line varies between the two BOSS observations, thus we did not combine the two spectra as in the case of the SDSS spectra.

Three Gemini spectra were taken on MJDs 56519, 56649, and 56685. In Figure 5.4, all three normalized Gemini spectra are plotted. In GEM1 we note the emergence of trough B, a separate medium-velocity absorber at 1350–1360 Å, which was not present in any of the SDSS or BOSS

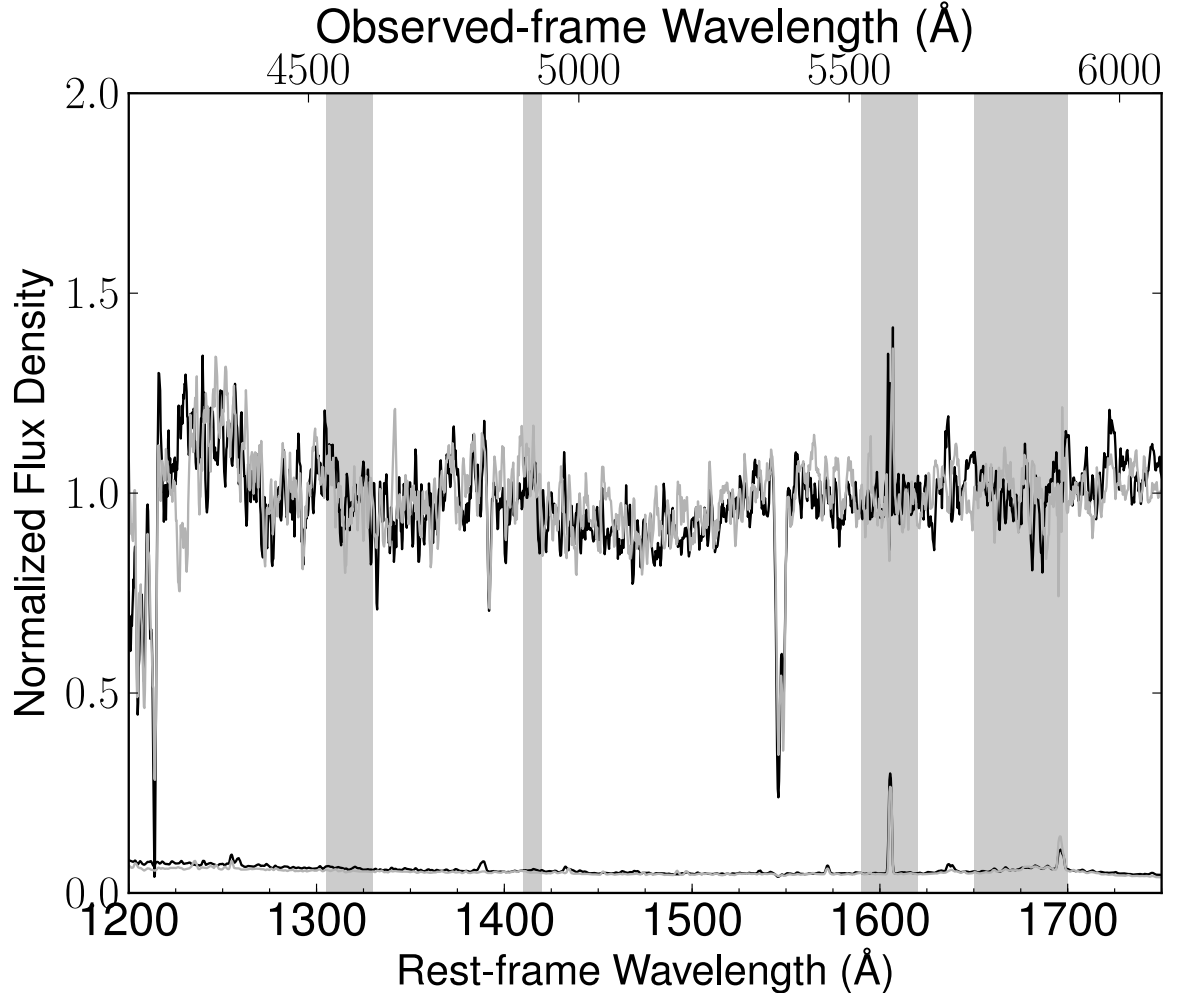


Figure 5.2: The normalized SDSS spectra. While there are some small differences between the two spectra (see description in § 5.1.1), they do not interfere with the two troughs we study later. As a result, we have combined the two SDSS spectra together for the remainder of the paper. The normalized error spectra are plotted at the bottom. The normalization windows are shown as gray regions.

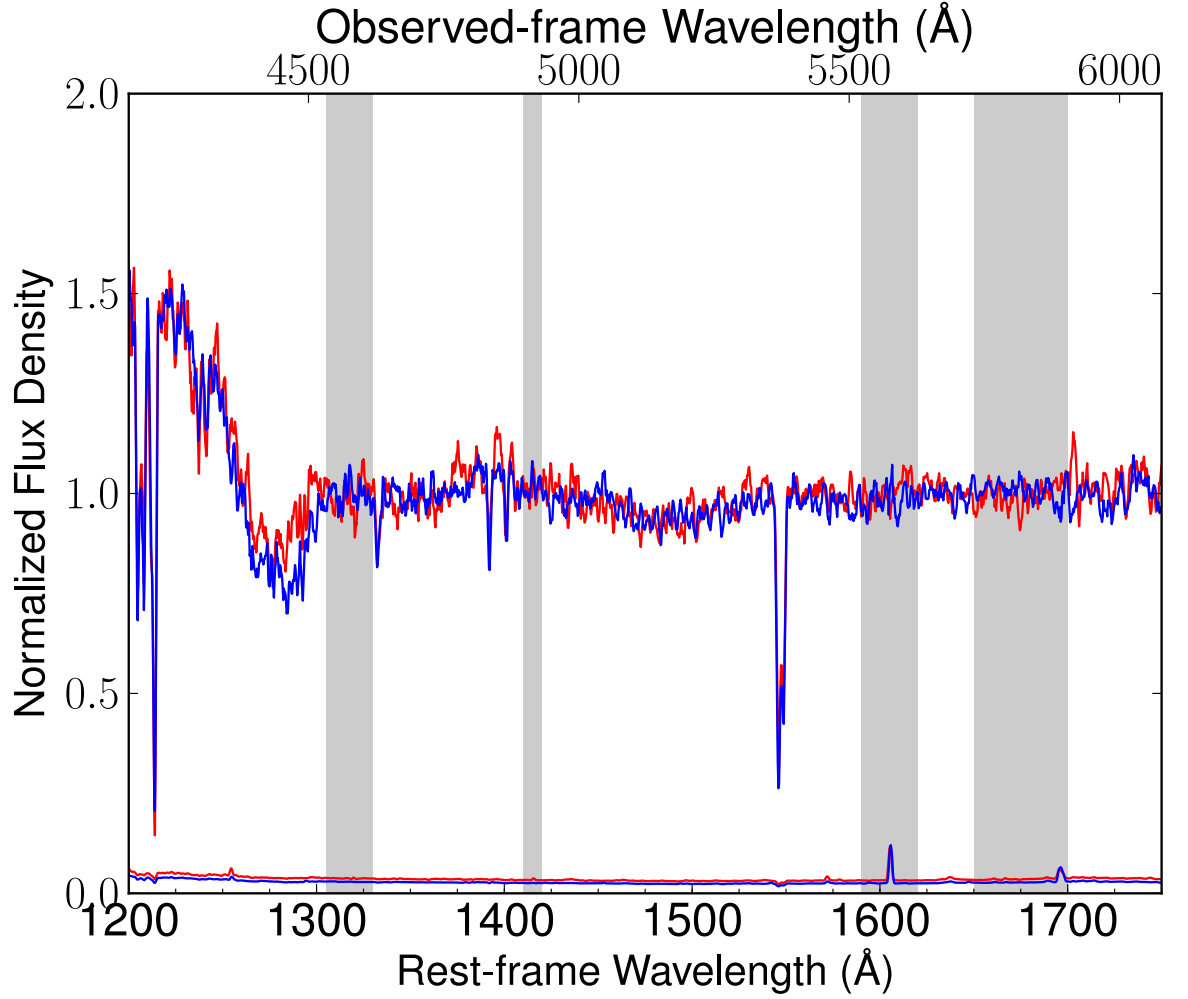


Figure 5.3: The normalized BOSS spectra. Since the high-velocity absorber at ~ 1280 Å has changed between the two epochs, we cannot combine the BOSS spectra. The normalized error spectra for both epochs are plotted at the bottom. The normalization windows are shown as gray regions.

spectra. The Gemini spectrum taken on MJD 56685 (orange) exhibits less spectral coverage on the red side; the flux density falls off quickly after ~ 1675 Å. To account for this, the third normalization window used for this spectrum was 1640–1650 Å.

5.1.2 Final Spectra

The final six spectra (note the two SDSS spectra were combined) are plotted in Figure 5.5. For reference, the emission features for Si IV at ~ 1400 Å and C IV at ~ 1550 Å are marked, although both emission lines appear to be weak. In our collected data, we note two broad absorption features, labeled ‘A’ and ‘B’ in the figure. Trough A was first observed in the BOSS1 spectrum. At its widest (BOSS2) trough A spans 40 Å (1262–1302 Å). Trough B was first observed in GEM1. At its widest (GEM1) it spans 24 Å (1344–1368 Å). The legend of Figure 5.5 indicates the number of rest-frame days since the previous observation.

5.1.3 Summary of Spectral Features of J0230

In all the spectra we obtained of J0230, the emission features are relatively weak compared to typical quasars; specifically, we measured the rest-frame equivalent widths (EWs) of the emission features: $\text{Ly}\alpha + \text{N V} = 8.0 \pm 0.1$ Å, $\text{Si IV} < 1.8$ Å, $\text{C IV} < 2.5$ Å, $[\text{Al III} + \text{C III}] = 6.1 \pm 0.2$ Å, and $\text{Mg II} = 9.8 \pm 0.9$ Å. When there is no apparent emission feature at the expected location of an ion, we measured the statistical noise in the spectrum in the ranges provided by the Vanden Berk et al. (2001) composite quasar spectrum (see Table 2 therein). Specifically, they measured the Si IV EW over 1360–1446 Å, and the C IV EW over 1494–1620 Å. For those regions we measure the statistical noise in our spectra to be 0.60 Å and 0.84 Å, respectively. The upper limits quoted above are three times this statistical noise to indicate the largest possible EW these emission features could have that would still be statistically below the noise in our data. Also note that our measurement of $\text{Ly}\alpha + \text{N V}$ is contaminated by the $\text{Ly}\alpha$ forest; the actual EW is likely larger. In Luo et al. (2015), a Weak Line Quasar (WLQ) is defined as a quasar whose emission lines have rest-frame equivalent widths of < 5 Å (they drew their sample of WLQs from Plotkin et al. 2010). While J0230 does not strictly meet the criterion laid in those works, its emission features are still far from a typical quasar’s. The original WLQ, PG 1407+265, has emission features with comparable EWs to J0230 (McDowell et al. 1995, see Table 2 therein), as does the prototypical WLQ, PHL 1811, which has the following EWs: $\text{Ly}\alpha + \text{N V} = 15$ Å, $\text{C IV} = 6.6$ Å, $[\text{Al III} + \text{C III}] < 4$ Å, and $\text{Mg II} = 12.9$ Å (Leighly et al., 2007). Further, quasars with EWs < 10 Å investigated so far have sufficient similarities (e.g., common X-ray weakness) and can likely be unified as per Luo et al. (2015) in a common physical model. Therefore, we consider J0230 a WLQ.²

²WLQs tend to have blueshifted broad emission lines in the UV, making systemic redshift determination more challenging than usual. Our adopted systematic redshift uncertainty of ± 380 km s^{−1} in J0230 is similar to the $+300$ km s^{−1} average difference between redshifts determined by narrow-line studies and those determined by SDSS for weak line quasars found by Plotkin et al. (2010).

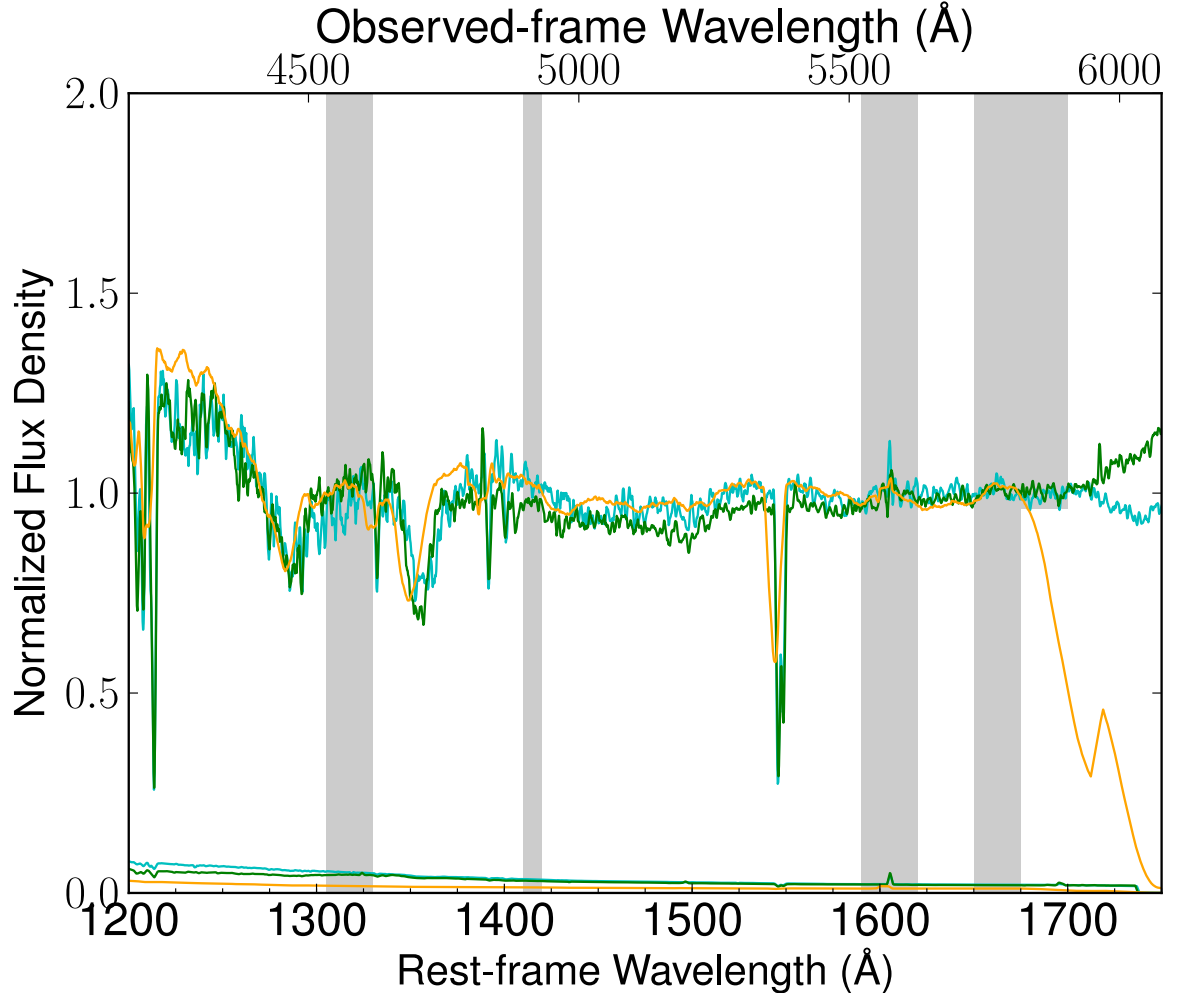


Figure 5.4: The normalized Gemini spectra. The normalization windows are indicated by the gray regions. The orange spectrum (GEM3) has slightly less coverage on the red end and thus we changed its third normalization window to 1640–1650 Å; this does not largely affect the results of the work. The normalized error spectra for all three epochs are plotted at the bottom.

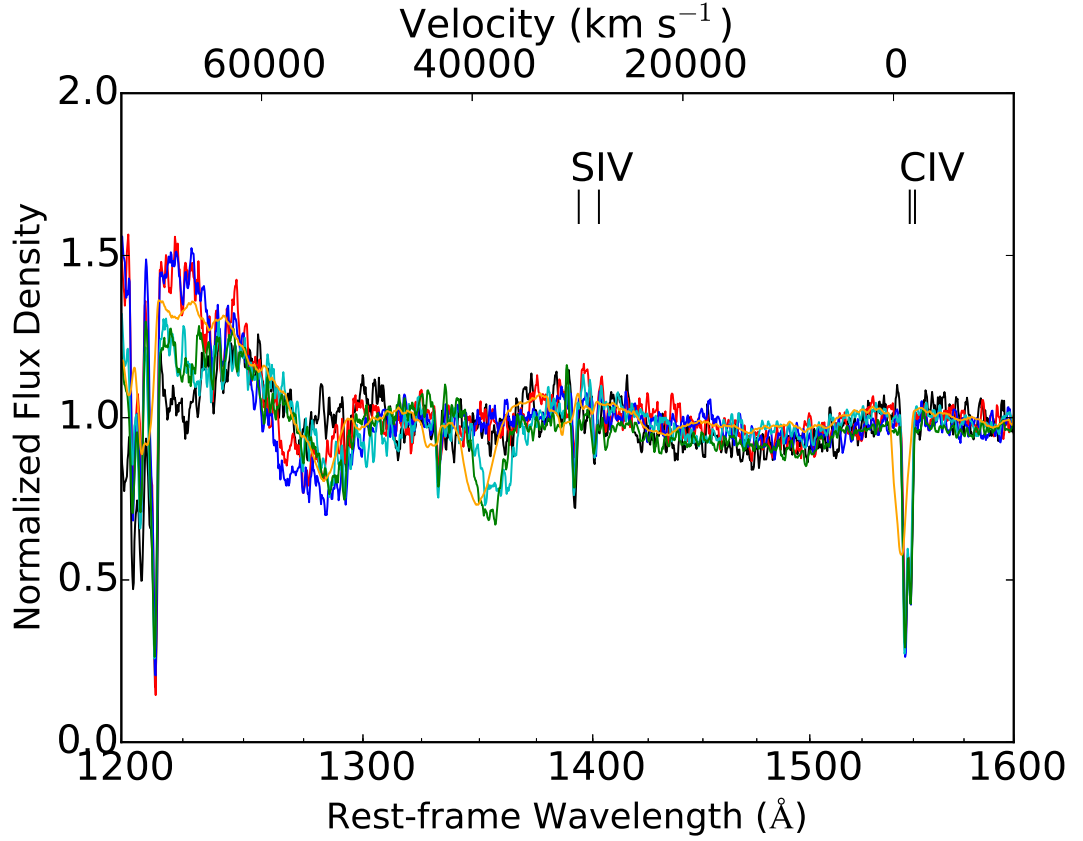


Figure 5.5: All 6 epochs of spectra plotted together. For reference, the emission features for Si IV at ~ 1400 Å and C IV at ~ 1550 Å are marked, as well as the two troughs ‘A’ and ‘B’ we observed to emerge during our monitoring campaign. In the legend the MJD of each observation is indicated as well as the number of rest-frame days since the previous observation. We also note the presence of a third mini-BAL feature near the systemic redshift of the quasar, which we refer to as trough ‘C.’ There was no significant change to trough C through all observations.

Also present in all spectra is a narrow C IV absorption feature at ~ 1550 Å, very close to the systemic redshift of J0230 (also seen in Si IV, C II, N V, and Ly α), hereafter trough C. There were changes in the absorption strength of trough C throughout our observations, however because this work was primarily focussed on emergent broad absorption, we did not include it in our analysis. Also, note that trough C is overlapping with the emission of C IV in the broad line region. These are known as associated absorption systems, and were historically removed from BAL analysis by the BALnicity Index (see § 5.2.2). The origin of this absorption could be physically distinct from other non-associated broad absorption, which is another reason we have left its analysis out.

The changes in the spectrum are best seen in Figure 5.6. In BOSS1 we note the appearance of trough A: a broad, high-velocity absorber covering the wavelength range 1260–1300 Å. Trough A grew to its strongest in BOSS2 by getting both deeper and wider; these changes were mostly in the low-velocity half of the trough, whereas the high-velocity half of the trough changed less. In the first Gemini spectrum (GEM1), the high-velocity half of trough A weakened greatly while its low-velocity half weakened only somewhat, in comparison to BOSS2. Between GEM1 and GEM2, trough A strengthened slightly on its high-velocity side. We note in GEM1 the emergence of trough B, a second high-velocity absorber in the wavelength range 1344–1368 Å. We are confident this absorption is due to highly blueshifted gas along the line-of-sight to J0230. It cannot be due to blueshifted Si IV absorption because that would require accompanying C IV at ~ 1500 Å. Further, there is some evidence to suggest there is accompanying Si IV and N V absorption at similar outflow velocities (see below). Trough B’s low-velocity end remained relatively unchanged (though slightly weaker) into GEM2, while its high-velocity side reached higher outflow velocities. Finally, between GEM2 and GEM3, trough A did not change appreciably, while trough B weakened on its low-velocity side and its high-velocity edge reached higher outflow velocities. Trough B also decreased in depth.

The presence of C IV absorption can be accompanied by absorption of one or more other ionic transitions, such as Si IV, Ly α , and N V. We searched for absorption of these ions that would correspond to the same outflow velocities as trough A or B. Figure 5.7 shows all 6 normalized spectra with a much heavier smoothing, and with a much wider wavelength coverage. We have marked the observed locations of the C IV absorption by trough A (dashed line) and by trough B (solid line), along with the expected locations of their accompanying Si IV, Ly α , and N V absorption. We have plotted the error spectra of the SDSS, BOSS, and GEM1 spectra along the bottom. For the purposes of clarity, the spectra were heavily smoothed in order to see features better in this more noisy part of the spectra. It is also of note the normalization was not repeated with new normalization windows in the region from 1000–1300 Å, thus the relative flux density levels are not necessarily accurate. This is only meant to be a search for possible accompanying absorption.

For trough A, there appears to be no accompanying Si IV absorption in any of the spectral epochs we obtained. In searching for accompanying Ly α +N V, we note that the wavelength coverage does not extend far enough into the blue for SDSS, BOSS1, or BOSS2 but does for the three Gemini

spectra. In these latter three epochs there may be N v, but no apparent Ly α is observed. For trough B, we note the possible presence of accompanying Si IV absorption in the three Gemini spectra, however, the absorption is coincident with the Ly α +N v emission systemic to J0230. Since it is very difficult to disentangle emission from coincident absorption, we cannot confirm this to be Si IV. The identification is also not certain because a flux density deficit was also seen at that location in the SDSS spectrum, before trough B appeared. There is probably N v absorption for trough B.

Archival photometry of J0230 is available since it is located in Stripe 82, a region of sky imaged by SDSS, multiple times over 7 years (MacLeod et al., 2010). We have obtained the photometry of J0230 from the SDSS archive, however, it is not concurrent with our spectroscopy. Thus it cannot help us interpret the spectroscopic variability we observe. J0230 was too faint for the Catalina Real-time Transient Survey (CRTS; Drake et al. 2009).

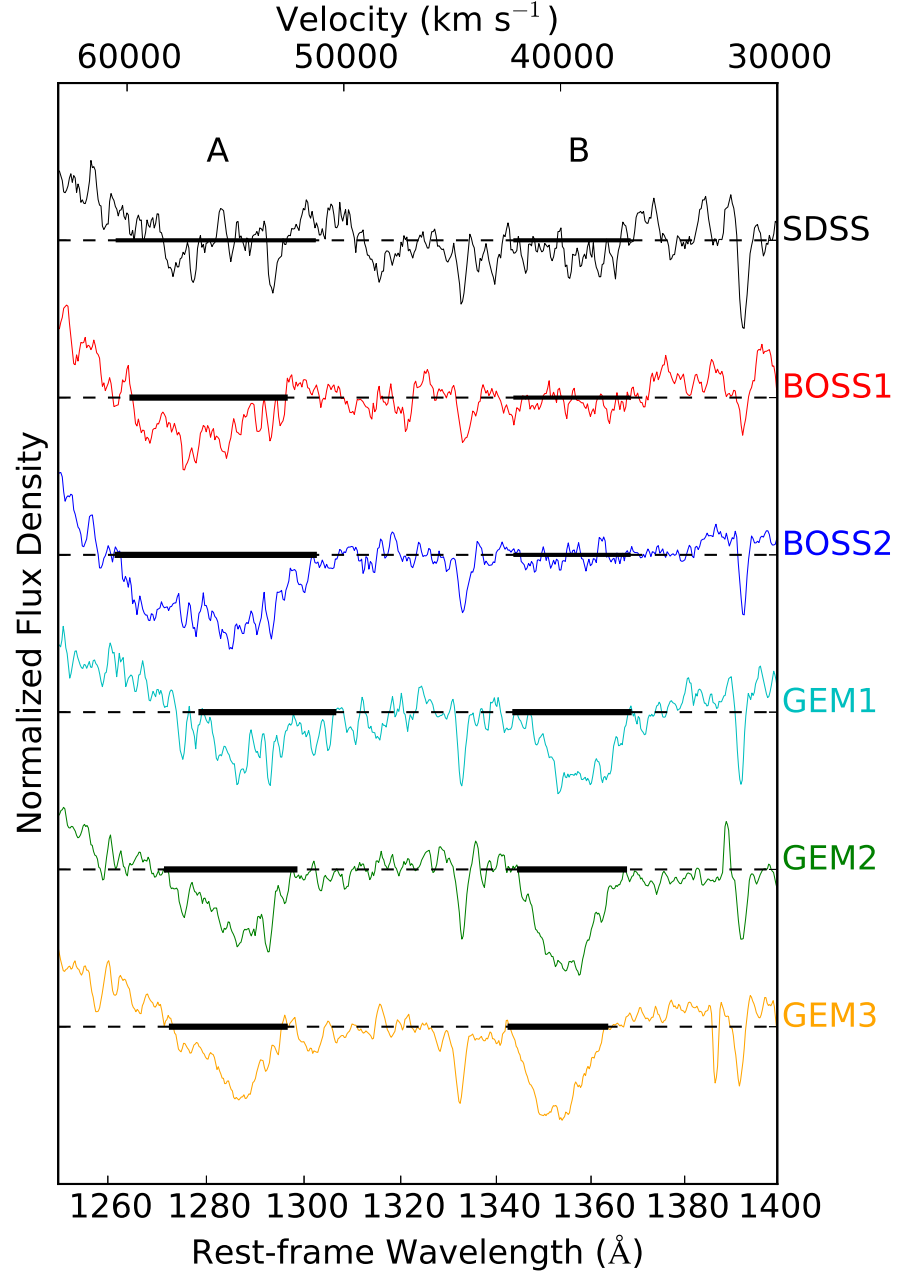


Figure 5.6: Each spectral epoch is plotted centred on the two absorbers, troughs A and B. We have separated the spectra artificially by 0.5 normalized flux density units, with the earliest epoch (SDSS) at the top, and the most recent (GEM3) at the bottom. The dashed lines indicate the normalized continuum level for each spectrum. The black bars indicate where we define the absorption features to begin and end. Note for the SDSS spectrum, there is no apparent absorption in either troughs A or B. Also note for SDSS, BOSS1, and BOSS2 there is no apparent absorption for trough B. For these cases we have placed a slightly thinner black bar across the regions that represent the widest that trough became. For trough A, this occurs in BOSS2 and for trough B this occurs in GEM1.

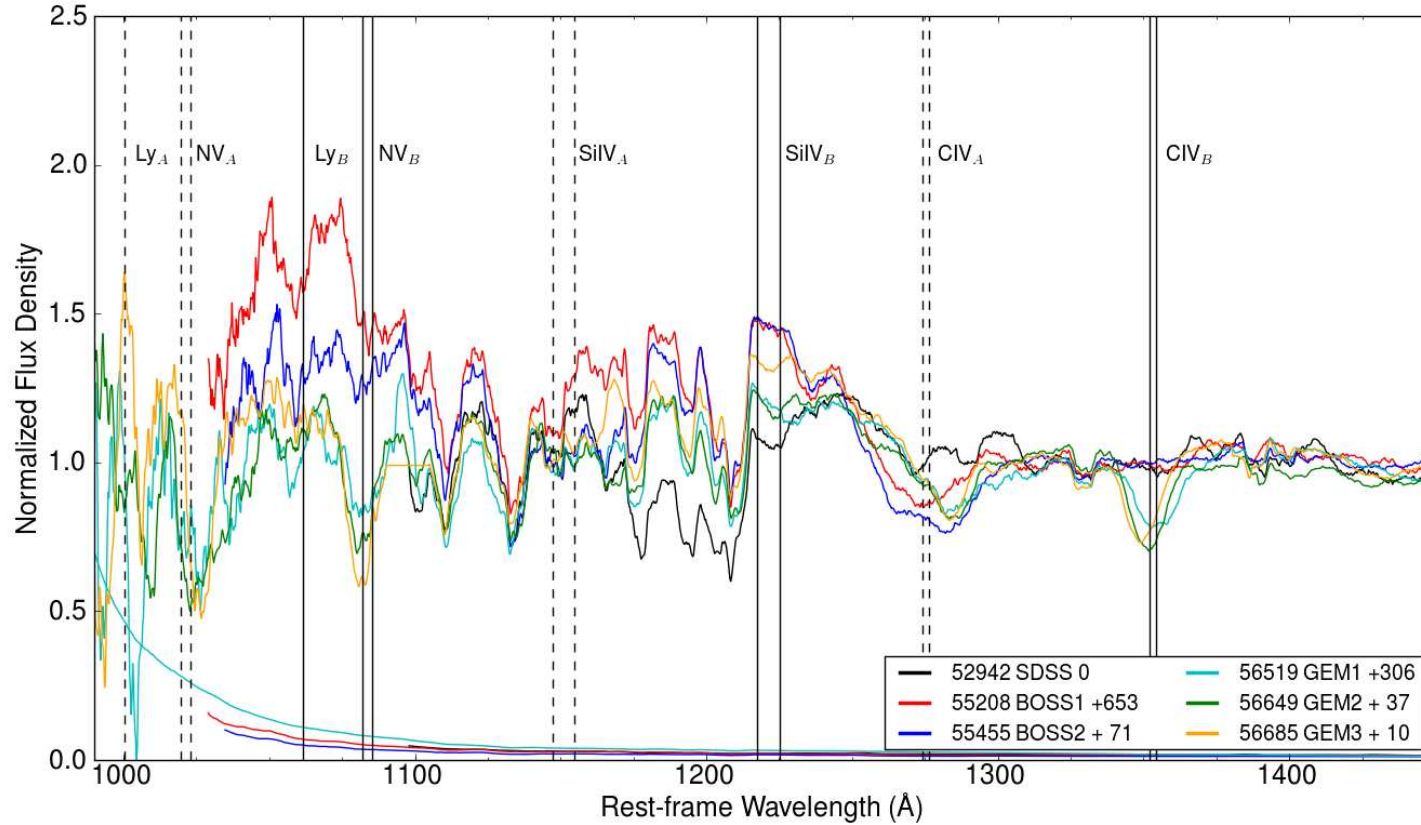


Figure 5.7: Plotted are the 6 normalized spectra of J0230 with heavier smoothing (boxcar with window of 25 pixels) and with a much wider wavelength coverage. We have marked the location of the trough A CIV absorption with a vertical dashed line; the expected locations of Si IV, NV, and Ly α absorption features that may accompany trough A's CIV are also marked with vertical dashed lines. The location of trough B's CIV absorption is marked with a vertical solid line, as are the expected locations of Si IV, NV, and Ly α absorption features that may accompany trough B's CIV. At the shortest wavelengths of the BOSS1 and BOSS2 spectra (at <1330 Å in the trough A rest-frame), the spurious broad 'emission' features are due to noise. It is of note these are the normalized spectra from § 5.1.1, which were created using continuum windows between 1300–1700 Å.

5.2 Measurements of Troughs A and B

We measure the properties of absorption troughs A, B, and C, such as the equivalent width (EW), the weighted centroid velocity v_{cent} , and the average trough depth, in all observations in order to compare changes from one epoch to the next.

In Figure 5.6, the 6 epochs of normalized spectra are plotted (separated artificially in the y direction). The bottom x-axis is the rest-frame wavelength, and the top x-axis is the outflow velocity relative to C IV ~ 1550 Å. The dashed lines indicate the continuum for each spectrum. The dark horizontal lines indicate where we define absorption is present for troughs A and B (see below on how these were chosen).

The EW was measured using the equations (3.4) and (3.5) in § 3.5.

The edges of troughs A and B in a given spectrum were identified by finding the locations where the flux density drops below, and stays below, the normalized continuum level of $F_c = 1$. In Figure 5.6, these edges are represented by black horizontal bars; in Table 5.2, ΔW is calculated using these edges. We applied Equations 3.4 and 3.6 to calculate the EW within the edges found. We note that the placement of the normalized continuum, and thus the locations of the edges of the troughs, is highly sensitive to the normalization process. Further, for trough A, the absorption appears to be truncated by the Ly α +N V emission complex; as a result we consider our EW measurements to be conservative.

Note for both troughs, some epochs do not exhibit absorption; both troughs A and B are not present in the SDSS spectrum, and trough B does not exhibit absorption in the SDSS, BOSS1, and BOSS2 spectra. For these cases, we took the largest trough width determined for each trough and applied it to the unabsorbed spectra. For example, in the case of trough A, the widest the trough was observed to be was in the BOSS2 spectrum at $1262 - 1302 = 40$ Å. We applied this range of the absorption profile in the unabsorbed spectra of SDSS1 and measured the EW. The resulting value for the SDSS spectrum was -0.18 ± 0.48 Å, indicating an EW consistent with zero. More examples of this can be found in Table 5.2 labeled with ellipses.

We measured the centroid velocity, v_{cent} , of the trough following the definition in Filiz Ak et al. (2013); it is the mean of the velocity in a trough where each pixel is weighted by its distance from the normalized continuum.

The mean depth of the trough was calculated in two ways. First, we measured d_{BAL} as in Filiz Ak et al. (2013), which is the mean distance from the normalized continuum level for each data point in the trough. Second, we measured d_{max7} as in § 3.5. We note that since the observations were taken with different telescope and instrument set ups, 7 pixels correspond to slightly different resolutions; however, the differences are too small to impact the measurements. For reference, the 7 pixels cover approximately 2 Å, or ~ 450 km s $^{-1}$ in all spectra.

5.2.1 Coordinated Variability

Work on BAL quasar variability indicates troughs from the same object can vary in synchronization with each other, which can lead to constraints on variability models (i.e., Filiz Ak et al. 2012, Wang et al. 2015; see discussion in § 5.4.1 below). In order to investigate how the variability of one trough in J0230 compares with others, we have created two plots. In Figure 5.8, the EW of each trough is plotted versus the rest-frame time elapsed since the SDSS epoch. In Figure 5.9, d_{max7} of each trough is plotted versus the rest-frame time elapsed since the SDSS epoch. The EW of trough C changed noticeably throughout the observations, particularly between SDSS and BOSS. Both trough A and B begin with a very low EW, consistent with zero, then emerge with a sharp and significant increase in later epochs (BOSS1 for A and GEM1 for B). There is an interesting pattern in the final three observations (the Gemini epochs), which occurs after both troughs have emerged and are established: the EW for both trough A and B increases for GEM2 and then returns to the same value it was in GEM1 for GEM3. This is also observed to occur in trough C. This pattern could be interpreted as absorption from three physically distinct clouds varying in a coordinated fashion (for reference, the time frame from GEM1 to GEM3 is 47 days). However, the uncertainties on our EWs are of similar scale to the amount of variability we are referring to in the Gemini epochs. Thus, this pattern does not represent statistically significant coordination in variability.

5.2.2 BALnicity Index

As described in § 3.2, the BALnicity Index is used to standardize what constitutes broad absorption, making comparison of variability between studies easier. For J0230, we have measured two BALnicity Indexes. First, we calculate the Absorption Index (AI_{450}), defined in Hall et al. (2002), following:

$$AI_{450} = \int_0^{v_{high}} \left(1 - \frac{f(v)}{0.9}\right) C' dv. \quad (5.1)$$

where $f(v)$ is the normalized flux density as a function of velocity, and C' is equal to 1.0 within a trough if the trough is wider than 450 km s^{-1} , otherwise it is set to 0.0. The integration begins at $v = 0 \text{ km s}^{-1}$ relative to the systemic velocity of the quasar and runs through the highest velocity at which absorption is present.

We also measure the modified BALnicity index, BI^* , following:

$$BI^* = \int_{v_{low}}^{v_{high}} \left(1 - \frac{f(v)}{0.9}\right) C dv, \quad (5.2)$$

which is described in § 3.2.

In Table 5.3, we list the BALnicity indices calculated using both methods. The total index value is measured over $v_{low} > 0$ and $v_{high} < 60,500 \text{ km s}^{-1}$, however, we also provide the individual contributions of each trough in the spectra. Note that for AI_{450} , trough C contributes to the total index, but for BI^* it does not.

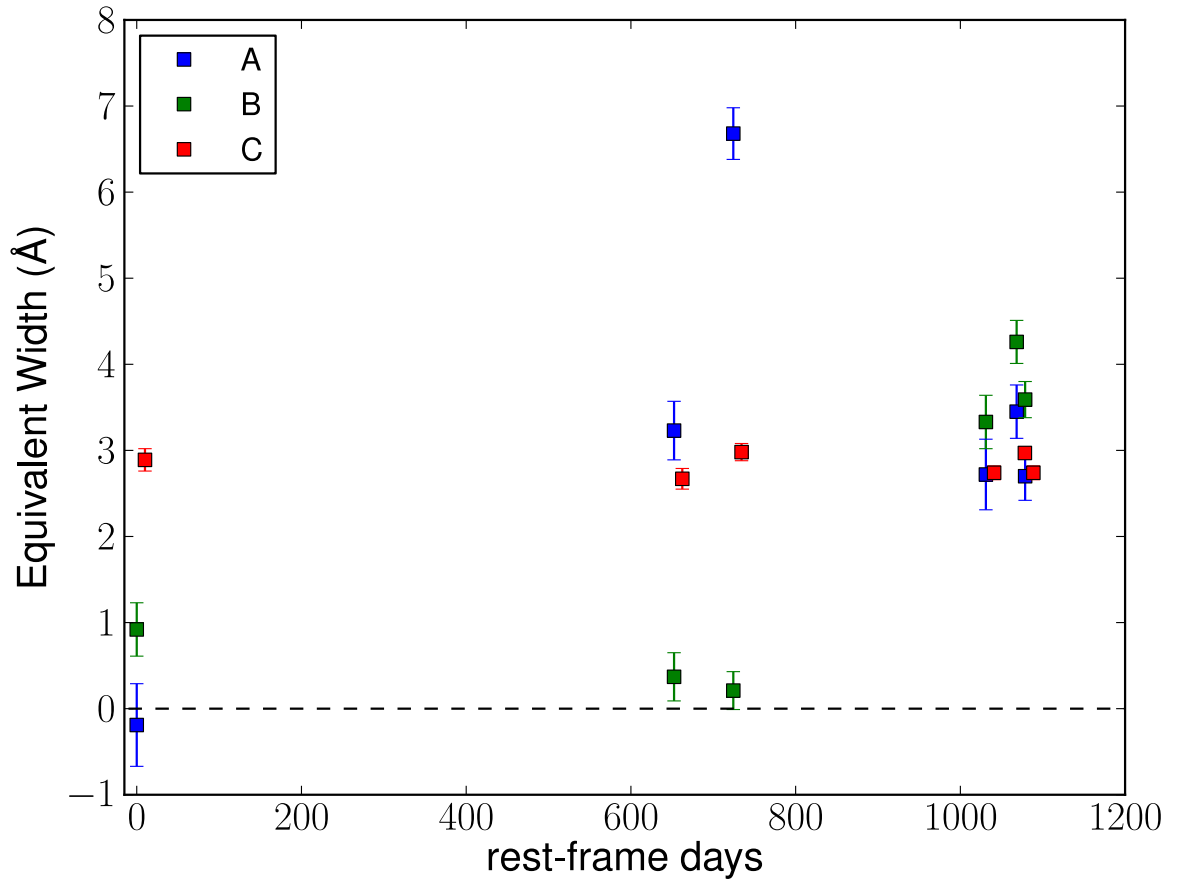


Figure 5.8: The measured equivalent widths (EW) for troughs A (blue), B (green), and C (red). At >1000 days, the trough C points are artificially shifted to the right by 10 days in order to avoid confusion with trough A data points.

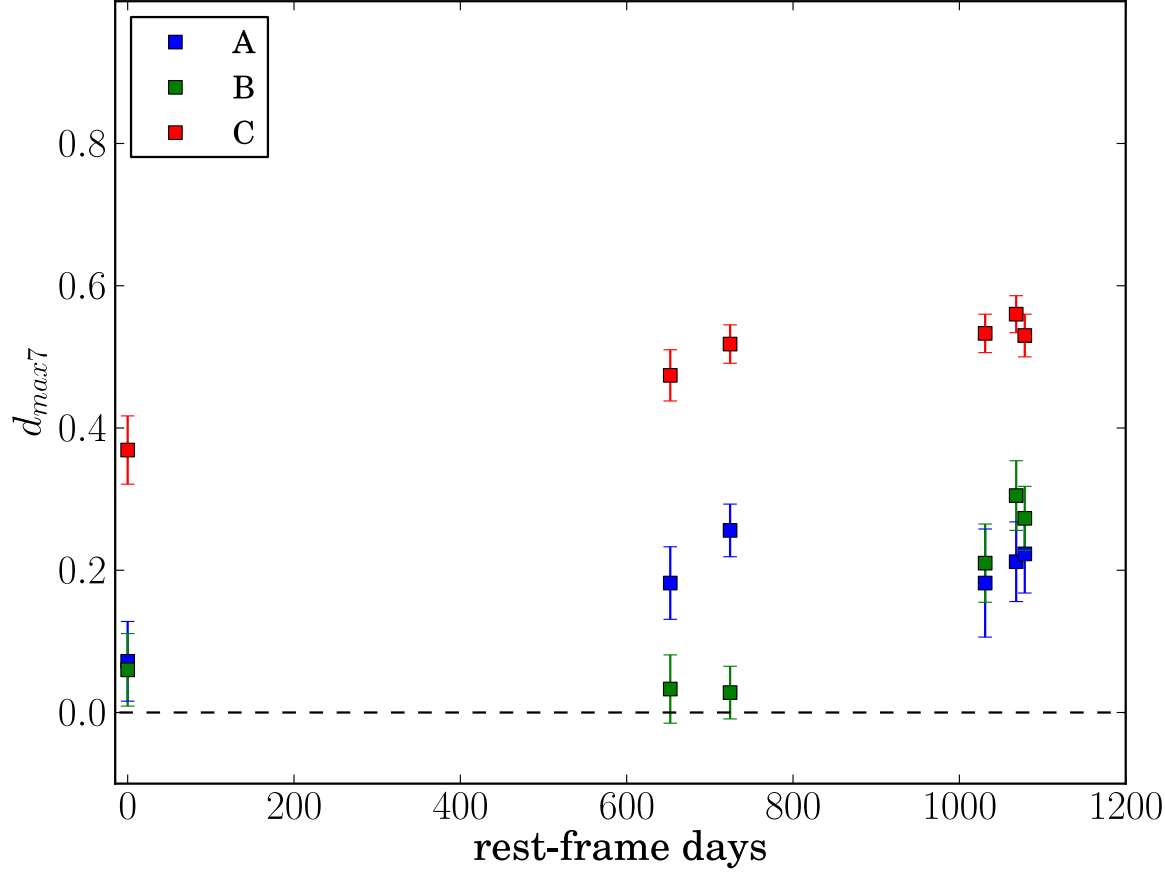


Figure 5.9: The maximum depth, d_{max7} , of trough A (blue), B (green), and C (red) as a function of rest-frame days. d_{max7} represents the lowest average 7 pixels in a row for each trough.

	Rest ΔT	$EW \pm \sigma_{EW}$	Δw	Δv	d_{max7}	v_{cent}	d_{BAL}
Trough A	(days)	(Å)	(Å)	(km/s)		(km/s)	
SDSS	0	-0.19 ± 0.48	...	...	0.07 ± 0.06	...	...
BOSS1	652.39	3.23 ± 0.34	31	7002	0.18 ± 0.05	56496	0.10
BOSS2	71.93	6.68 ± 0.30	40	9028	0.26 ± 0.04	56004	0.17
GEM1	306.67	2.72 ± 0.41	27	6063	0.18 ± 0.08	53769	0.10
GEM2	37.33	3.45 ± 0.31	26	5860	0.21 ± 0.06	55020	0.13
GEM3	10.32	2.70 ± 0.28	23	5185	0.22 ± 0.06	55101	0.12
Trough B							
SDSS	0	0.92 ± 0.31	...	...	0.06 ± 0.05	...	...
BOSS1	652.39	0.37 ± 0.28	...	...	0.03 ± 0.05	...	...
BOSS2	71.93	0.21 ± 0.22	...	...	0.03 ± 0.04	...	...
GEM1	306.67	3.33 ± 0.31	24	5214	0.21 ± 0.05	39212	0.14
GEM2	37.33	4.26 ± 0.25	22	4780	0.31 ± 0.05	39726	0.11
GEM3	10.32	3.59 ± 0.21	20	4352	0.27 ± 0.04	40224	0.10
Trough C							
SDSS	0	2.89 ± 0.13	8	1549	0.49 ± 0.04	87	0.37 ± 0.05
BOSS1	652.39	2.67 ± 0.12	8	1550	0.47 ± 0.04	78	0.33 ± 0.05
BOSS2	71.93	2.98 ± 0.10	10	1935	0.52 ± 0.03	68	0.30 ± 0.05
GEM1	306.67	2.74 ± 0.08	7	1356	0.53 ± 0.03	163	0.39 ± 0.04
GEM2	37.33	2.97 ± 0.07	7	1356	0.56 ± 0.02	125	0.42 ± 0.04
GEM3	10.32	2.74 ± 0.08	7	1356	0.53 ± 0.03	212	0.39 ± 0.04

Table 5.2: Measurements made on trough A, B, and C. The SDSS epoch was set to be the time origin of our observations. An ‘...’ indicates where no absorption is visible in the spectrum. Values of EW for these cases used the widest possible ΔW the trough was observed to reach (BOSS2 for trough A, GEM1 for trough B).

	AI_A	AI_B	AI_C	total AI	BI_A^*	BI_B^*	BI_C^*	total BI^*
SDSS	0.0	0.0	477 ± 3	477 ± 3	0.0	0.0	0.0	0.0
BOSS1	152 ± 5	0.0	437 ± 2	589 ± 5	0.0	0.0	0.0	0.0
BOSS2	746 ± 6	0.0	490 ± 2	1236 ± 6	561 ± 5	0.0	0.0	561 ± 5
GEM1	103 ± 6	323 ± 6	455 ± 2	880 ± 8	0.0	115 ± 4	0.0	115 ± 4
GEM2	293 ± 6	547 ± 6	491 ± 2	1331 ± 9	74 ± 4	242 ± 4	0.0	316 ± 5
GEM3	210 ± 6	433 ± 5	453 ± 2	1096 ± 7	35 ± 3	155 ± 3	0.0	190 ± 4

Table 5.3: The BALnicity was calculated using two different definitions: AI_{450} and BI^* (see § 5.2.2). We calculated the total index over a velocity range of $v_{low} > 0$ and $v_{high} < 60,500$ km s⁻¹. We also calculated the individual contributions to the index by each trough in the spectra. In the case of AI_{450} , trough C contributed to the measurement; for completeness, we provide its index measurement. In BI^* , trough C did not contribute to the total. Note the uncertainties quoted here are statistical only. Systematic uncertainty introduced by the placement of the continuum is not taken into account. A reasonable continuum uncertainty of $\pm 5\%$ translates to a BALnicity Index uncertainty of $\pm 5\%/d_{BAL}$.

5.3 Black Hole Mass Estimate

The physical size of the accretion disk surrounding the SMBH in quasars cannot be measured directly, as they are too small on the sky to resolve. However, we can estimate the size of a portion of the accretion disk if we know the mass of the black hole. Remembering from Chapter 1, the temperature of the black-body radiation at the far edge of the accretion disk is relatively low, and the temperature closer to the inner edge is much higher. A higher mass black hole would have faster orbits closer to the inner edge of the disk, and thus higher temperatures. As a result, the size of the portion of the accretion disk we are interested in is dependent on the mass of the SMBH at the centre. Here we estimate the mass of the black hole so that we can estimate the size of the accretion disk at the wavelengths absorbed by troughs A and B in the next section.

Observations in the literature have shown that the broad emission lines originate from a region that is virialized (see Rafiee & Hall 2011 and references therein). As a result, one can use the velocity dispersion of the broad lines to estimate the mass of the black hole. For J0230, we use the technique from the previously cited work, which is based on the velocity dispersion of the Mg II λ 2796, 2803 Å emission line. A full description of this technique can be found in Rafiee & Hall (2011). Equation 9 of that work is

$$M_{BH}/M_{\odot} = 30.5[\lambda L_{3000}/(10^{44} \text{ erg s}^{-1})]^{0.5}\sigma^2, \quad (5.3)$$

where L_{3000} is the intrinsic luminosity per unit rest-frame Å at 3000 Å rest-frame, $\lambda = 3000$ Å, and σ is the intrinsic line dispersion of the Mg II emission line in km s^{-1} . There is intrinsic scatter of ± 0.15 dex ($\pm 35\%$) and systematic uncertainty of ± 0.10 dex ($\pm 24\%$) in this equation.

The two BOSS spectra of J0230 represent the best coverage we have of that wavelength regime. We combined the two BOSS spectra by averaging them together weighted by the uncertainties at each pixel, and then fit a line to the continuum using windows 2650–2700 Å, 2900–3000 Å. After fitting and removing the continuum, we fit a Gaussian to the remaining Mg II emission in the region 2700–2900 Å. In Figure 5.10 the fitted Gaussian is plotted over the normalized mean BOSS spectrum. The best-fit parameters were $\mu = 2805$ Å for the line centre and $\sigma = 22.1$ Å for the standard deviation. The standard deviation in the Gaussian fit indicates the velocity dispersion of the Mg II emission feature, which is caused by the Doppler broadening of an AGN broad line region orbiting the SMBH. We convert $\sigma = 22.1$ Å to $2,370 \text{ km s}^{-1}$, which is the velocity dispersion in the Mg II line of J0230.

To calculate the quasar luminosity we used

$$\lambda L_{3000} = 4\pi D_L^2 f_{3000} \times 3000(1+z), \quad (5.4)$$

where D_L is the luminosity distance, f_{3000} is the observed flux density at rest-frame wavelength 3000 Å, and z is the redshift (Hogg, 1999). We measured f_{3000} from the combined BOSS spectrum to be $f_{3000} = 3.35 \times 10^{-17} \text{ erg s}^{-1} \text{ cm}^{-2} (\text{observed } \text{Å})^{-1}$. Adopting a flat cosmology described with $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_M = 0.3$, and $\Omega_\Lambda = 0.7$, the luminosity distance to $z = 2.473$ is $D_L = 2.01 \times 10^{10} \text{ pc}$,

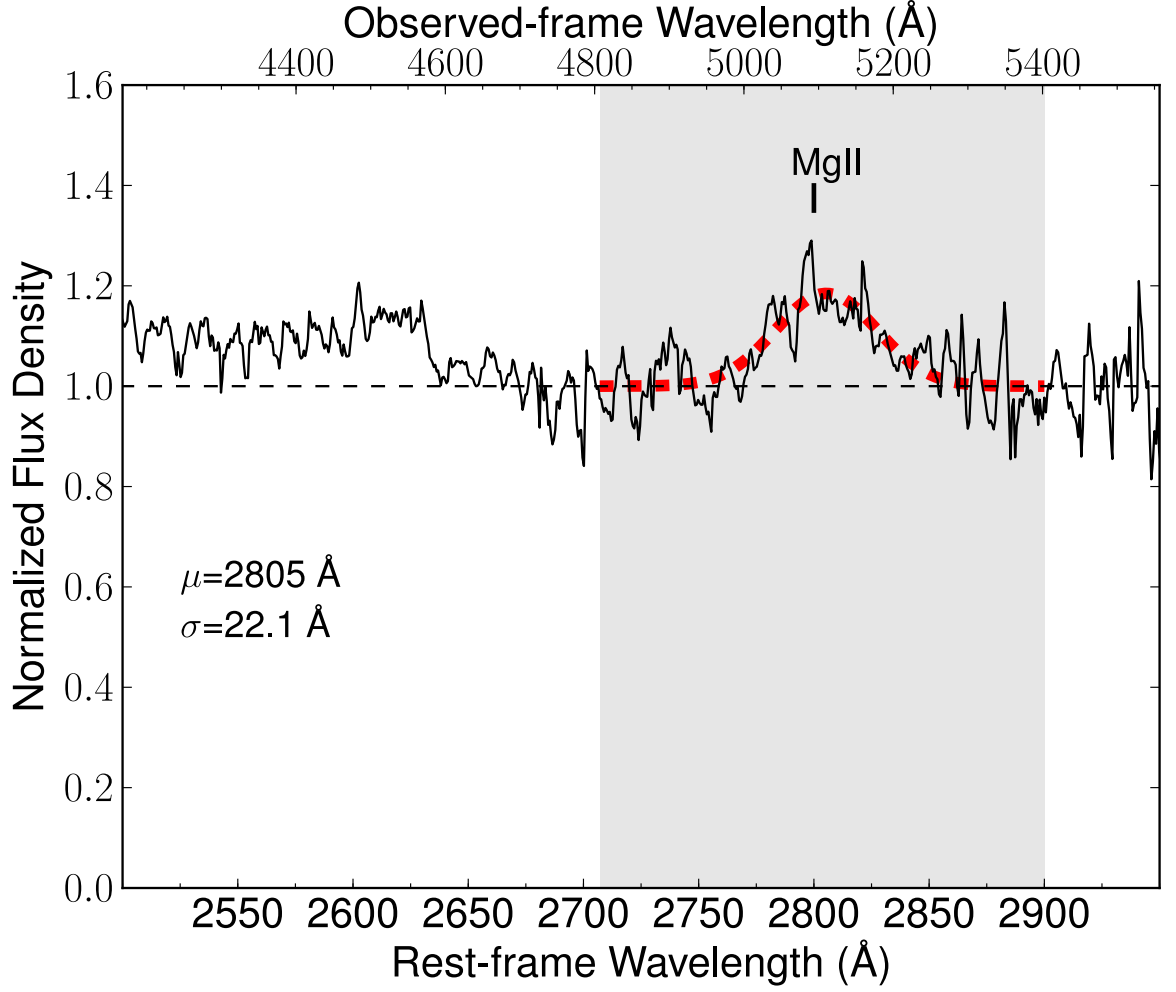


Figure 5.10: Combined BOSS spectra (black), continuum fit (dashed black), and Gaussian fit (dashed red) to the Mg II emission feature at $\sim 2800 \text{ Å}$. The fit was applied only to the data in grayed out region. The best-fit Gaussian parameters to the data are shown in the lower left. μ is the line centre, and σ is the standard deviation.

or 6.21×10^{28} cm. Therefore, we have $\lambda L_{3000} = 1.69 \times 10^{46}$ erg s $^{-1}$. Finally, we calculate the mass of the SMBH to be $M_{BH}/M_{\odot} = 2.2 \times 10^9$ with an intrinsic scatter of $\pm 0.8 \times 10^9$ ($\pm 35\%$).

The Eddington Luminosity, L_{Edd} , is the maximum luminosity allowed, on long time-scales, for an object powered by spherically symmetric accretion (Netzer, 2013). For a SMBH of this mass the Eddington Luminosity is $L_{Edd} = 3.45 \times 10^{47}$ erg s $^{-1}$. Using a bolometric correction of $BC_{3000} = 5$ derived in Richards et al. (2006), this quasar has an estimated $L_{Bol} = 8.45 \times 10^{46}$ erg s $^{-1}$, and therefore this quasar has an estimated $f_{Edd} \equiv L_{Bol}/L_{Edd} = 0.25$, where L_{Bol} is the luminosity after taking into account all of the electromagnetic spectrum. The Schwarzschild radius, R_{Sch} , is the distance from a non-rotating SMBH at which the escape velocity is the speed of light, determined by $R_{Sch} = 2GM/c^2$. In the case of J0230, the mass measured above would result in $R_{Sch} = 6.6 \times 10^9$ km.

It is worth pointing out that Plotkin et al. (2010) present some evidence to suggest that some Mg II emission lines of WLQs could exhibit non-virialized behaviour (namely, the emission feature is blueshifted from the systemic redshift, though only by 360 km s $^{-1}$ on average; see § 5.2 and 6.1 of that work). We see no such evidence of a non-virialized Mg II emission feature in J0230: a single Gaussian function fits the emission line well, its peak is actually redshifted by $\sim 510 \pm 380$ km s $^{-1}$ from the position of Mg II expected from the composite spectrum of Vanden Berk et al. (2001).

Moreover, we have calculated black hole masses for the objects in Plotkin et al. (2010) using the Mg II emission line and find that the resulting masses are larger than the black hole masses they calculate using the dispersion in H β by only a factor of two. A deviation of that factor is not statistically significant given the uncertainties on our black hole mass estimate.

5.4 Discussion

As mentioned in the introduction, broad absorption trough variability in quasars can be explained by transverse motion of the absorbing clouds across the line-of-sight to the accretion disk, or by changes in the ionization parameter of the absorbing cloud, or by a combination of these. Here we analyze two possibilities individually laying out constraints where possible. The kinetic luminosity of an outflow, expressed in units of energy/s, is a measure of the rate at which material is being moved by the wind. Unfortunately The range of possible locations for the gas is large enough to preclude useful constraints on the kinetic luminosity of the outflow (Dunn et al., 2010), especially since the solid angle covered by this extremely high velocity outflow is unknown.

5.4.1 Pure Transverse Motion Variability Model

In the transverse-motion model it is assumed the absorption parameters of the cloud of gas are unchanged, and all changes to the EW, the velocity profile, and the maximum depth of the trough can be explained by an absorbing cloud moving to cover more or less of the accretion disk. We assume the absorbing gas starts in a circular orbit in the accretion disk and is launched radially

outward. Any evolution of an absorption feature (i.e., an emergent trough) can be explained as long as the constraints from time-scales yield plausible transverse velocities.

The transverse velocity of an absorbing cloud across the line-of-sight is derived by dividing the distance the cloud travels by the travel time it took to get there. We approximate the time it took to get there as the time between successive observations. In reality, the cloud could have taken much less time to travel this distance, but we can only constrain by length of time between observations. In order to measure the distance covered by an absorbing cloud between those observations we must both estimate the size of the continuum region it is traversing, and also model the relative sizes and shapes of the cloud and continuum region.

We approximate the size of the continuum region at a given temperature to be represented by the α -disk model presented in Shakura & Sunyaev (1973), hereafter SS73, with the following model parameters. We set $\alpha = 0.1$, a free parameter in the model that governs the amount of accretion as a result of turbulence, typically $0 < \alpha < 1$. An accretion efficiency of $\eta = 0.057$, which is the efficiency at which the black hole converts rest mass to radiation; the value we use here is the efficiency of a non-spinning black hole (Netzer, 2013). Given these parameters, the rate of mass accretion onto the black hole would be $\dot{m} \equiv f_{Edd}/\eta = 0.25$ (Netzer, 2013). Using an accretion disk defined by these parameters, we can estimate $D_{95}(1320)$, the continuum diameter within which 95% of the 1320 Å continuum is emitted. We use the 1320 Å continuum, which is the region in between troughs A and B, because it allows us to use a continuum region that is the same size for both troughs; we note the size of the accretion disk would only change a small percentage if using the trough A or B centroid wavelengths. We find $D_{95}(1320) = 63 R_{Sch}$, therefore, $D_{95}(1320) = 4.2 \times 10^{11}$ km. That gives a light-crossing time of 1.4×10^6 s = 16 days.

However, accretion-disk sizes inferred from gravitational-microlensing studies and photometric-reverberation studies (e.g., Morgan et al. 2010, Blackburne et al. 2011, Jiménez-Vicente et al. 2012, Edelson et al. 2015) are approximately a factor of four larger than the theoretical size predicted in the SS73 α -disk model (see a full discussion in Hall et al. 2013). Therefore, we increase our estimated continuum-source diameter by a factor of four, to $D_{95}(1320) = 252 R_{Sch} = 1.7 \times 10^{12}$ km. The uncertainty in this number is likely a factor of two. A disk that size has a light-crossing time of 5×10^6 s = 64 days.

With the estimated size of the emitting region, and, given some simple models of clouds moving into or out of the line-of-sight of an emitting region, we can estimate a maximum and minimum transverse velocity of an absorption cloud that would be responsible for the emergence and variability of troughs A and B.

The most dramatic change we observed in the absorption depth of J0230 occurred in trough B when it emerged between the BOSS2 and GEM1 observations; the change in depth was $\Delta d_{max7} = 0.21 - 0.03 = 0.18$ over a period of 307 rest-frame days. As per the transverse-motion model, if we consider this change in depth to be entirely due to more of an optically thick absorbing cloud

moving into the line-of-sight to the emitting region, it suggests that over 307 rest-frame days, the emitting region went from having 3% of its flux density blocked to having 21% blocked, or a 21% covering fraction, C . Note in order for changes in absorption depth to equate to changes in covering fraction we are assuming the lines are optically thick. (If the lines are optically thin, the absorber must reach a larger covering fraction of the emission region in the same time span, requiring even higher transverse velocities.)

In Capellupo et al. (2013), two simple models were proposed for clouds crossing the emitting region (see Figure 14 therein). The first scenario is the ‘crossing disks’ model, where the absorbing cloud is projected on the sky as a circle (or a disk) and is crossing a circular emitting region (where the emitting region appears much larger than the absorbing cloud). In the second scenario the absorber is much larger than the background emitter it is traversing; this is the ‘knife-edge’ model. As mentioned above, the crossing speeds in these two scenarios are measured by dividing the distance traveled by the time it took to travel there. The change in covering fraction, ΔC , is the fraction of the emitting region the absorber crosses in the time-frame between observations. Therefore, in the ‘crossing disks’ scenario, the minimum distance traveled by the gas responsible for the emergence of trough B is $\sqrt{\Delta C} D_{95}(1320)$, and the crossing time is $\Delta T = 307$ days. Therefore, $\sqrt{0.18} \times 64$ light-days = 27 light-days in 307 days. Therefore the transverse speed is $26,400 \text{ km s}^{-1}$. However, if we assume the cloud has traversed to the exact opposite side of the emitting region, the distance traveled is the complete 64 light-days in 307 days. This results in a transverse velocity of $62,500 \text{ km s}^{-1}$. In the ‘knife-edge’ scenario, the distance traveled is $\Delta C D_{95}(1320) = 12$ light-days in 307 days. This equates to $11,700 \text{ km s}^{-1}$. Thus, given the above two scenarios, we can place the transverse velocity of a cloud responsible for the emergence of trough B in the range $11,700 < v(\text{km s}^{-1}) < 62,500$. For trough A, the most dramatic change in absorption depth also occurred during its emergence, which was between SDSS and BOSS1; the change in depth was $\Delta d_{max7} = 0.18 - 0.07 = 0.11$ over a period of 652 rest-frame days. Applying the same relations as above we can place the transverse velocity of a cloud responsible for the emergence of trough A in the range $3,200 < v(\text{km s}^{-1}) < 29,500$.

While these two models can be useful in interpreting observations in a campaign with two epochs, our unique dataset consists of six epochs. Analyzing the behaviour of the absorption features over all six epochs allows us to test the predictive power of the above two scenarios. For instance, trough B was consistent with zero absorption in the SDSS, BOSS1, and BOSS2 observations (see Table 5.2). The trough appeared between the observation of BOSS2 and GEM1, which was over a time period of 307 days, then for the next 2 observations (GEM2, and GEM3) the trough remained close to the same depth and EW (within the uncertainties). Assuming an absorber is moving at a constant velocity transverse to the line-of-sight, the above behaviour rules out the ‘knife-edge’ scenario, which would only cover more area as time goes on.

If we assume the emitting region has a uniform flux density across its area (as Capellupo et al. 2013 does), then the ‘crossing disk’ scenario can explain trough B’s behaviour. However, research

into the theoretical understanding of accretion disks - through the work of SS73 and Dexter & Agol (2011) (among others) - indicates the emitting region is unlikely to be homogeneous. If we assume the emitting region is more like a SS73 disk, where the majority of the flux density is concentrated toward the centre of the emitting region, we can also rule out the ‘crossing disks’ scenario.³ A crossing disk of fixed size traversing a SS73 accretion disk at a constant velocity would produce an increasing amount of observed covering fraction as it moved across the first half of the disk, but then a decreasing amount of covering as it traversed the second half of the disk. If trough B appeared in GEM1 as a result of transverse motion, we would have expected to see the depth of the absorber decrease appreciably in the subsequent observations of GEM2 and GEM3. Since this is not the case, the ‘crossing disks’ scenario is unlikely to be the correct interpretation of the variability of trough B.

Over 6 epochs, the nature of trough A’s variability also rules out the ‘knife-edge,’ but agrees with the augmented ‘crossing disks’+SS73 scenario. Specifically, there was no measured absorption in SDSS after which there was an increase in absorption in BOSS1 which continued to increase in both depth and EW into BOSS2. Then by GEM1 through GEM3, both the depth and EW returned back to values similar to those measured in BOSS1. This is consistent with a cloud smaller in angular size than the emitting source traversing into the line-of-sight for BOSS1, crossing the central portion of the disk leading to the measurements of BOSS2, continuing on to the second half of the disk for GEM1 and GEM2, but has not reached the other side yet as there is still measured absorption in GEM3. If we apply the relations from the ‘crossing disks’ scenario above, the velocity range this absorber would have is $10,000 < v \text{ (km s}^{-1}\text{)} < 18,000$. At $18,000 \text{ km s}^{-1}$ we expect trough A to disappear completely approximately 350 days after the GEM3 observation. At $10,000 \text{ km s}^{-1}$ we expect it to disappear approximately 1,500 days after the GEM3 observation.

There is one plausible scenario of transverse motion that can match the observed depth changes in trough B in the context of a SS73 disk: a ‘flow-tube’ (similar to that proposed by Arav et al. 1999; see their Figure 10). In Figure 5.11, we have plotted a log-luminosity map of an accretion-disk emitting at $1320 \text{ \AA}$ powered by a SMBH equal to that of J0230 (see § 5.3). The emitted light is much more concentrated towards the centre (though note there is a region occupied by the black hole where no emission is observed). We have plotted over top of the map an example of our proposed flow-tube scenario. The tube is traversing the continuum region at some impact parameter, i , away from the centre, and has some width, w . The tube extends infinitely to the left in this figure. We note that our flow-tube geometry and dynamics differ from that proposed in Arav et al. (1999). Specifically, we have chosen a flow-tube that is homogeneous from centre to edge and is in the midst of establishing itself along our sight-line before settling into a long-term configuration as discussed in Arav et al. (1999).

If a flow-tube similar to the one shown in Figure 5.11 were to move across the emitting region

³see Fig. 5.11 for an example of the luminosity gradient of a SS73 accretion-disk; this figure will be discussed in more detail later

of J0230, it would serve to create a sharp increase in absorption as it crossed close to the centre of the disk, but due to there being very little flux density at the edges of a SS73 disk, not much more coverage would occur as it traversed the second half of the continuum region. This geometry would match the behaviour we see in the variability of trough B.

We have investigated whether a flow-tube of this nature could successfully reproduce the variability in trough B, and at what velocities it could do this, by simulating flow-tubes of various widths and impact parameters traversing a SS73 disk, measuring how much flux density is covered as a function of distance across the disk the simulated flow-tubes produce, and then attempting to match the observed covering fractions for trough B to the simulated covering fraction vs. distance generated by the flow-tubes. Referring to Figure 5.11, the traversed distance is measured along the x-axis of the disk, and the direction of motion of each simulated flow-tube is from the negative x direction towards the positive x direction.

Matching the observations to our simulations was done via the following prescription: A given simulated flow-tube has covering fraction as a function of x , $C(x)$. We search for a distance across the accretion disk, x_0 , that matches the covering fraction for BOSS2, namely $0 < C(x_0) < C(\text{BOSS2}) + 1\sigma$, which is the last time trough B was measured to have a depth consistent with zero. When found, we go searching for the next closest x_1 that satisfies $C(\text{GEM1}) - 1\sigma < C(x_1) < C(\text{GEM1}) + 1\sigma$. We calculated the velocity, v , required to cover the distance from x_0 to x_1 , given the known time between successive observations (307 days from BOSS2 to GEM1). We then searched for the next x_2 that satisfies $C(\text{GEM2}) - 1\sigma < C(x_2) < C(\text{GEM2}) + 1\sigma$. When a match is found, we use the simulated distance from x_1 (GEM1) to x_2 (GEM2), and the velocity the flow-tube is moving at, v , calculated above, to determine the length of time it would take for the flow-tube to cover the distance $x_1 - x_2$. If the time is equal to the time between GEM1 and GEM2 observations (37 days) then we continue the search to see if $C(\text{GEM3})$ also matches. We look for x_3 that satisfies $C(\text{GEM3}) - 1\sigma < C(x_3) < C(\text{GEM3}) + 1\sigma$. Similar to above, we use the distance from x_2 (GEM2) to x_3 (GEM3), and the v above to determine the length of time it would take for the flow-tube to cover that distance. If that time is equal to the time between GEM2 and GEM3 observations (10 days) then we have found a combination of width and impact parameter for a simulated flow-tube that matches the variability in covering fraction as well as the time between successive observations. In Figure 5.12, we have plotted the parameter space of width vs. impact parameter that we investigated with the simulated flow-tubes. The gray region displays the combinations of parameters that resulted in a flow-tube's final covering fraction (after it had completely traversed the disk) between 15% and 30%, which is a healthy margin for the GEM3 covering fraction. The black points represent the combinations that fit the variability of BOSS2 through to GEM3. In Figure 5.13 we plot a histogram of all possible velocities we determined from the above analysis. The mean velocity of the distribution is $36,800 \text{ km s}^{-1}$ with a range spanning $8,000 < v \text{ (km s}^{-1}\text{)} < 56,000$.

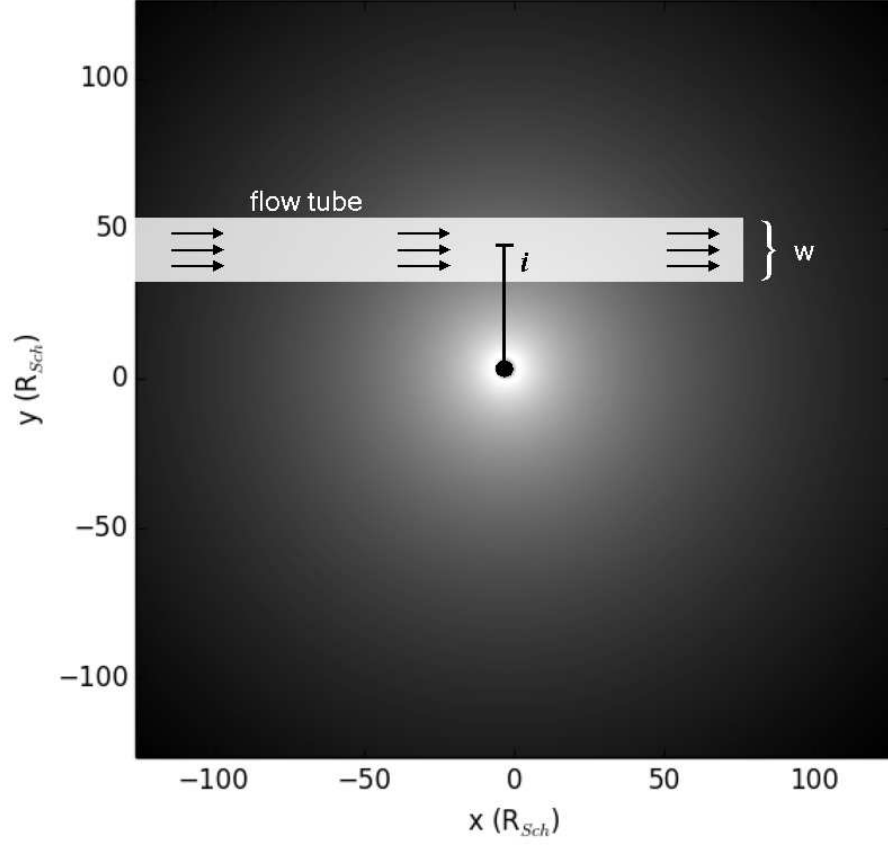


Figure 5.11: An example of a flow-tube traversing a simulated emitting region of an accretion-disk, plotted face-on. The logarithm of the luminosity of the disk is represented by the gray scale. Over-plotted is an example of a flow-tube traversing the disk, which would serve to cover some of the light, creating absorption. In this representation, the tube extends infinitely to the left but terminates at the right edge drawn. The width of the tube is w and the impact parameter relative to the centre of the accretion disk is i . Note there is a region at the very centre occupied by the black hole where no luminosity is observed.

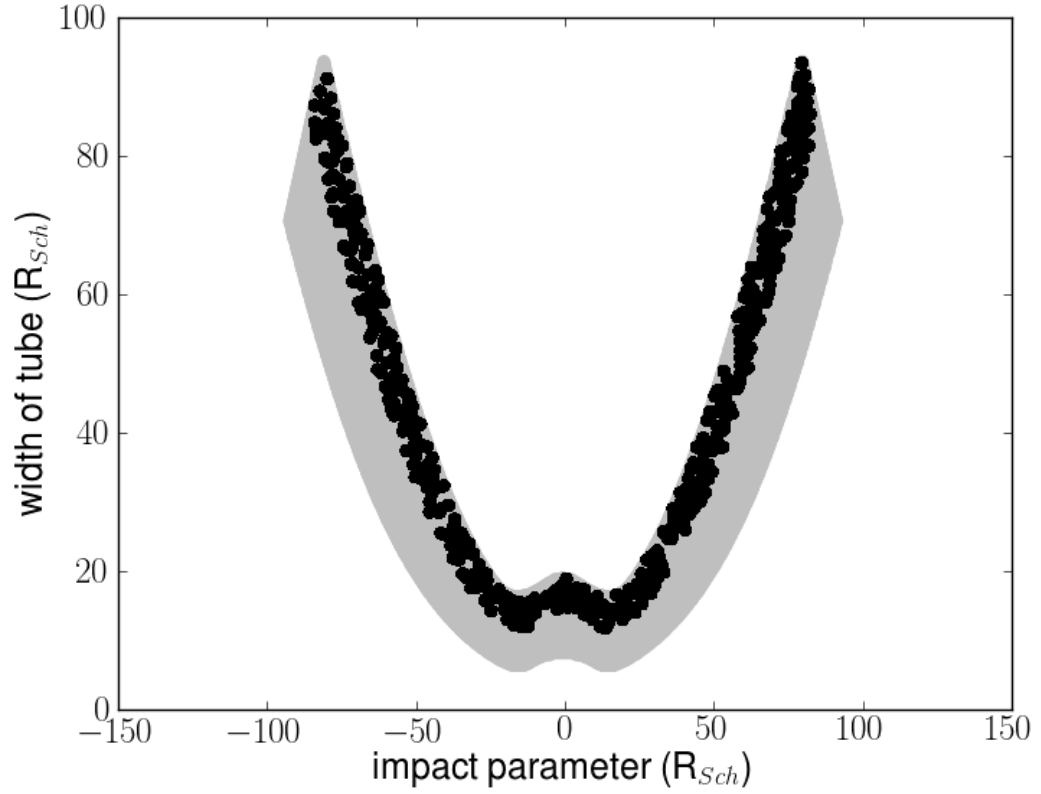


Figure 5.12: Width of flow-tube vs. the distance from centre of accretion disk the flow-tube traverses (impact parameter). It is plotted in units of $R_{Sch} = 6.6 \times 10^9$ km. The gray region represents all possible combinations of flow-tubes that resulted in a final covering fraction between 15% and 30%. The black points are the combinations of parameters that not only matched all covering fractions in our observations, but did so within the observation time constraints. The x-axis is plotted as distance from centre of tube to centre of accretion disk, where positive and negative values represent opposite sides of centre.

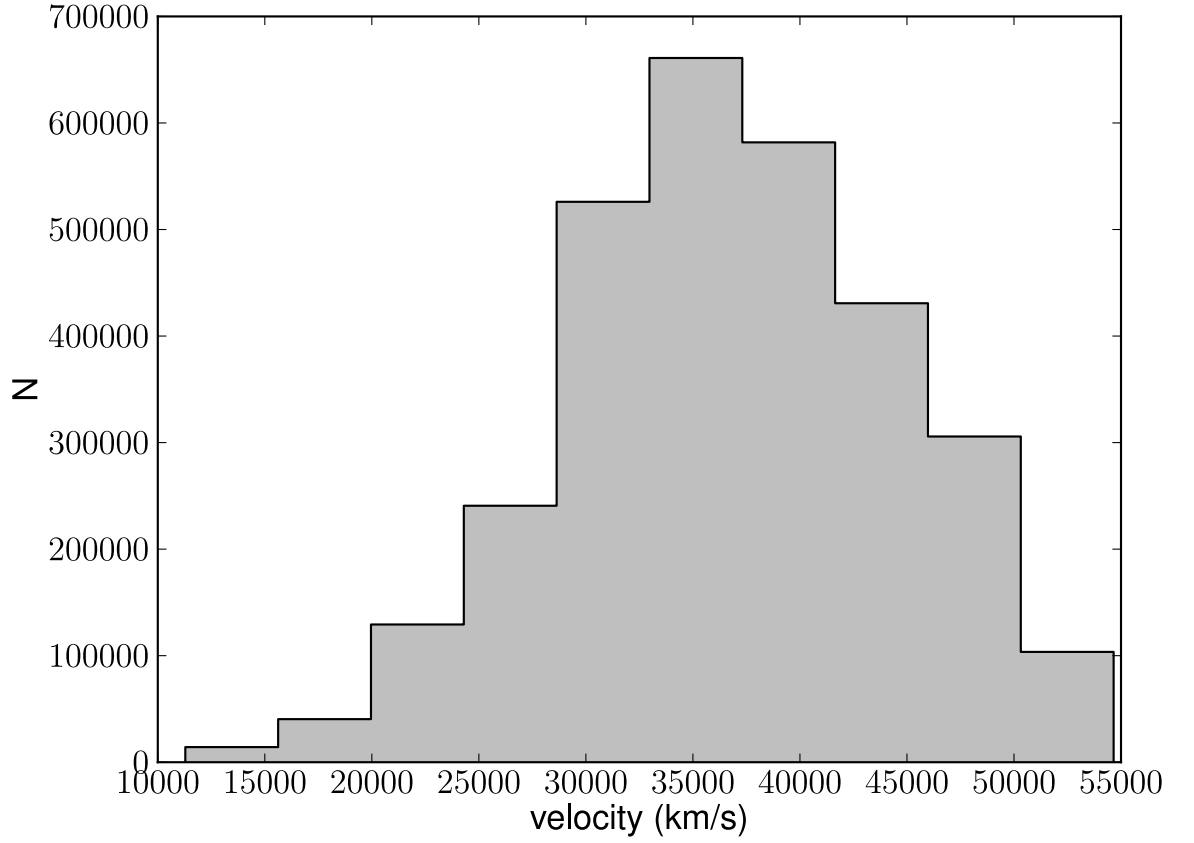


Figure 5.13: The range of possible velocities of a flow-tube traversing the emitting region of J0230. These were determined by simulating flow tubes of various widths and impact parameters across a SS73 disk scaled to match J0230's mass and monochromatic luminosity at $1320 \text{ \AA}$, L_{1320} . In order to be a plausible velocity, the tube must recreate the covering fraction at each spectral epoch, given one velocity, as well as match the time between observations.

Trough A could still be explained as a flow tube, but a simple flow tube model is not consistent with its d_{max7} and EW variations. The best fit despite those variations would yield a slower transverse velocity because the time over which the biggest change occurred (SDSS-BOSS1) is larger than for trough B. Note that a slower transverse velocity is consistent with trough A's higher line-of-sight velocity, as gas which is closer to terminal velocity is likely farther from the quasar with lower transverse velocity due to angular momentum conservation.

In summary, we have found that pure transverse motion can plausibly explain the variability of both trough A and B over all 6 epochs of observation in our dataset. Trough A is best explained by a 'crossing disks' traversing a SS73 disk at velocities between $10,000 < v \text{ (km s}^{-1}\text{)} < 18,000$. This model and velocity range allow us to predict trough A will disappear between $350 < t \text{ (days)} < 1500$ after our last observation (GEM3). Trough B is best explained by a flow-tube that has recently moved into the line-of-sight, travelling in the velocity range $8000 < v \text{ (km s}^{-1}\text{)} < 56,000$. In this scenario, we have no constraint on how far a flow-tube extends, and thus cannot predict when trough B will disappear.

Constraining Distances in a Radiatively-Driven Wind Model

With some simple assumptions, we can constrain the current distance and the launching distance for the absorbing clouds that cause trough A and B. First, we assume the absorbers have reached maximum velocity and they both have some transverse velocity v_{trans} at their current distance, r_C , from the SMBH. We also assume they were launched from a circular orbit at r_L , which has an orbital velocity $(GM_{BH}/r_L)^{0.5}$.

From conservation of angular momentum for a gas parcel of mass m , we have

$$m \times r_L \sqrt{\frac{GM_{BH}}{r_L}} = m \times r_C v_{trans}. \quad (5.5)$$

Thus, the BAL gas transverse velocity is $v_{trans} = \sqrt{GM r_L / r_C^2}$, assuming it started in a circular orbit at r_L and is now observed at distance r_C from the black hole. The final radial velocity is $v_\infty = F \sqrt{GM/r_L}$ where the scaling factor F is $1.5 < F < 3.5$ if the wind is accelerated by radiation pressure on ions in dust-free gas (see Murray et al. 1995; Laor & Brandt 2002; Baskin et al. 2014). To solve for r_L and r_C , we take $F = 2.5 \pm 1.0$ and assume that the observed radial velocity $v_{rad,obs}$ equals the terminal velocity v_∞ . If the latter assumption is incorrect, the true r_L will be smaller, so we call the value we obtain with that assumption $r_{L,max}$. Given the minimum velocity determined for trough A above, $v > 10,000 \text{ km s}^{-1}$, we find $r_{L,max} = 78_{-50}^{+74} R_{Sch} = 0.02_{-0.01}^{+0.02} \text{ pc}$ and $r_C \leq 186 \pm 75 R_{Sch} = 0.04 \pm 0.02 \text{ pc}$, where the uncertainties on the values of the radii correspond to the values assumed for F . The minimum velocity determined for trough B above was $8,000 \text{ km s}^{-1}$, which yields $r_{L,max} = 175_{-115}^{+165} R_{Sch} = 0.04_{-0.02}^{+0.04} \text{ pc}$ and $r_C \leq 350 \pm 75 R_{Sch} = 0.07 \pm 0.03 \text{ pc}$.

Note that the results of this section and the next assume the wind is radiatively driven, which is not the only theoretical approach to driving disk-winds away from the central engine. Another

prominent model, for instance, is winds driven by magnetic forces. Using these models to constrain distances or measure acceleration (next section) is beyond the scope of this work.

Acceleration in a Radiatively-Driven Wind Model

The above estimate of $r_{L,max}$ assumes that the gas producing trough B has reached maximum velocity, which may or may not be correct. Here we explore some implications if that assumption is incorrect. At the small radii inferred above, the gas may still be accelerating. We can make an order of magnitude estimate of the expected acceleration using some simple assumptions. We stress that these assumptions are not unique, only illustrative.

The radial velocity of a radiatively-accelerated wind is approximately $v(r) = v_\infty(1 - r_L/r)^{1.15}$ (Murray & Chiang, 1997). The acceleration of the wind is

$$a(r) = \frac{dv}{dt} = v \frac{dv}{dr} = 1.15 \frac{v_\infty^2 r_L}{r^2} \left(1 - \frac{r_L}{r}\right)^{1.30}. \quad (5.6)$$

If we assume a terminal velocity of $v_\infty = 60,000 \text{ km s}^{-1}$ for trough B, because the observed velocity of trough A shows that C IV absorption can be seen to that high a velocity, then $r_L = 78_{-50}^{+75} R_{Sch}$. If we set trough B's observed velocity $v_{rad,obs} = 40,000 \text{ km s}^{-1} = v(r_C)$, we find $r_C = 3.4r_L = 265_{-170}^{+255} R_{Sch}$. (Incidentally, that yields a transverse velocity for trough B of $v_{trans} = 7,200_{-2100}^{+3000} \text{ km s}^{-1}$, consistent with the lower limit on the transverse motion velocity we determined for a flow-tube in § 5.4.1). The expected acceleration at $r_C = 265 R_{Sch}$ for a wind launched at $r_L = 78 R_{Sch}$ is $35_{-11}^{+17} \text{ km s}^{-1} \text{ day}^{-1}$ (the maximum acceleration in that model is $86 \text{ km s}^{-1} \text{ day}^{-1}$).

This value is much larger than previous measurements of accelerating BAL winds. For example, Hall et al. (2007) measured an acceleration in a C IV trough found in SDSS J024221.87+004912.6 at approximately $0.1 \text{ km s}^{-1} \text{ day}^{-1}$. The acceleration in J0230, if confirmed, would be the largest ever detected in a BAL outflow.

Using the Gemini South telescope, we have obtained a new spectral epoch of J0230 roughly 100 rest-frame days after the GEM3 epoch of this work. If the above transverse motion variability model is correct, then we predict trough B's centroid velocity will have increased in velocity by $3,500_{-2400}^{+5200} \text{ km s}^{-1}$ in that data. The results of the new observations will be presented in a future paper (Rogerson et al., in preparation).

This analysis was not done for trough A because we have no reliable terminal velocity to suggest the cloud might accelerate to.

5.4.2 Pure Ionization Parameter Variability Model

In this model, we assume the absorbing clouds are not moving across the emitting region of the quasar, and thus any variability observed in troughs A and B is due to changes in the ionization parameter of the absorbing clouds. In Filiz Ak et al. (2012, 2013), the authors observed coordinated variability of distinct C IV BAL troughs in the same quasar, even if the troughs are separated by as

much as $10,000\text{--}20,000\text{ km s}^{-1}$. Other studies, such as Grier et al. (2015), observed BAL troughs to vary across the entire trough, rather than distinct sections. We do not observe either of these behaviours in J0230: we find no significant evidence for coordinated variations between troughs A and B (they are separated by $\sim 15,000\text{ km s}^{-1}$), and we observe distinct regions of the absorption profiles to vary, while others do not (specifically in trough B, see § 5.2.1). Nevertheless, if we assume the changes observed in the troughs are due to an ionization state change, we can place constraints on the physical properties of the absorbing gas. Note that in this model only fully saturated troughs will not vary.

The two absorbers responsible for troughs A and B cannot have the same distances and densities (including density as a function of velocity) to explain the two trough’s different responses to the same underlying ionizing light. The exception would be if the absorber closer to the quasar significantly reduces the ionizing light reaching the absorber farther away. Whether the effect is significant or not depends on the optical depth to ionizing radiation of the absorber closer to the quasar.

Below, we assume that faster-responding gas has higher density. If the changes in trough A are due purely to ionization parameter variability, then the high-velocity part of this trough has higher density (it responded more quickly, and then vanished). If the changes in trough B are due purely to ionization parameter variability, then the low-velocity part of trough B has higher density (it responds faster to ionizing light changes), and the density drops off with increasing velocity.

One possible pure ionization variability scenario is the following. Prior to the SDSS spectra, the ionizing flux F_{ion} was high, leading to weak absorption. Between SDSS and BOSS1 observations, F_{ion} decreased, leading to an increase in C IV absorption (dense trough A appears). After BOSS2, F_{ion} recovered somewhat, leading to weaker trough A absorption. Between BOSS2 and GEM1, the lower-density trough B appears in response to the earlier decrease in F_{ion} . The above scenario suggests that, barring any major future ionizing flux variability, both trough A and trough B will decrease in strength with time. Any other trough that appears will show slower evolution in its EW than trough B does, due to the new trough’s required lower density.

Ionization Constraints on Electron Density and Distance

Constraints can be placed on the distance from the continuum source to the absorbing gas, as well as the density of that gas using the time-scale of the variability in the absorption. This approach has been used in multiple works (see Hamann et al. 1995, Hamann et al. 1997, Narayanan et al. 2004, Arav et al. 2012, and references therein). Below, we reproduce the approach taken in Grier et al. (2015).

Consider gas initially in photoionization equilibrium in the case where the ionization rate out of ionization stage i changes from its equilibrium value I_i to $(1 + f)I_i$, and the rate out of stage $i - 1$ changes from I_{i-1} to $(1 + f)I_{i-1}$,⁴ where f is the fractional change in I_i . Immediately after this

⁴Where we have assumed the fractional change for I_i and I_{i-1} is the same.

change:

$$\frac{dn_i}{dt} = -fn_i I_i + fn_{i-1} I_{i-1} + [-n_i(I_i + R_{i-1}) + n_{i-1} I_{i-1} + n_{i+1} R_i = 0], \quad (5.7)$$

where n_i/n_{i-1} is the population density of ionization stage $i/i-1$, respectively, and the quantity in brackets is the equilibrium value of $\frac{dn_i}{dt}$ and is therefore zero. In equilibrium, $n_{i+1}/n_i = I_i/R_i$ where R_i is the recombination rate to stage i , because appearance/increase of stage i by recombination from stage $i+1$ must be balanced by appearance/increase of stage $i+1$ by ionization from stage i . Thus we can substitute $n_{i-1} I_{i-1} = n_i R_{i-1} = n_i \alpha_{i-1} n_e$ (using $R_{i-1} = \alpha_{i-1} n_e$, where α_{i-1} is the recombination coefficient to stage $i-1$, and n_e is the electron density) and rewrite $\frac{dn_i}{dt}$ as

$$\frac{dn_i}{dt} = -fn_i I_i + fn_i \alpha_{i-1} n_e \quad (5.8)$$

which can be written as

$$\frac{dn_i}{n_i} \equiv \frac{dt}{t_i^*} \text{ with } t_i^* = [-f(I_i - n_e \alpha_{i-1})]^{-1} \quad (5.9)$$

which is an equation for variations on a characteristic time-scale t_i^* : $n_i(t) = n_i(0) \exp(t/t_i^*)$.

To summarize, for gas which is initially in photoionization equilibrium, the characteristic time-scale for density changes in ionization stage i of some element in response to an ionizing flux change can be written as t_i^* above (a modified version of Eq. 10 of Arav et al. 2012), where $-1 < f < +\infty$ is the fractional change in I_i , the ionization rate per ion of stage i [$I_i(t > 0) = (1+f)I_i(t=0)$], α_{i-1} is the recombination coefficient to ionization stage $i-1$ of the ion, and a negative time-scale represents a decrease in n_i with time. Note that this equation only considers photoionization processes; collisional processes are neglected. This is physically appropriate if $n_i \gg n_{i-1}$. Gas which shows varying ionic column densities is not in a steady state by definition, but such gas can still be in equilibrium with a varying ionizing flux if its t_i^* is considerably shorter than the flux variability time-scale (§ 6 of Pietrini & Krolik 1995). For optically thin gas at distance r from a quasar with spectral luminosity L_ν at frequency ν , the ionization rate per ion of stage i is given by

$$I_i = \int_{\nu_i}^{\infty} \frac{(L_\nu/h\nu)\sigma_\nu}{4\pi r^2} d\nu \quad (5.10)$$

where σ_ν is the ionization cross-section for photons of energy $h\nu$.

If the absorbing gas is far enough from the quasar that $I_i \ll n_e \alpha_{i-1}$, then the relevant time-scale is $t_{rec} = 1/f n_e \alpha_{i-1}$ (which is just the recombination time of the ion in the $f = -1$ case where the ionizing flux drops to zero), and the observed absorption variability time-scale constrains the density of the absorber. However, if the absorbing gas is close enough to the quasar that $I_i \gg n_e \alpha_{i-1}$, then the relevant time-scale is $t_i = -1/f I_i$ and the absorption variations of the ion reflect the ionizing flux variations of the quasar, with no density constraint derivable just from absorption variations.⁵

⁵No constraint on n_e is derivable even though we can write the time-scale as

$$t_i^* = \left[-f \alpha_i n_e \left(\frac{n_{i+1}}{n_i} - \frac{\alpha_{i-1}}{\alpha_i} \right) \right]^{-1} \quad (5.11)$$

An observed time-scale for variations in optically thin absorption therefore constrains the absorbing gas to either have a density $n_e > n_{min}$ and $r > r_{equal}$, where r_{equal} is the distance at which $I_i = n_{min}\alpha_{i-1}$, or to be located at $r < r_{equal}$ with almost no constraint on the density.

As noted in Arav et al. 2012, there are limitations to using time-scale arguments to infer physical characteristics of an absorber. In that work, the authors indicate “a more physically motivated approach is to use lightcurve simulations that are anchored in our knowledge of the power spectrum behaviour of observed AGN lightcurves;” however, such detailed work is not justified by the relatively scarce data available for J0230.

To determine the constraints on the emergence of troughs A and B, we assume a temperature of $\log T = 4.3$ (Krolik 1999) so that the recombination coefficient is $\alpha_{CIII} = 2.45 \times 10^{-11} \text{ cm}^3 \text{ s}^{-1}$ (from the CHIANTI online database; see Dere et al. 1997, Landi et al. 2013). For the simple case of the ionizing flux dropping to zero, $f = -1$ and the time-scale t_i^* can be approximated as the recombination time, $t_{rec} \sim 1/n_e\alpha_{CIII}$.

Using the time between observations of SDSS and BOSS1 for trough A of 652 days as an upper limit to the recombination time, we calculate a lower limit on the density of the gas to be $n_{e,A} \geq 724 \text{ cm}^{-3}$. Using the lower limit density of $n_{e,A} \geq 724 \text{ cm}^{-3}$, we calculate the minimum distance from the quasar at which that lower limit is valid. From its observed flux density at rest-frame wavelength 3000 Å, our quasar has $L_{bol} = 8.45 \times 10^{46} \text{ erg s}^{-1}$. We adopt the spectral energy distribution of Dunn et al. (2010) to calculate L_ν . Therefore, if the emergence of trough A is due to ionization variability, the absorber either has a density of $n_{e,A} \geq 724 \text{ cm}^{-3}$ and is at $r_{equal,A} \geq 2 \text{ kpc}$, or is at $r < 2 \text{ kpc}$ with no constraint on the density.

Trough B emerged between BOSS2 and GEM1; a period of 307 days. Using this as an upper limit to the recombination time, we perform the same calculation and determine if the appearance of trough B is due to ionization variability, the absorber either has a density $n_{e,B} \geq 1540 \text{ cm}^{-3}$ and is at $r_{equal,B} \geq 1.37 \text{ kpc}$, or is $r < 1.37 \text{ kpc}$ with no constraint on the density.

Our values for n_e are one or two orders of magnitude lower than those found in Grier et al. (2015) and Capellupo et al. (2013) (which found values $\sim 10^5 \text{ cm}^{-3}$) and our values of r_{equal} are 10 times larger than those works (which found values $\sim 100 \text{ pc}$). Further, our values of r_{equal} are much higher than the launching radius of BAL winds expected from theoretical work, which predict $\sim 10^{-3} \text{ pc}$ (e.g., Murray et al. 1995). Nonetheless, other works have reported outflow radii on similar scales to that we infer for J0230 in a pure ionization variability model (see Table 10 of Dunn et al. 2010, and references therein), and the radius at which a BAL wind is observed is not necessarily the radius at which the wind is launched (e.g., Faucher-Giguère et al. 2012).

Finally, we can place an upper limit constraint on n_e by searching for absorption features from other ions of carbon, specifically C II $\lambda 1335$ Å. Given the minimum density and r_{equal} distances

(see equation (2) in Hamann et al. 1997, equation (3) in Arav et al. 2015) because in our case $n_{i+1}/n_i = n_{CV}/n_{CIV}$, and that ratio increases more rapidly than n_e decreases as the ionization parameter increases (Kallman & McCray, 1982).

determined above, troughs A and B are created by absorbers with an ionization parameter of $U_H \simeq 0.06$.⁶ If we lowered the ionization parameter by a factor of ~ 50 , either by gas at larger radii or at higher density, the resulting ionization state would yield C II absorption roughly half as deep as the observed C IV. This was measured off Figure 3 of Hamann et al. 1995, which indicates a factor of ~ 50 is required to meet the C II-C IV ratio mentioned.

A reduction by a factor of ~ 50 in ionization parameter gives us upper limits to both the minimum density and the r_{equal} ; therefore, the absorber that caused the emergence of trough A has $724 \text{ cm}^{-3} \leq n_{e,A} \leq 3.62 \times 10^4 (r_{equal,A}/r)^2 \text{ cm}^{-3}$ and is between $r_{equal,A} \leq r \leq 7r_{equal,A}$. Similarly, the absorber that caused the emergence of trough B is constrained by $1540 \text{ cm}^{-3} \leq n_{e,B} \leq 7.70 \times 10^4 (r_{equal,B}/r)^2 \text{ cm}^{-3}$ and $r_{equal,B} \leq r \leq 7r_{equal,B}$. These upper limits only work in the scenario where we approximate the recombination time as $t_{rec} \sim 1/n_e \alpha_{C III}$.

In Figure 5.14, we have plotted the possible values of the density of the absorbing gas n_e and the distance the absorber is from the source r , given constraints imposed by the time-scale arguments above for trough B. The vertical and horizontal dashed lines are the locations of the $r_{equal,B}$ and the minimum electron density $n_{e,B}$, respectively. Any combination of parameters above the red line would have too high a density or too far a distance to be ionized to C IV (and lead to the upper limit arguments above). There is also a region of too low density or too far away that requires too long a time-scale for the proper response. The allowed regions 1 (between the red and blue curves) and 2 (to the left of the green curve) represent the combinations of parameters possible. There is also a region of too high ionization at low densities and small radii which is not visible at the scale shown. Note that in the discussion at the end of § 5.4.2 we assumed that faster-responding gas has higher density, although from Figure 5.14 that is only certain if the gas is at $r > r_{equal}$. A corresponding plot for trough A would look similar.

5.5 Summary

We have presented the discovery and analysis of two extremely high-velocity and highly-variable C IV BAL troughs in the quasar SDSS J023011.28+005913.6. We retrieved 4 spectra of J0230 from the SDSS+BOSS archives, and obtained 3 of our own spectra using the Gemini Observatory. The longest time between observations was ~ 650 rest-frame days, and the shortest was ~ 10 rest-frame days.

1. We discovered a C IV BAL trough outflowing from J0230 at $\sim 60,000 \text{ km s}^{-1}$ (trough A), the largest velocity of a BAL wind observed to-date. During follow up observations, we discovered a second C IV BAL trough outflowing at $\sim 40,000 \text{ km s}^{-1}$ (trough B). See Figure 5.5.

⁶This is for our assumed SED from Dunn et al. 2010, $U_H = Q_H/4\pi n_H c$, with $Q_H = 6.08 \times 10^{56}$ hydrogen-ionizing photons s^{-1} and $n_H = 0.82n_e$.

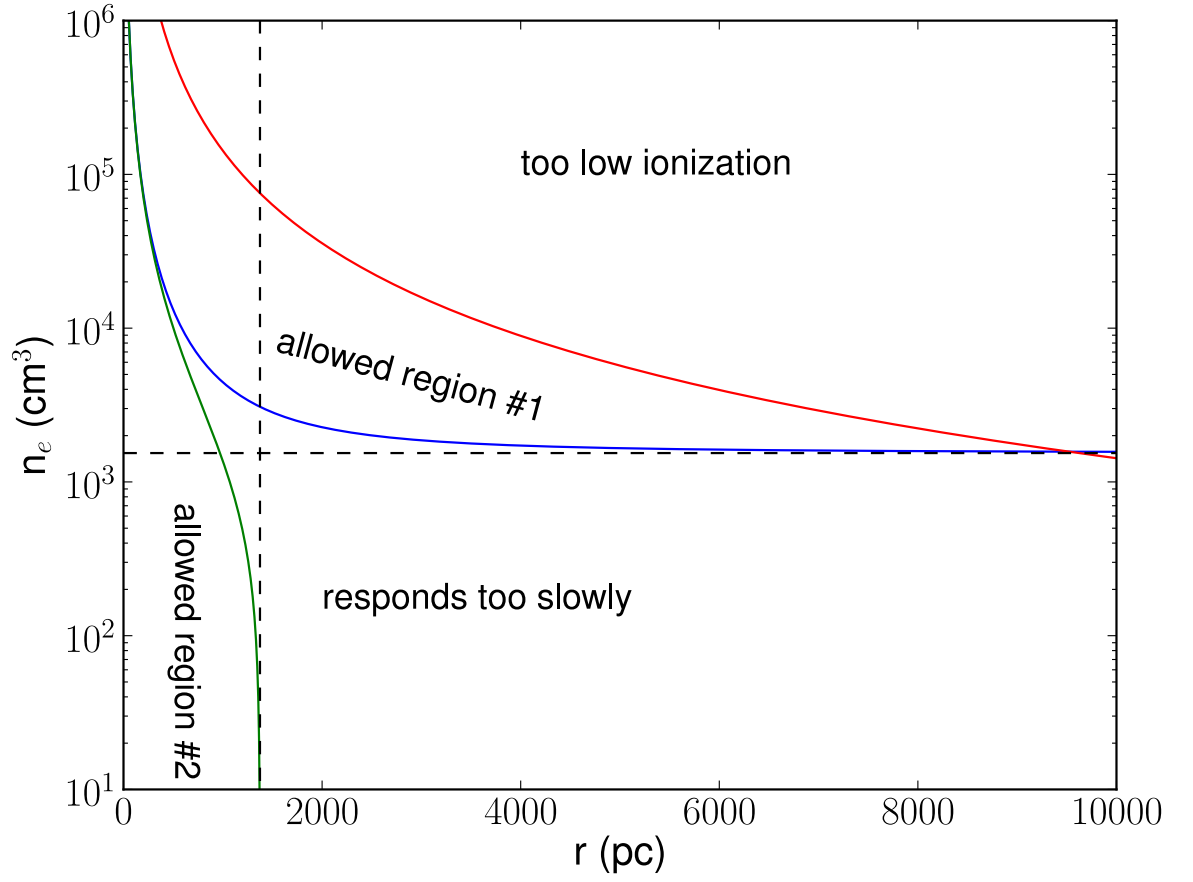


Figure 5.14: The possible combinations of density and distance for the gas that created trough B. The horizontal dashed line represents the density if the ionizing flux dropped to zero and we use the time between observations as the recombination time. The vertical dashed line represents minimum distance from the quasar at which the lower limit to the density is valid.

2. In troughs A and B we observed variability of both the depth and shape of the troughs on scales as short as 10 days in the rest-frame. See Table 5.2.
3. A dataset of six spectral epochs straddling the emergence of both troughs allowed us to rule out some simple models of bulk motion as the origin of the variability. It also allowed us to propose and test more complex and realistic models of bulk motion, such as flow-tube geometries and an augmented ‘crossing disks’+SS73 scenario. See § 5.4.1.
4. We found the variability of trough A is best explained by a ‘crossing disk’ traversing a SS73 disk at velocities between $10,000 < v \text{ (km s}^{-1}\text{)} < 18,000$. This model and velocity range allow us to predict trough A will disappear between $350 < t \text{ (days)} < 1500$ after our last observation (GEM3). See § 5.4.1.
5. Trough B is best explained by a flow-tube that has recently moved into the line-of-sight, travelling in the velocity range $8,000 < v \text{ (km s}^{-1}\text{)} < 56,000$. In this scenario, we have no constraint on how far a flow-tube extends, and thus cannot predict when trough B will disappear. See § 5.4.1.
6. Given some simple, conservative assumptions in a transverse velocity model, we constrained the distance from the black hole to the absorbing gas responsible for trough A $r_C \leq 186 \pm 75 R_{Sch} = 0.04 \pm 0.02 \text{ pc}$ given $v_{trans} > 10,000 \text{ km s}^{-1}$ and for trough B we constrain the distance to be $r_C \leq 350 \pm 140 R_{Sch} = 0.07 \pm 0.03 \text{ pc}$ for $v_{trans} > 8,000 \text{ km s}^{-1}$. See § 5.4.1.
7. If we assume changes to the ionization parameter is the reason for the variability observed, the absorber responsible for trough A either has $724 \text{ cm}^{-3} \leq n_{e,A} \leq 3.62 \times 10^4 (r_{equal,A}/r)^2 \text{ cm}^{-3}$ and is between $r_{equal,A} \leq r \leq 7r_{equal,A}$, or is at $r < 2.00 \text{ kpc}$ with no constraint on the density. Similarly, the absorber that caused the emergence of trough B is either constrained by $1540 \text{ cm}^{-3} \leq n_{e,B} \leq 7.70 \times 10^4 (r_{equal,B}/r)^2 \text{ cm}^{-3}$ and $r_{equal,B} \leq r \leq 7r_{equal,B}$, or is at $r_{equal} \geq 1.37 \text{ kpc}$, or is at $r < 1.37 \text{ kpc}$ with no constraint on the density. See § 5.4.2.

Chapter 6

Conclusions

Broad absorption line variability is a tool with which we probe the inner regions of a quasar. In this study we visually identified a specific type of variability: emergent broad absorption. Emergence is defined as the case where absorption was originally not present in the quasar at the given wavelength but appeared in a new observation. The emergent absorption was followed-up with new observations. Unique to this study, we analyzed how these troughs vary over the course of 3 to 7 observational epochs, ranging in rest-frame time from as short as 2 days to as long as 1200 days.

Below is a summary of the more notable conclusions found in this work.

1. Visual comparison of multiple spectra of the same quasar from DR7, DR9, and DR10 resulted in an emergent rate of $1.50 \pm 0.14\%$ between DR7–DR9, and $1.99 \pm 0.15\%$ for DR7–DR10. Of the 306 visually confirmed cases of absorption, 105 were followed up by Gemini, 103 resulted in quantitative detection of absorption. Thus, the visual inspection is robust. See § 2.1.
2. Using a modified version of the BALnicity Index, 653 individual broad absorption troughs were identified in 360 spectra of the 105 targets in our dataset. Each trough was at least $1,000 \text{ km s}^{-1}$ wide and found anywhere between $0 < v \text{ (km s}^{-1}\text{)} < 65,000$, where 0 km s^{-1} is at the systemic redshift of the quasar, and positive velocities are towards the observer. See § 3.3.
3. To account for troughs splitting apart or merging into one between epochs, we defined an absorption complex to be a region in a quasar spectrum that, over the multiple spectra available, has had one or more BAL trough in at least one epoch. The 653 individual troughs are reduced to 219 absorption complexes in this definition. See § 3.4.
4. Over 105 quasars, there were 36 instances of a quasar transitioning from non-BAL to BAL. By design, this mostly occurred in the SDSS-BOSS transition. There were 11 cases of quasars transitioning from BAL to non-BAL. See § 4.3.

5. In the 219 absorption complexes, there 123 cases of emergence, 56 cases of disappearance, and 347 cases of no significant change occurring. This is a rate of $(123/526) = 23 \pm 2$ % of emergence in regions identified to be variable. See § 4.3.
6. As expected, the weighted-mean ΔEW from SDSS-BOSS was 4.16 ± 0.10 Å, increasing in EW. After the SDSS-BOSS transition, however, there was a significant trend to decrease. The weighted-mean ΔEW from BOSS-GEM was -0.93 ± 0.09 Å. See § 4.4.
7. Despite the above averages, a more detailed analysis that took into account the time between observations found: if an absorption complex begins to increase in EW between two observations, it is equally likely to continue increasing in the next observation, as it is to switch to decreasing. Based on our analysis this indicates the coherence time-scale of BAL EW variations must be less than 100 days. See § 4.4.
8. Coordinated variability, which is two troughs in the same quasar either increasing or decreasing at the same time, occurs at a rate of 68.3%. The rate of anticoordination was 19.8%. This strongly indicates ionizing flux variations are a strong contributor to BAL variability.
9. In coordinated variability, we also determined that troughs that are closer together in velocity are more likely to coordinate their variability than those further apart. We also determined troughs were equally likely to increase in synchronization as they were to decrease in synchronization. There was an apparent difference between a lower velocity trough increasing while a high velocity trough decreased as compared to a lower velocity trough decreasing while a high velocity trough increased. However, small number statistics means we cannot confirm this result. It is possible this coordination dependence on velocity separation is related to the density of the clouds. Higher-velocity clouds have lower densities and thus would respond to changes in the ionizing flux differently. See § 4.5.
10. The change in equivalent width, ΔEW , with respect to time between successive observations in our data matches that in the literature. Our data filled in the region on medium time-scales of 0.5 – 1.0 years in the rest-frame that been largely unexplored in the literature. See Figure 4.13.

In the case study of J023011, we performed more detailed analyses of the emergence and variability of its two troughs that yielded more specific results. They are listed below.

1. We discovered a C IV BAL trough outflowing from J0230 at $\sim 60,000$ km s $^{-1}$ (trough A), the largest velocity of a BAL wind observed at ultra-violet wavelengths to-date. During follow up observations, we discovered a second C IV BAL trough outflowing at $\sim 40,000$ km s $^{-1}$ (trough B). See Figure 5.5.
2. In troughs A and B we observed variability of both the depth and shape of the troughs on scales as short as 10 days in the rest-frame. See Table 5.2.

3. A dataset of six spectral epochs straddling the emergence of both troughs allowed us to rule out some simple models of bulk motion as the origin of the variability. It also allowed us to propose and test more complex and realistic models of bulk motion, such as flow-tube geometries and an augmented ‘crossing disks’+SS73 scenario. See § 5.4.1.
4. We found the variability of trough A is best explained by a ‘crossing disk’ traversing a SS73 disk at velocities between $10,000 < v_{trans} \text{ (km s}^{-1}\text{)} < 18,000$. This model and velocity range allow us to predict trough A will disappear between $350 < t \text{ (days)} < 1500$ after our last observation (GEM3). See § 5.4.1.
5. Trough B is best explained by a flow-tube that has recently moved into the line of sight, traveling in the velocity range $8,000 < v \text{ (km s}^{-1}\text{)} < 56,000$. In this scenario, we have no constraint on how far a flow-tube extends, and thus cannot predict when trough B will disappear. See § 5.4.1.
6. Given some simple, conservative assumptions in a transverse velocity model, we constrained the distance from the black hole to the absorbing gas responsible for trough A $r_C \leq 186 \pm 75 R_{Sch} = 0.04 \pm 0.02 \text{ pc}$ given $v_{trans} > 10,000 \text{ km s}^{-1}$ and for trough B we constrain the distance to be $r_C \leq 350 \pm 140 R_{Sch} = 0.07 \pm 0.03 \text{ pc}$ for $v_{trans} > 8000 \text{ km s}^{-1}$. See § 5.4.1.
7. If we assume changes to the ionization parameter is the reason for the variability observed, the absorber responsible for trough A either has $724 \text{ cm}^{-3} \leq n_{e,A} \leq 3.62 \times 10^4 (r_{equal,A}/r)^2 \text{ cm}^{-3}$ and is between $r_{equal,A} \leq r \leq 7r_{equal,A}$, or is at $r < 2.00 \text{ kpc}$ with no constraint on the density. Similarly, the absorber that caused the emergence of trough B is either constrained by $1540 \text{ cm}^{-3} \leq n_{e,B} \leq 7.70 \times 10^4 (r_{equal,B}/r)^2 \text{ cm}^{-3}$ and $r_{equal,B} \leq r \leq 7r_{equal,B}$, or is at $r_{equal} \geq 1.37 \text{ kpc}$, or is at $r < 1.37 \text{ kpc}$ with no constraint on the density. See § 5.4.2.

The most significant result from this work is that not only have we confirmed the presence of coordinated variability of multiple troughs in quasars (which has been observed before in both Capellupo et al. 2013 and Filiz Ak et al. 2013), but troughs closer in velocity tend to coordinate more often than troughs with larger separation. Coordination amongst two troughs at differing velocities points to the cause of variability being changes in the ionizing flux at the absorbing cloud. However, there is still a large amount of anticonordinated variability occurring in our dataset. Thus changes to the ionization state of the absorbers is unlikely to be the only cause of variability. Some is still likely a result of bulk motion of gas across the line of sight. It is possible to have both modes of variability occurring in unison, and it may be difficult to disentangle the two in general.

6.1 Future Directions

In § 4.4, we attempted to determine if a BAL’s past variability was a predictor of its variability in the future. Unfortunately, our dataset did not have the number statistics, nor the time resolution

to conclude that it could. Certainly one can imagine that if a trough were to be observed from zero EW to a full trough with multiple spectral epochs, it would be possible to use a history of increasing to predict the trough will continue to increase with some constraint on time. In our dataset, that coherence time-scale must be less than 100 days in the rest-frame. Performing a monitoring program with high time resolution for a medium-sized set of quasars would help determine a coherence scale. For example, a set of 10 bright BAL quasars observed once a week for an entire observing semester would provide enough data to answer this question. It would be recommended to choose a set of quasars from the dataset presented herein, due to the already confirmed variable absorption in them.

A monitoring program focussed on high time resolution could inform understanding on the nature of coordinated variability as well. We observed an apparent difference between two types of anticonordinated variability that would challenge our understanding of the quasar model if it were proven correct. The only way to determine its validity would be a campaign of observations on quasars with multiple troughs with higher time resolution.

In the dataset presented here, there were a few quasars that presented very complicated and informative variability. The case study of J023011 was an example of how targeted studies can lead to more specific results. To that end, continued monitoring of quasar J015017 (see Figure 4.8) would help disentangle the different signals of ionization changes and bulk motion. Further, the detailed analysis performed on J023011 can be extended to the entire dataset, and would result in a whole other study outside the scope of this work.

Finally, present in our dataset were a large number of Si IV absorbers accompanying the C IV we studied here. Studying these features was outside the scope of the work. There are a number of important questions that can be answered upon analysis of those features, such as: do the Si IV absorbers emerge simultaneously with the C IV? Also, do the Si IV absorbers also vary in a coordinated fashion?

6.2 In Summary

The variability of broad absorption lines in quasars is clearly a useful tool for studying the inner regions of the quasar engine. We have used it to show that changes in the ionization state of an absorbing cloud is a significant contributor to the observed broad absorption variability in the UV spectra of quasars, confirming a signal seen in at least two other works. As a result, theoretical models will require a mechanism by which to change the ionizing flux incident upon the absorbing clouds, some of which we have already discussed.

Further study of variability of broad absorption lines and the field of quasar winds in general will help answer questions, such as: what is the overall contribution of quasar winds to the host galaxy?

Appendix A

Multi-Epoch Spectra for 105 Quasars

In this section we provide all spectra for all quasars considered in the analysis. That totals 360 normalized spectra over 105 quasars. The objects are sorted by right ascension in ascending order (i.e., 00h–23h), the full SDSS DR7 name is located in the top left of each figure. The rest-frame wavelength in Angstroms ($\text{\AA}$) is on the bottom x-axis. The top x-axis displays the outflow velocity in km s^{-1} relative to the systemic redshift of the quasar, as measured from the C IV emission feature at $\sim 1550 \text{ \AA}$. The y-axis is normalized Flux Density units. Each spectrum available for a given quasar is plotted, artificially separated in the y-direction to make comparisons between epochs easier. There is a dotted line placed at the continuum level for each spectrum. The spectrum with the smallest MJD is at the top, and each successive epoch in chronological order is placed below. Colours denote where the data came from: black/grey indicates a SDSS spectrum, blue/red indicates a BOSS spectrum, any other colour indicates a Gemini spectrum. The vertical grey regions represent the absorption complexes identified in § 3.4. In each spectrum, the centroid velocity of each absorption complex is denoted by two small vertical black bars, which represent the C IV doublet at $\lambda\lambda 1548.202, 1550.774 \text{ \AA}$. The expected locations of Si IV absorption that could accompany each C IV doublet are denoted by two small vertical dashed lines, which represent the Si IV doublet at $\lambda\lambda 1393.755, 1402.770 \text{ \AA}$.

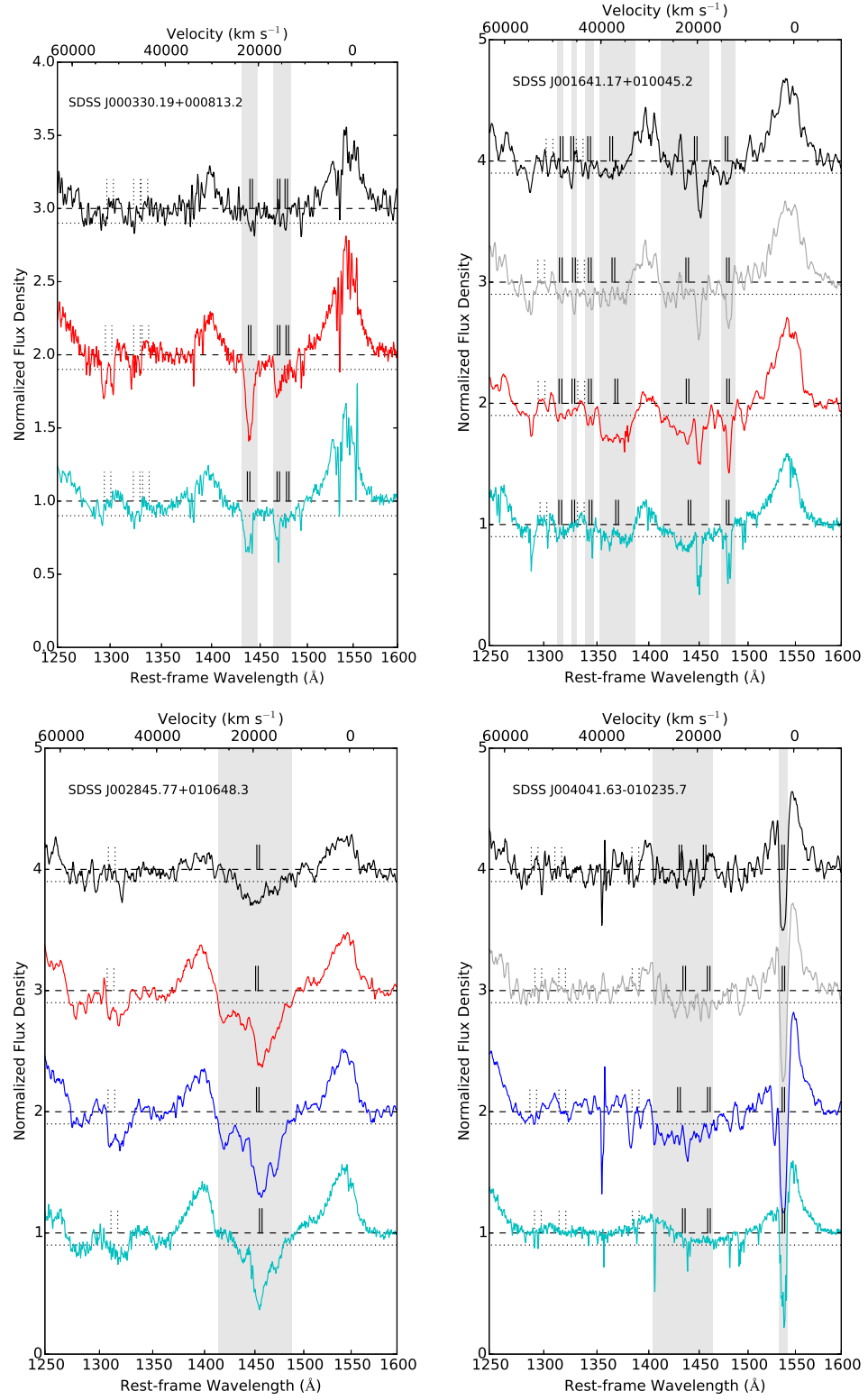
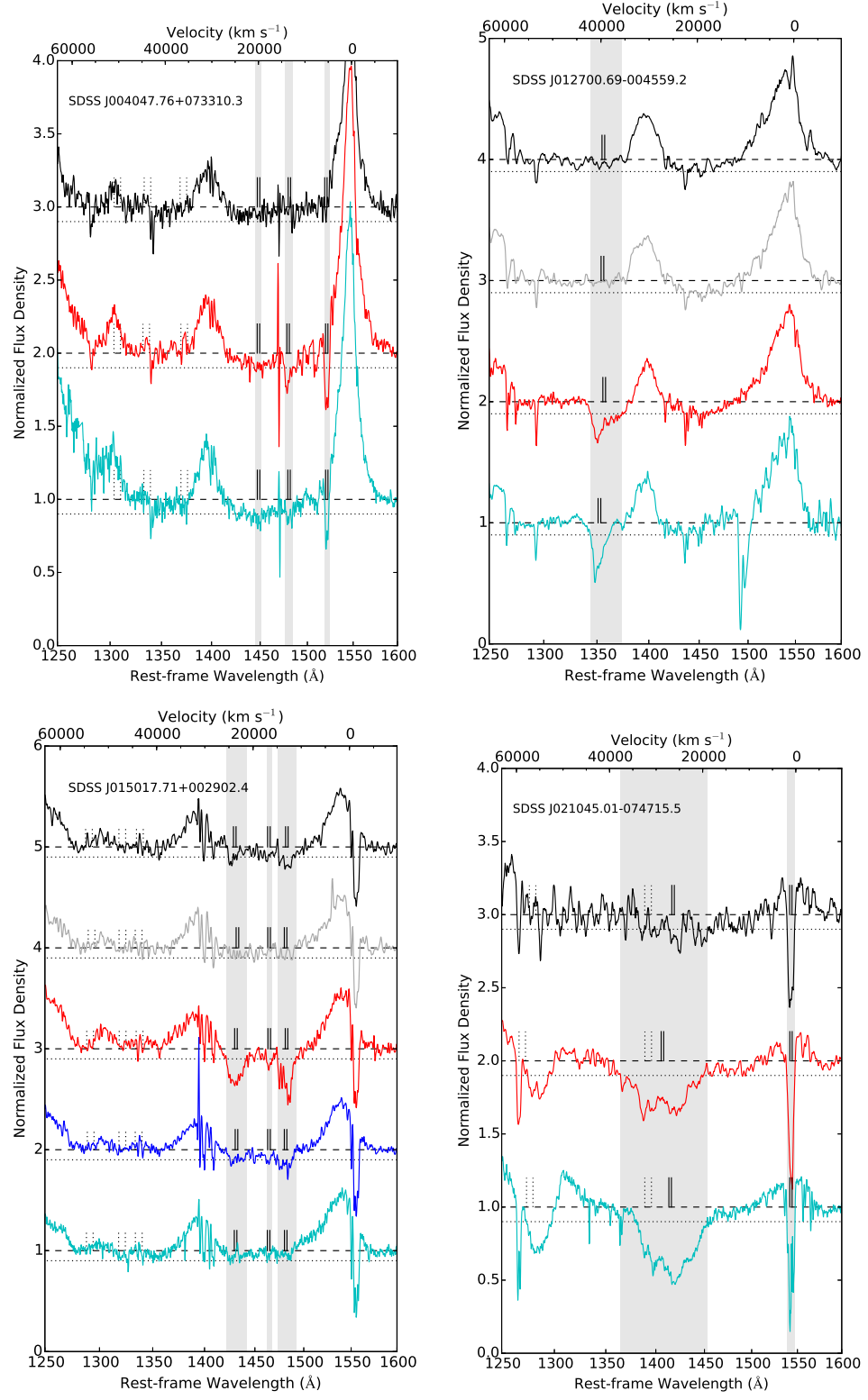
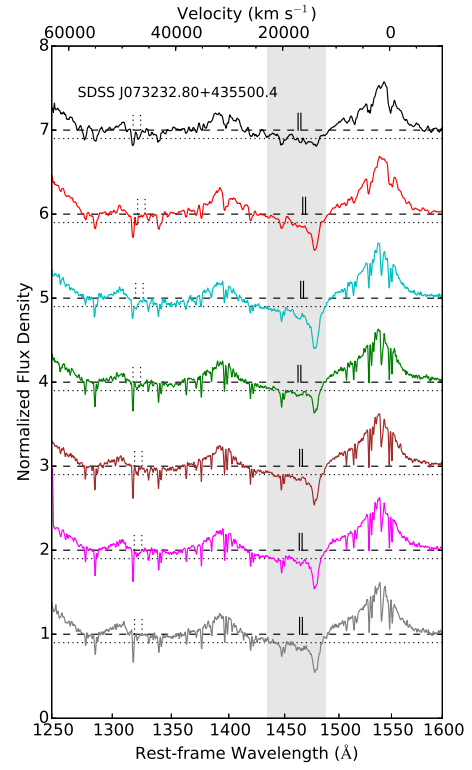
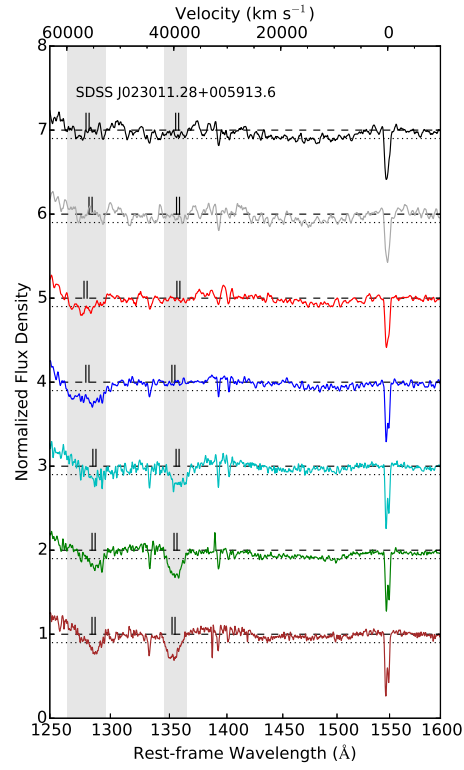
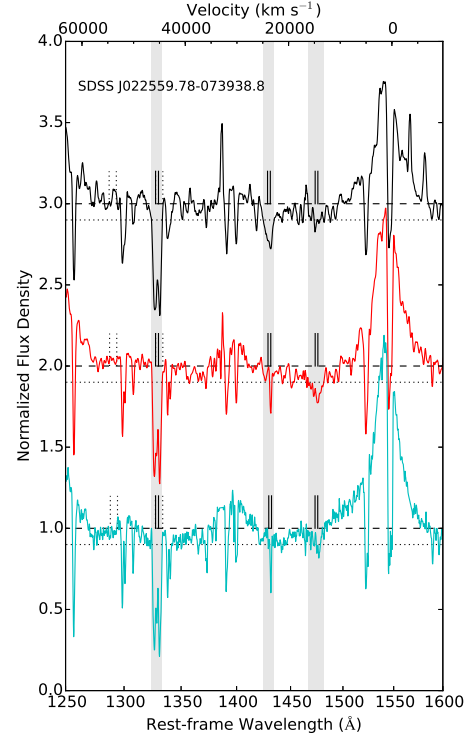
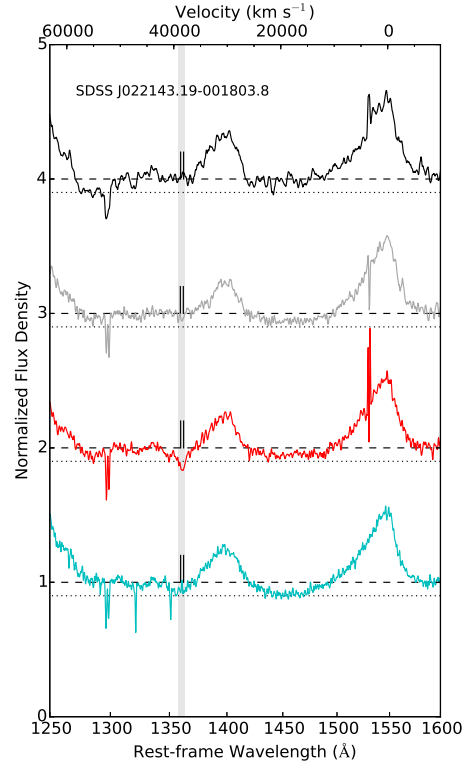
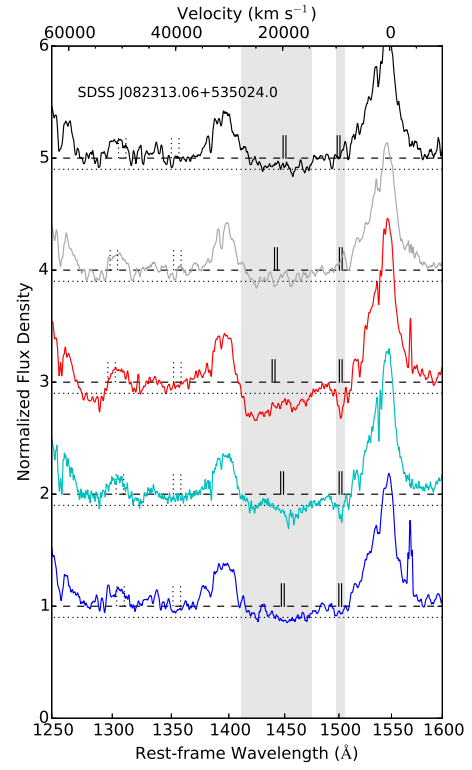
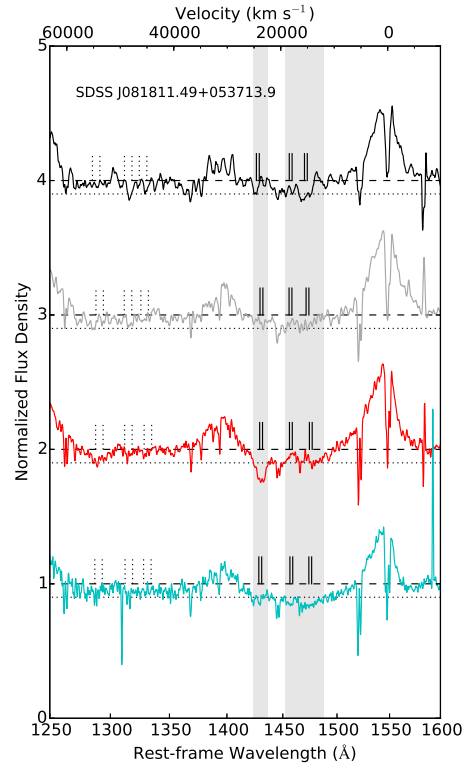
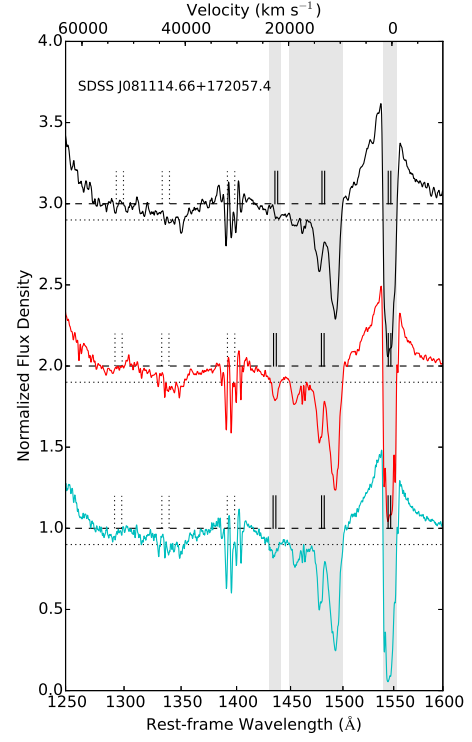
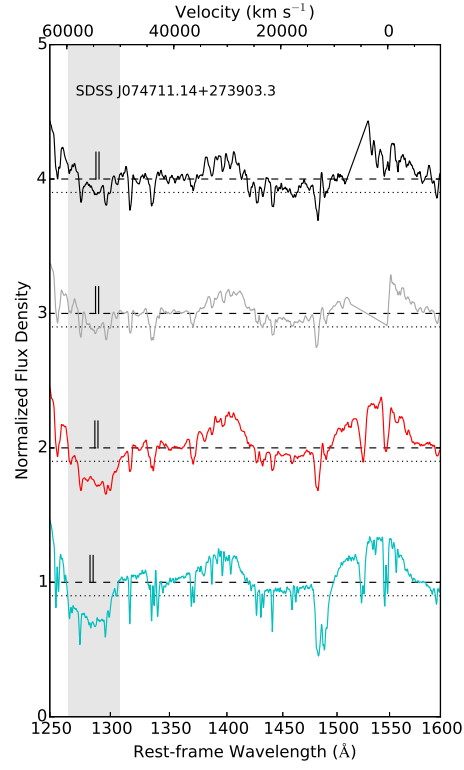
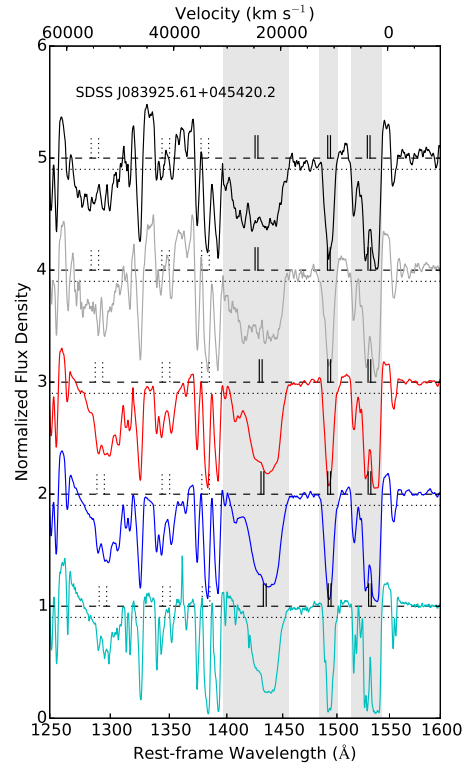
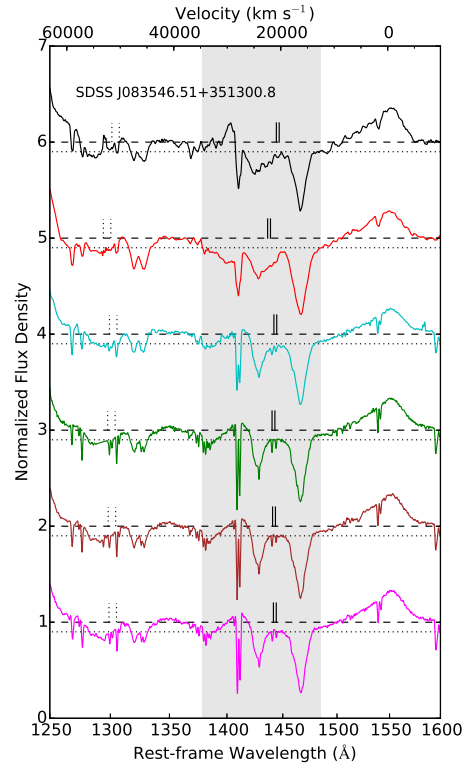
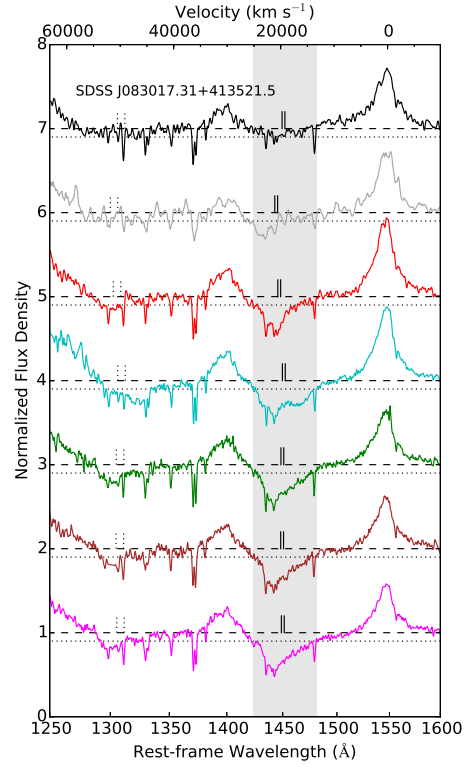
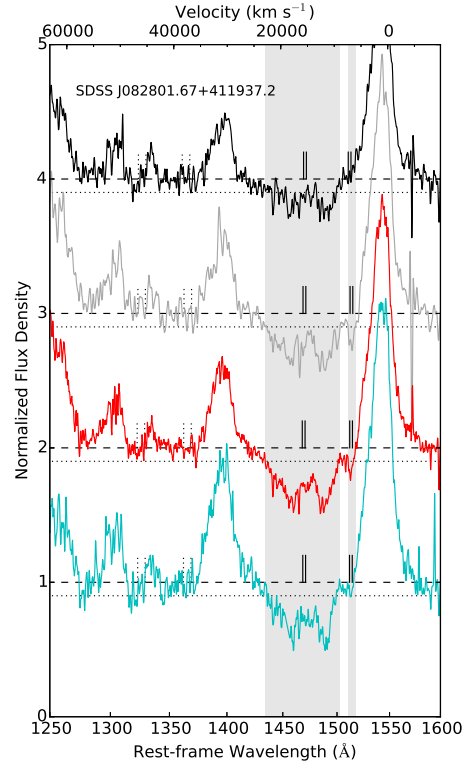


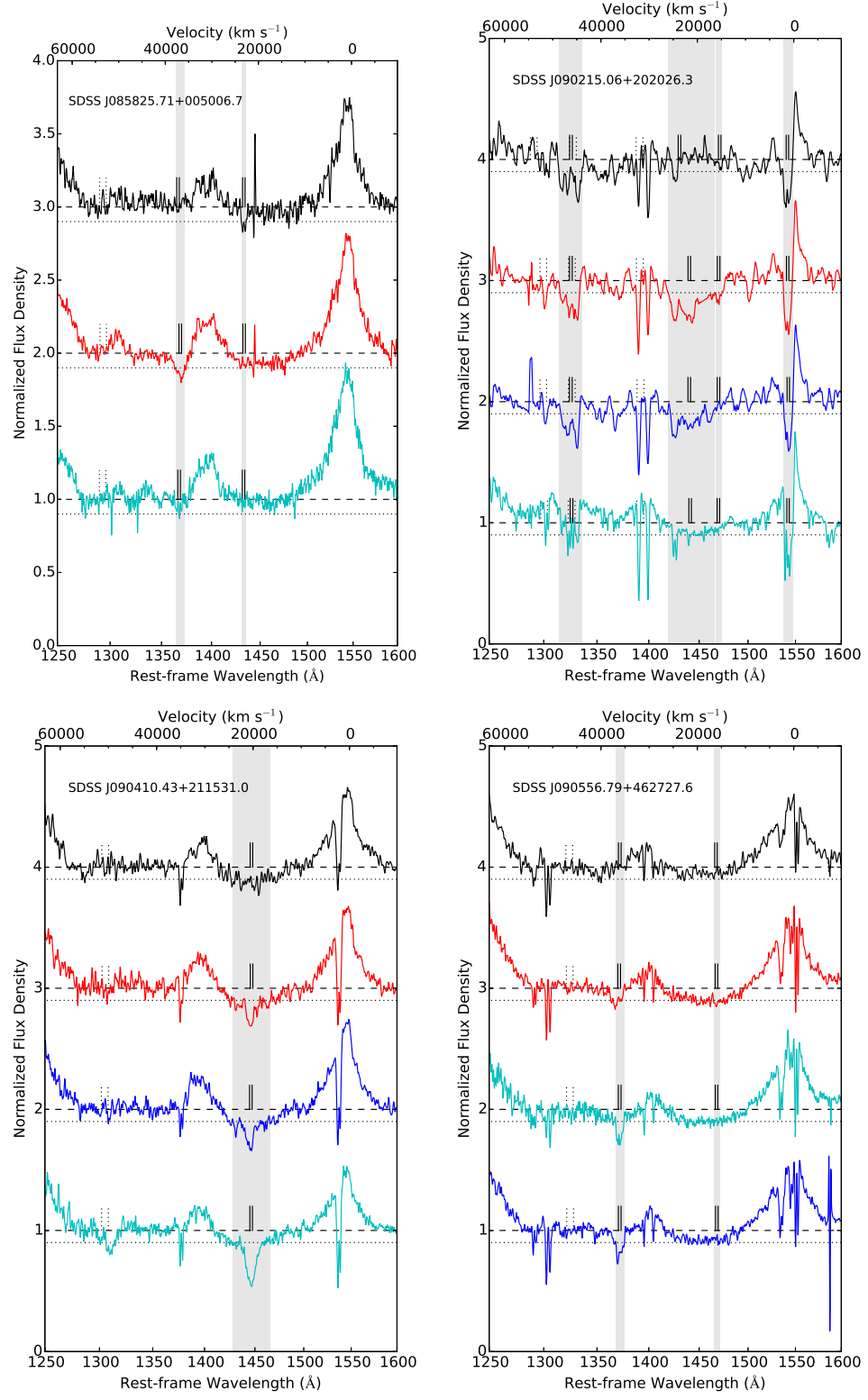
Figure A.1: Spectra for all 105 quasars in the data set. Continued on the following pages...

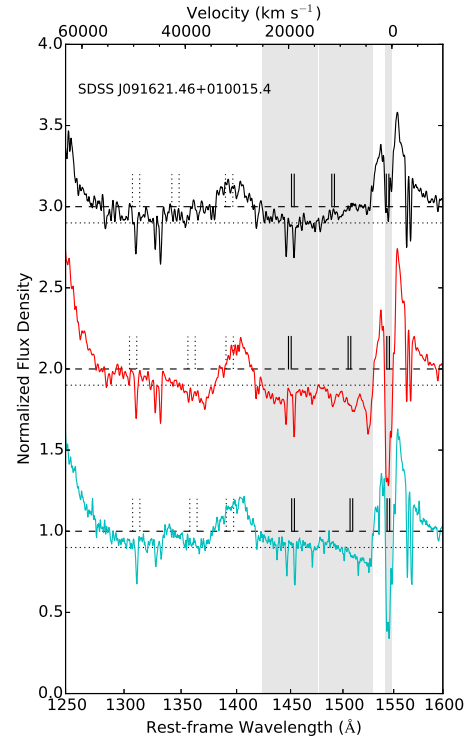
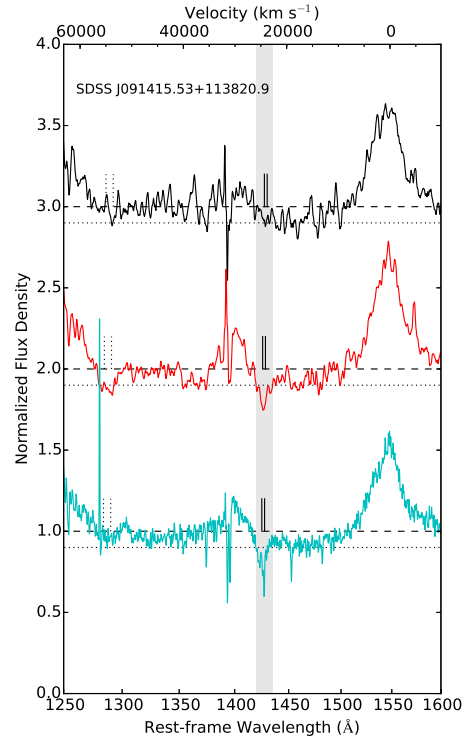
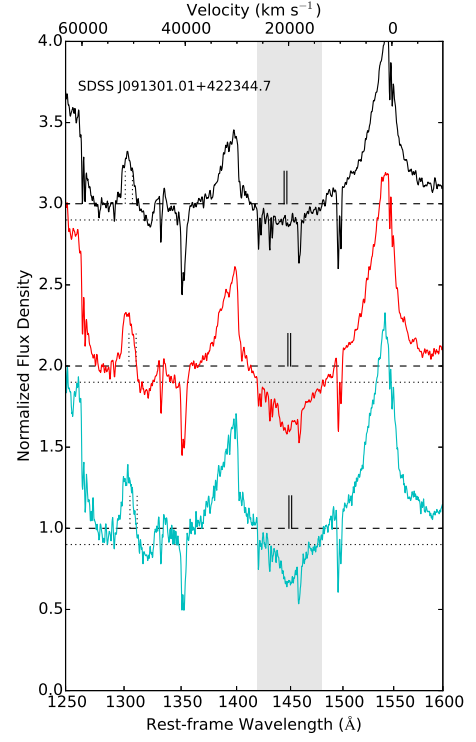
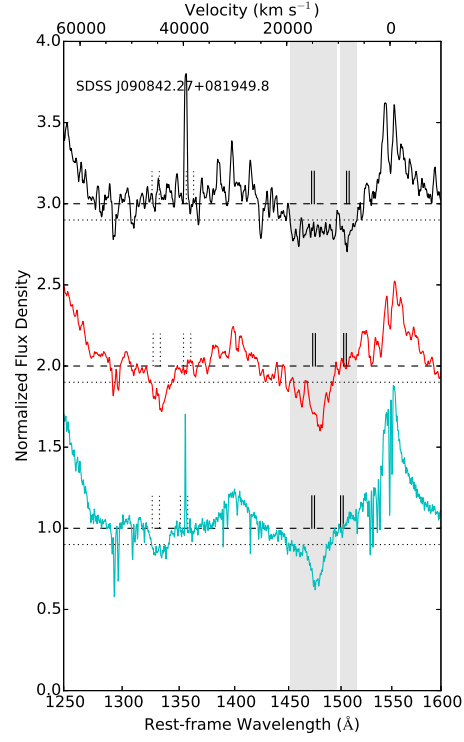


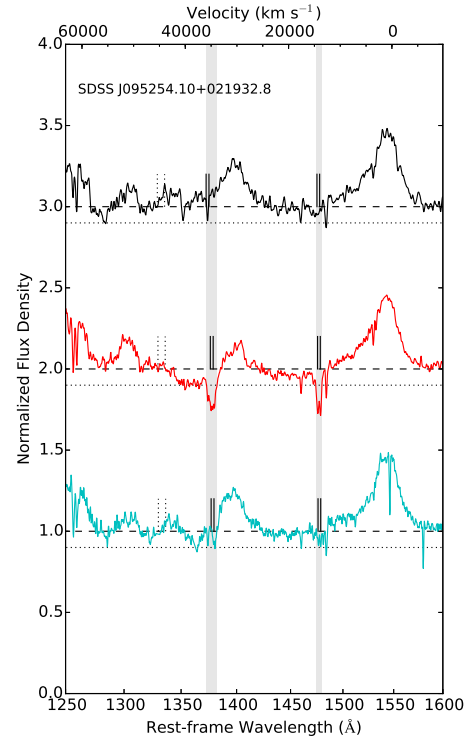
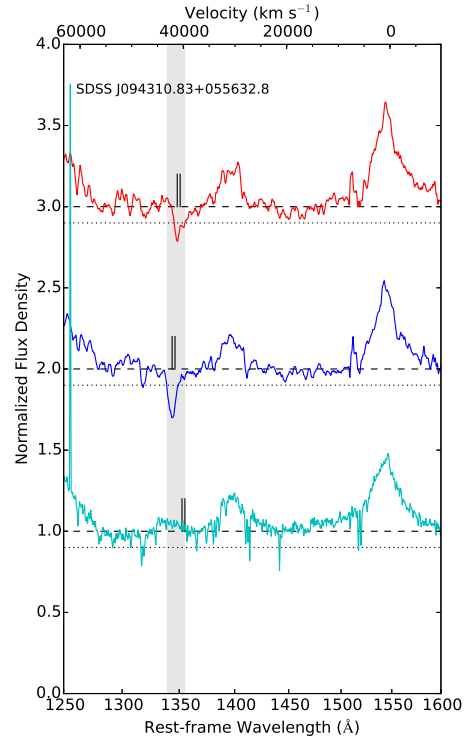
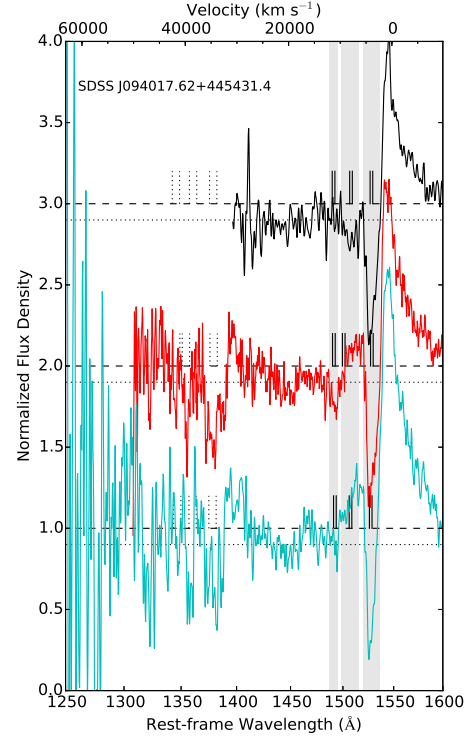
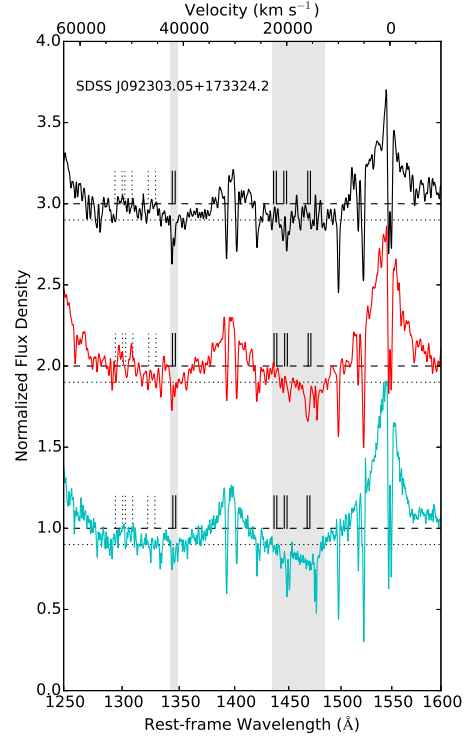


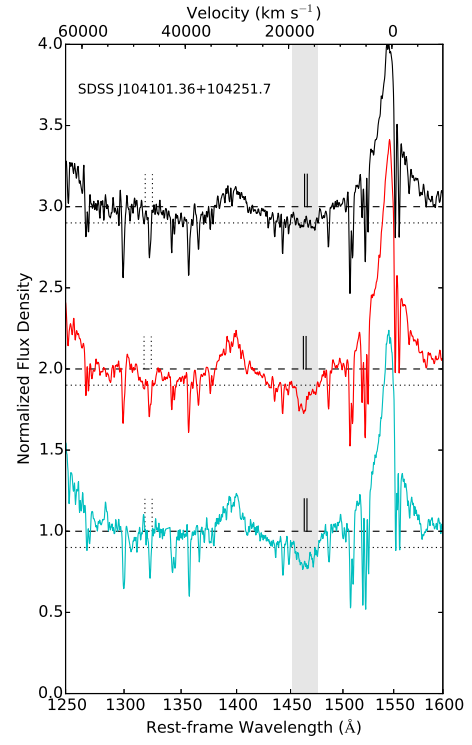
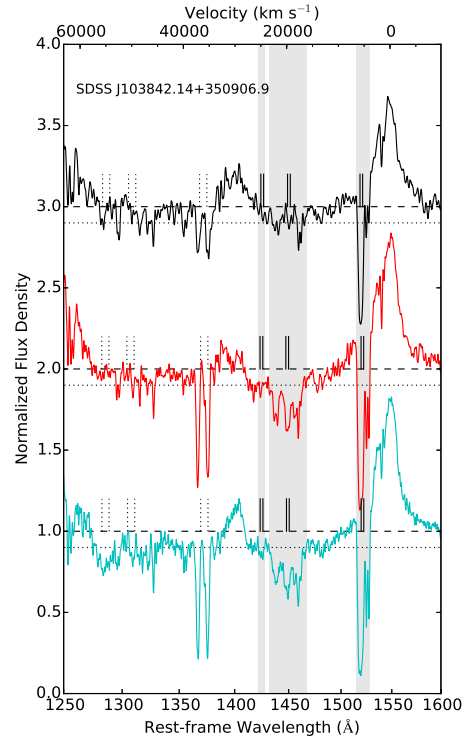
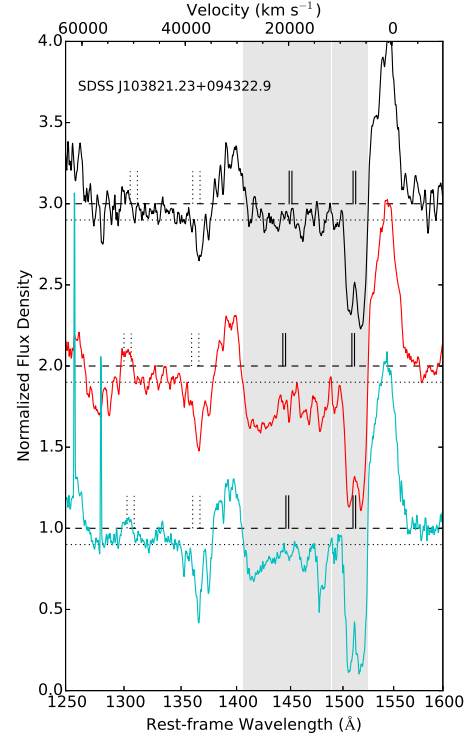
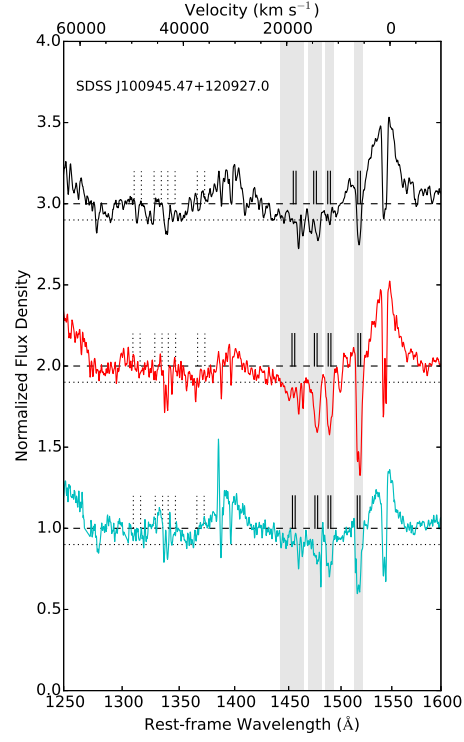


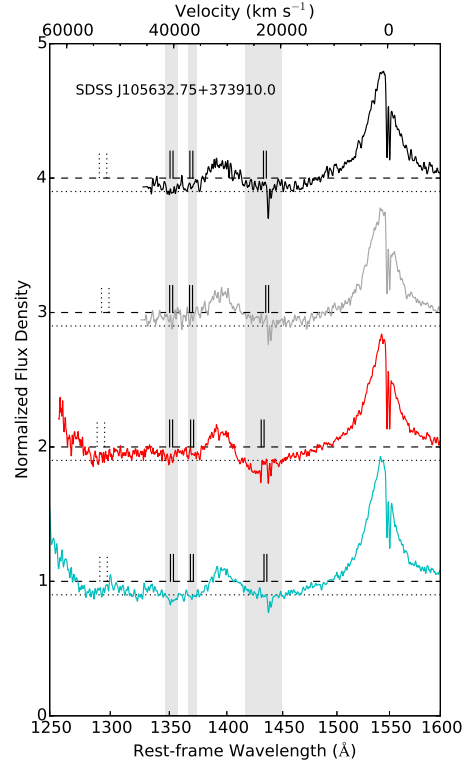
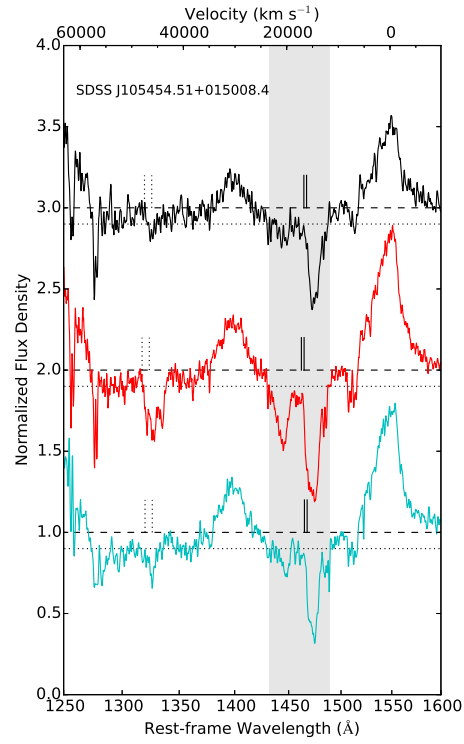
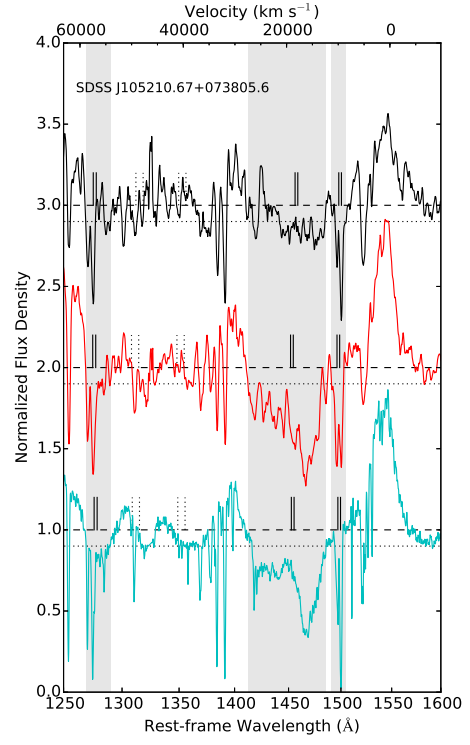
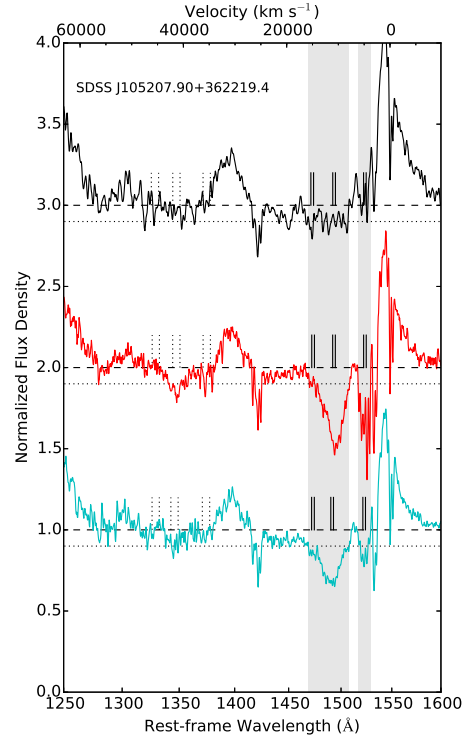


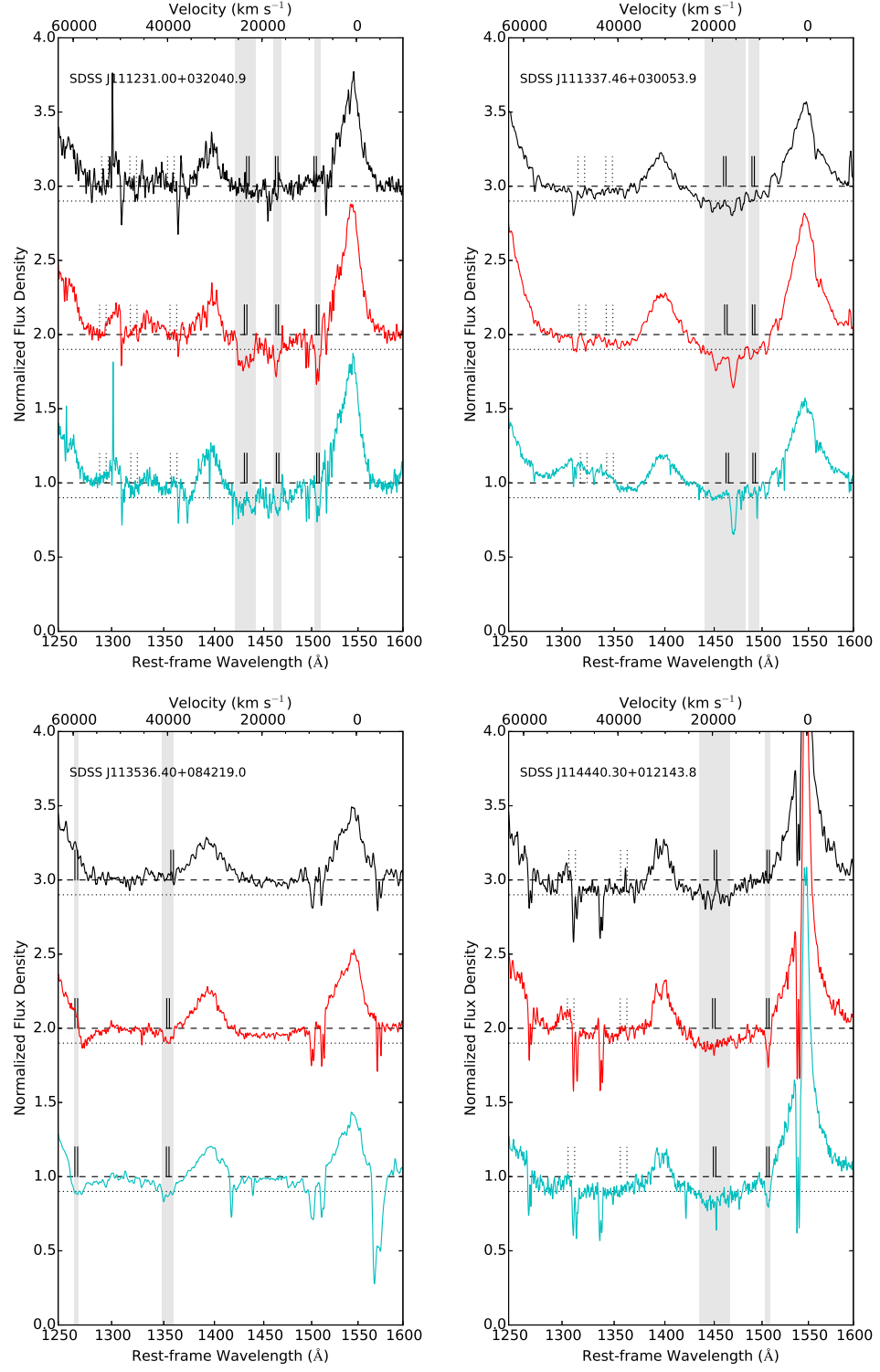


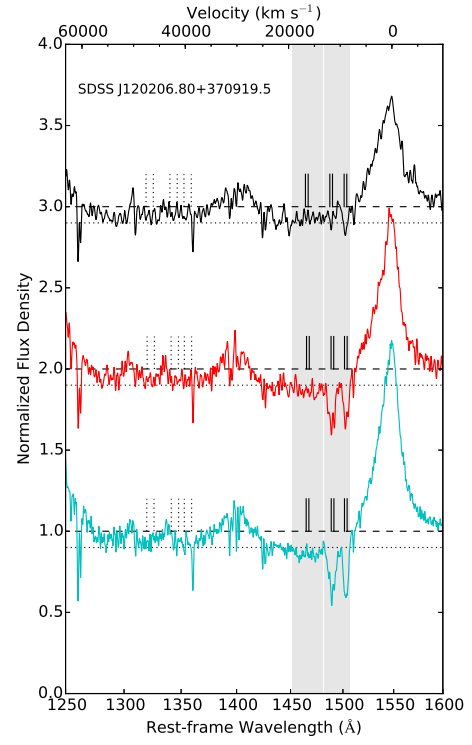
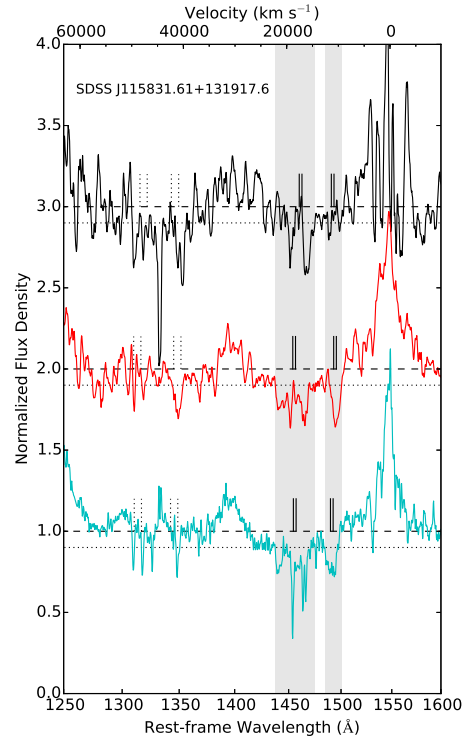
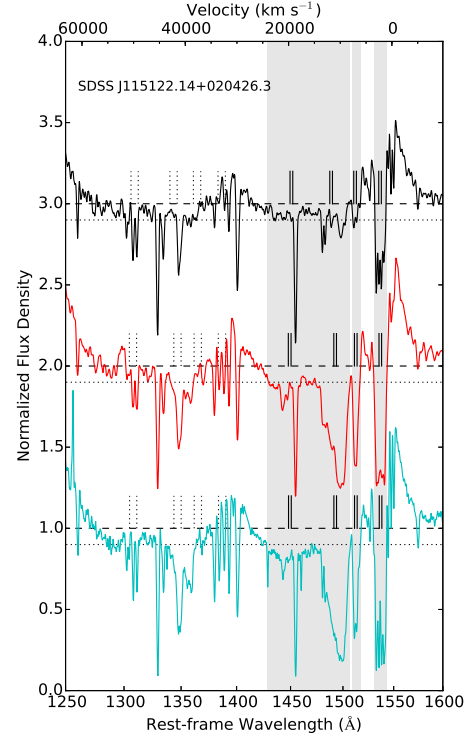
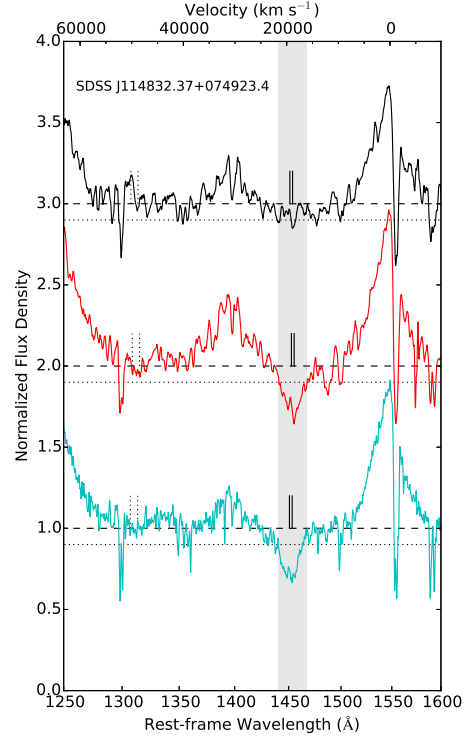


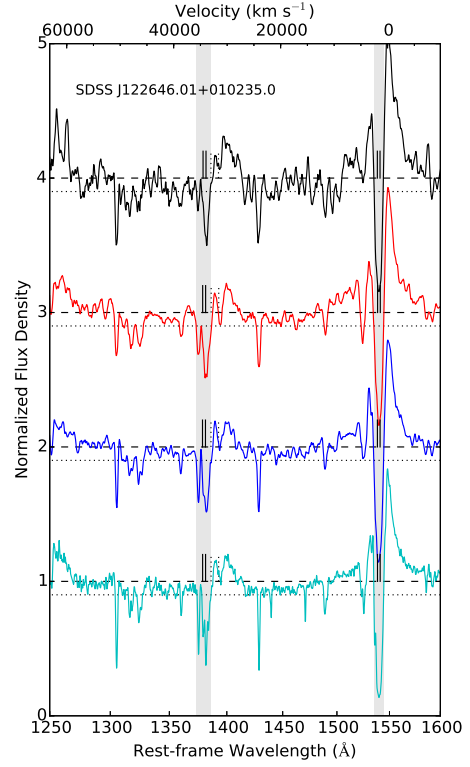
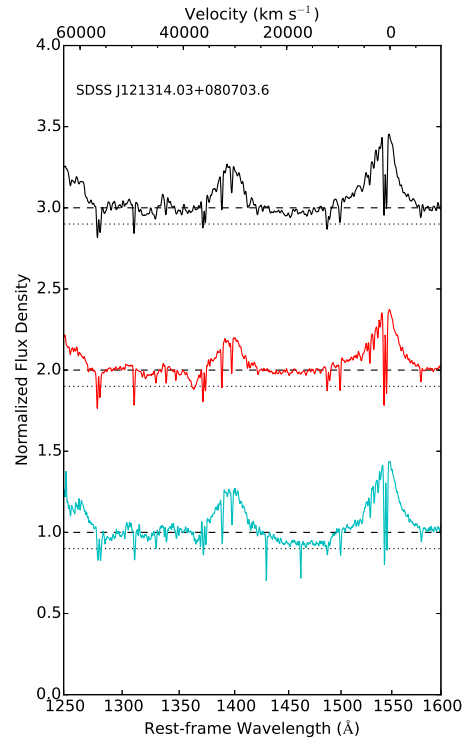
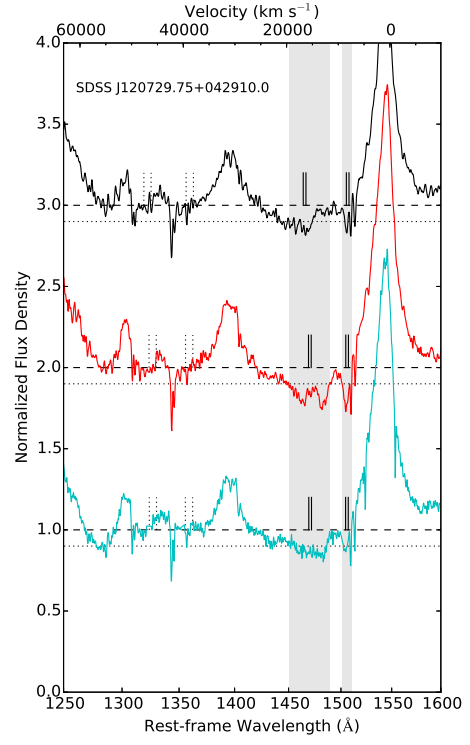
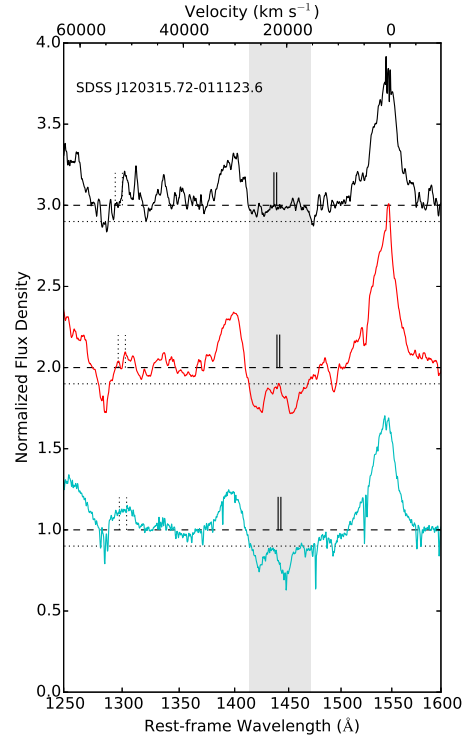


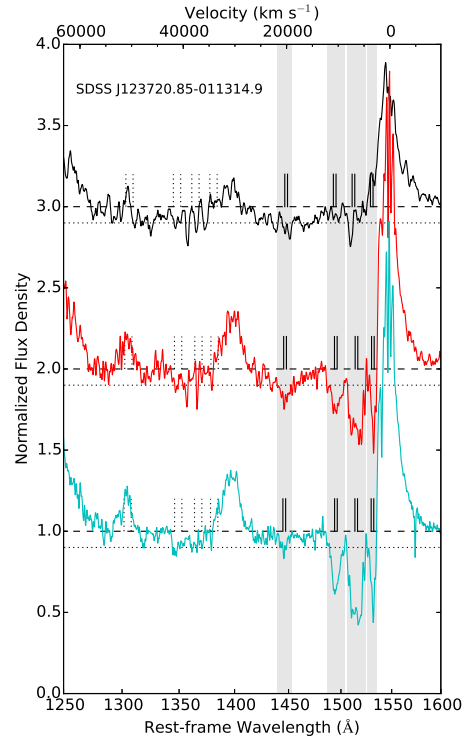
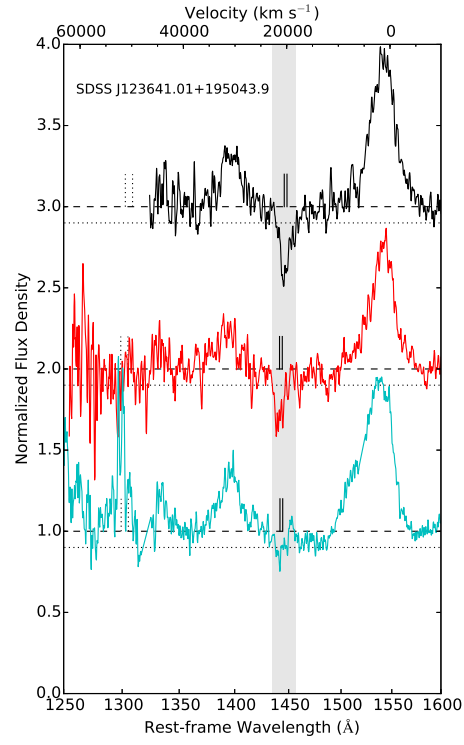
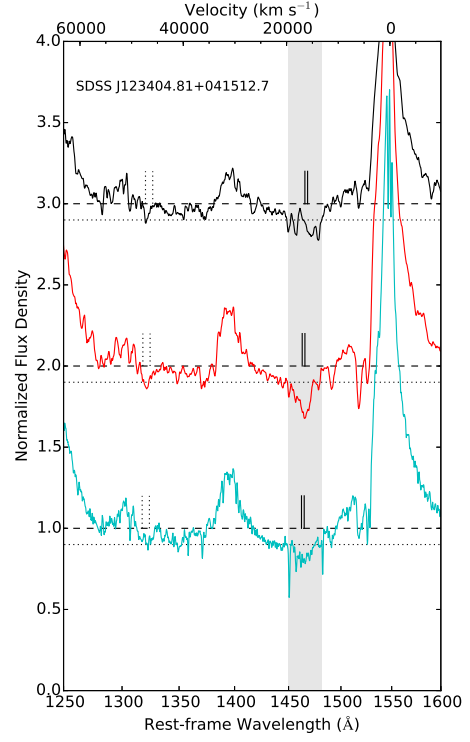
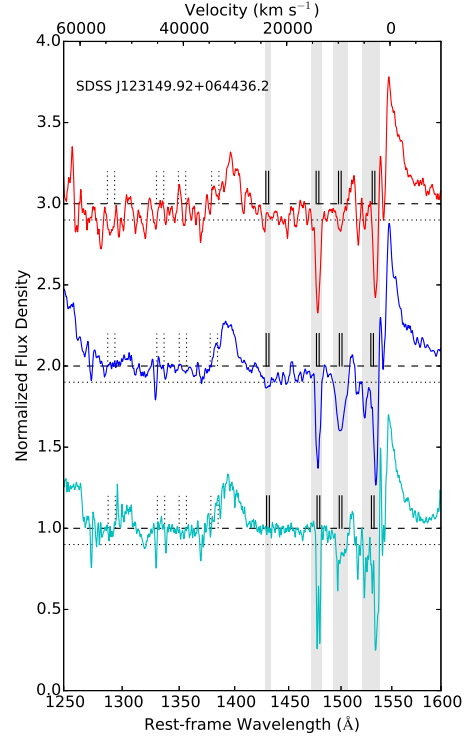


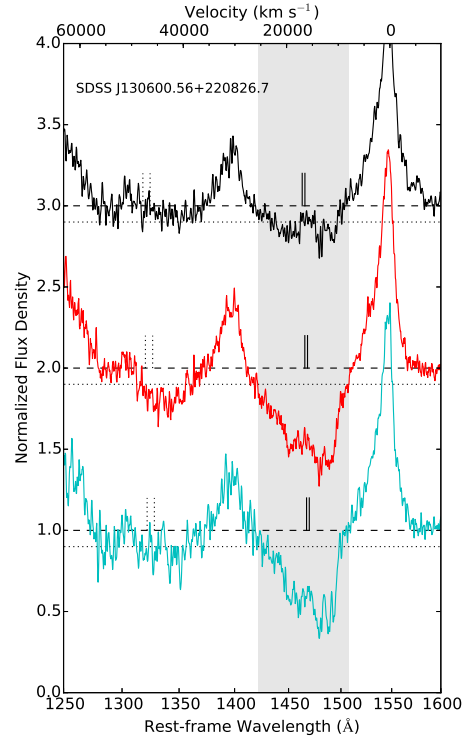
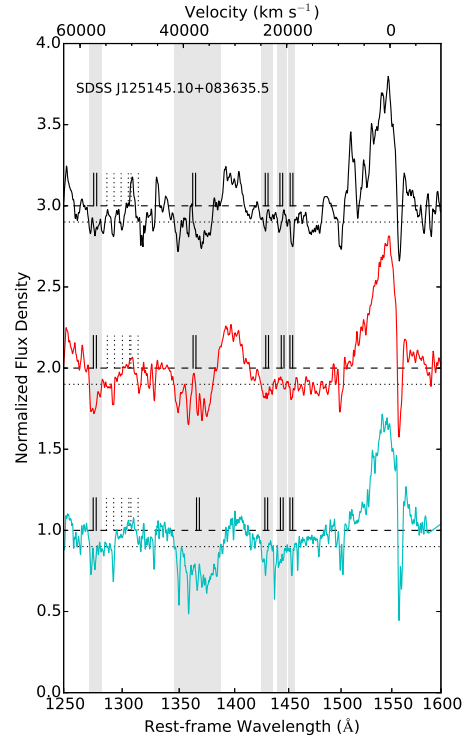
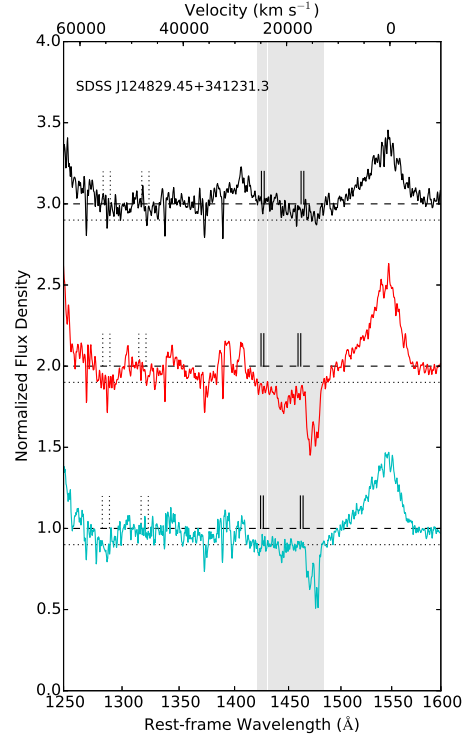
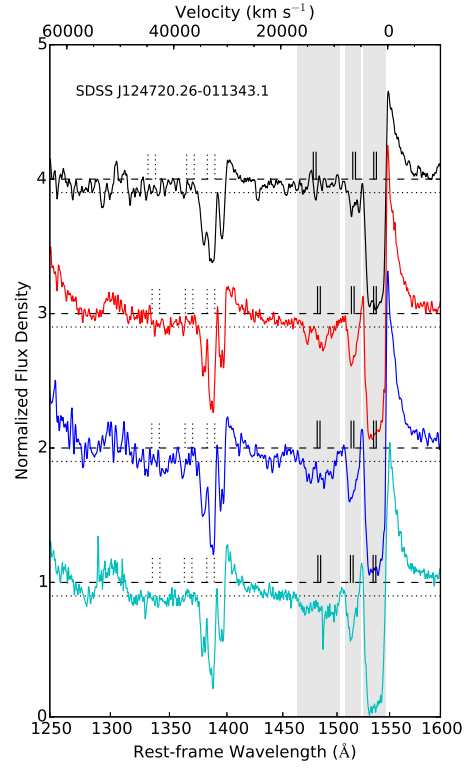


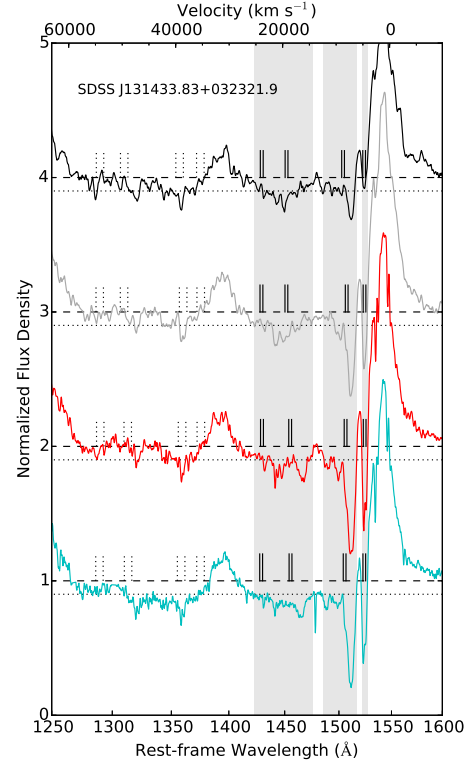
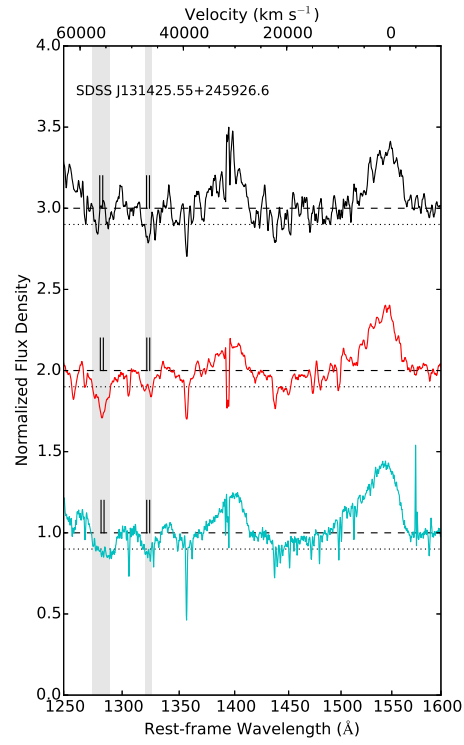
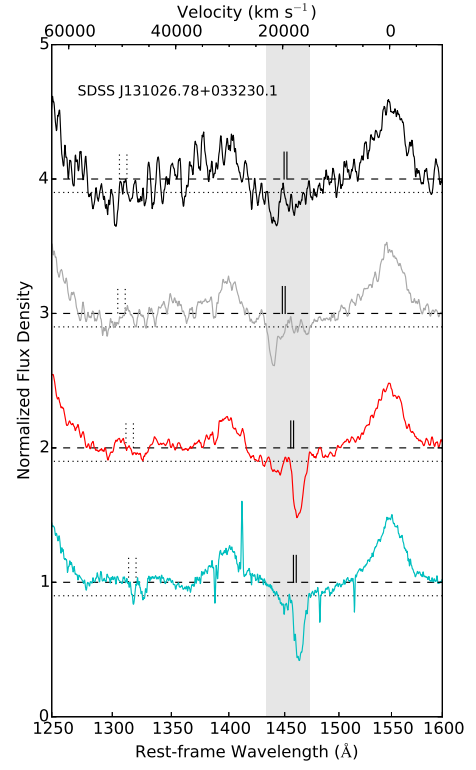
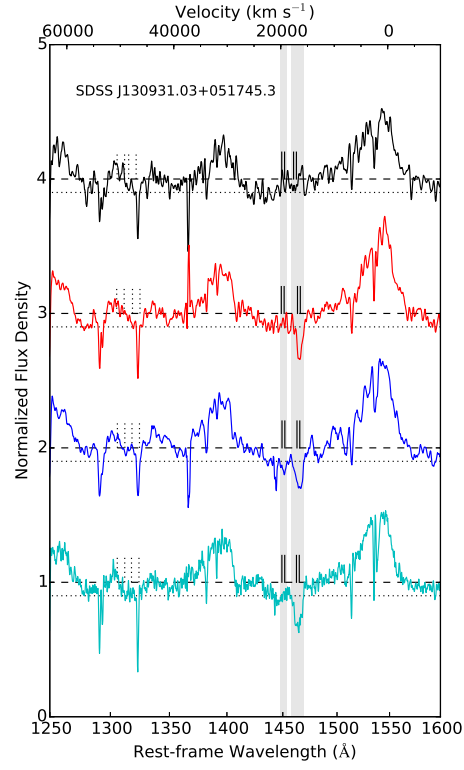


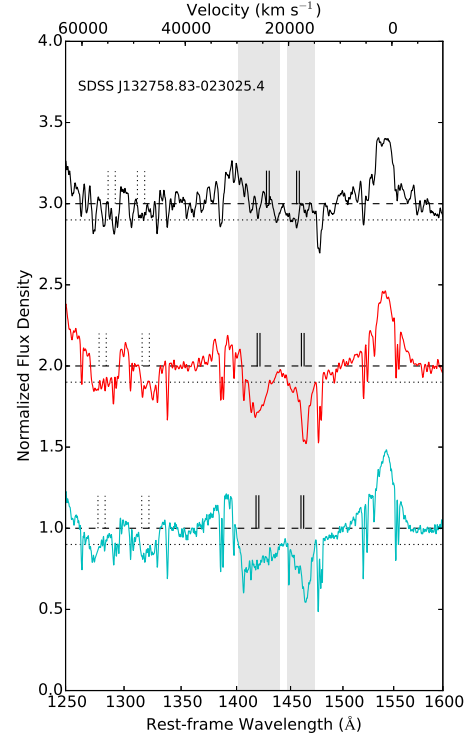
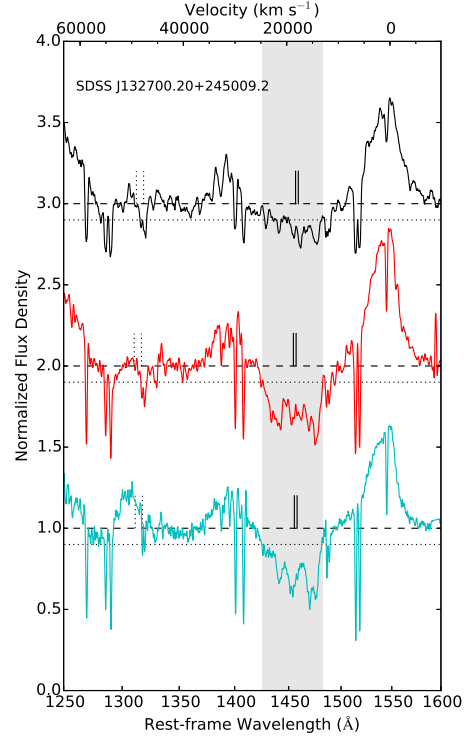
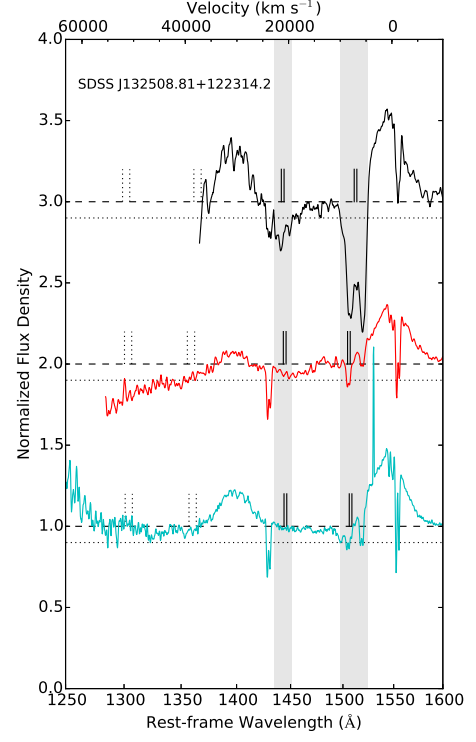
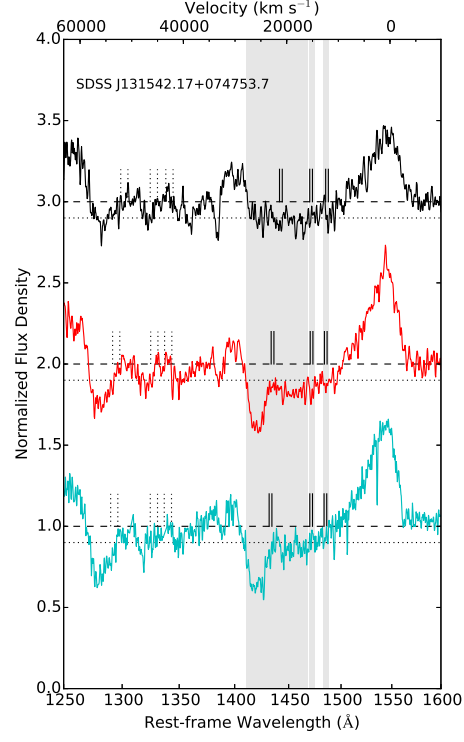


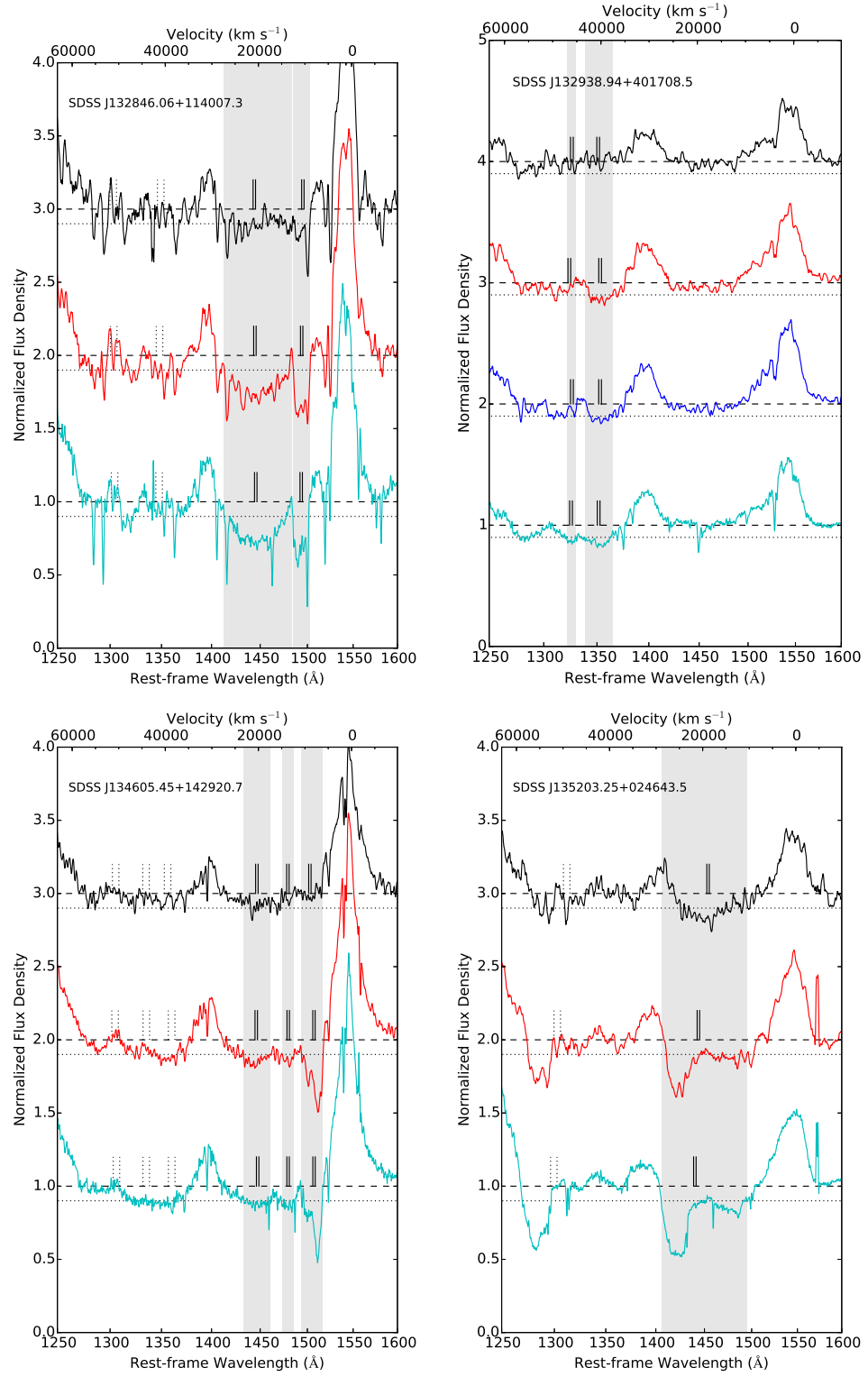


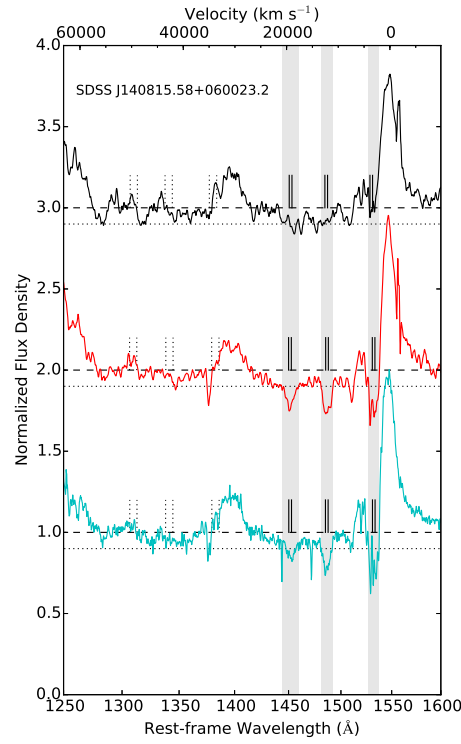
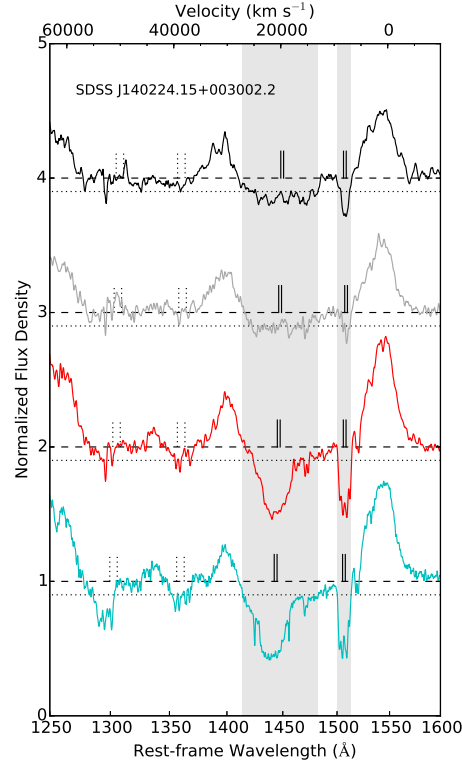
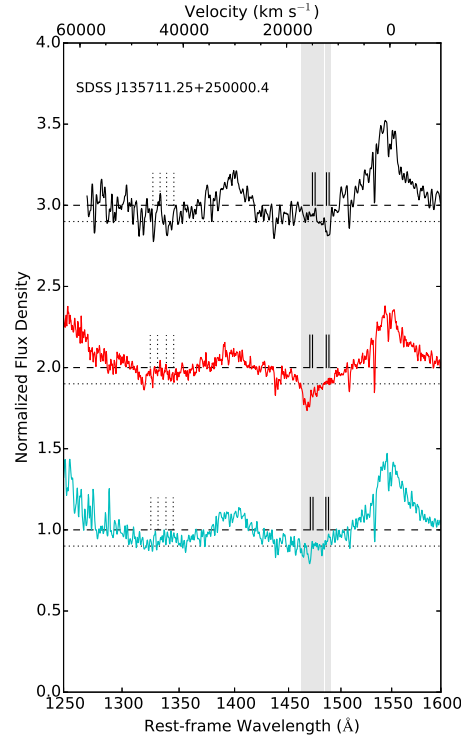
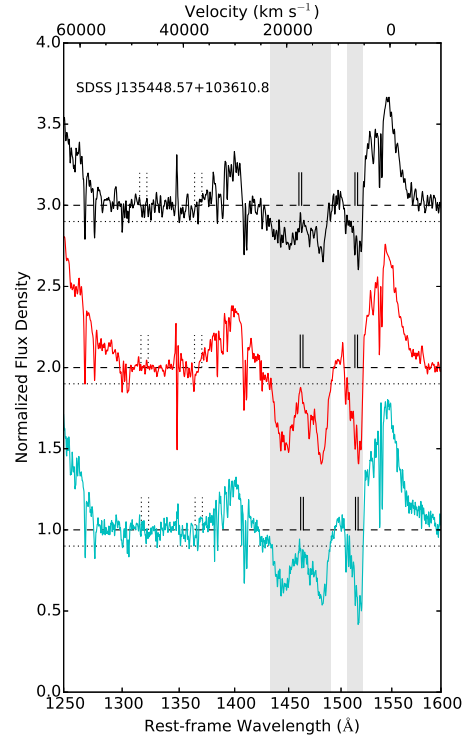


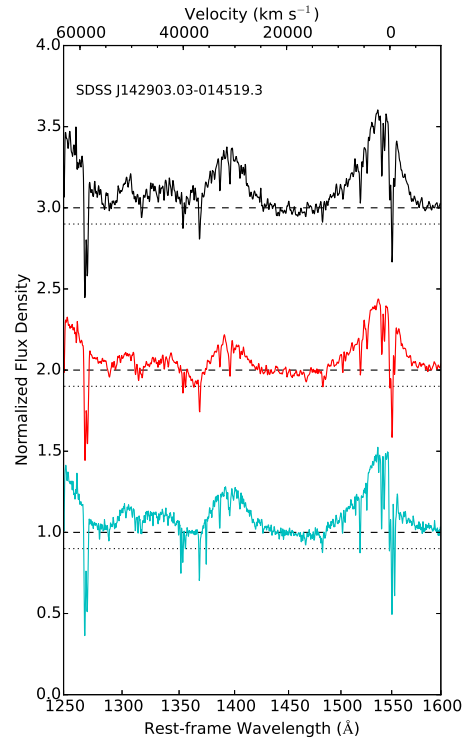
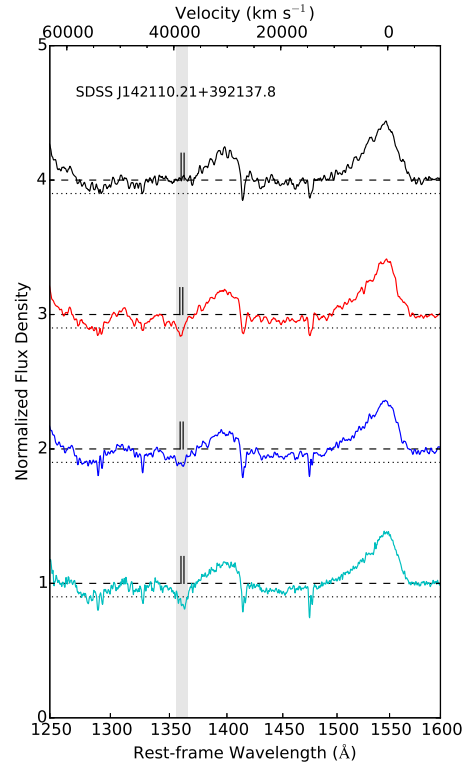
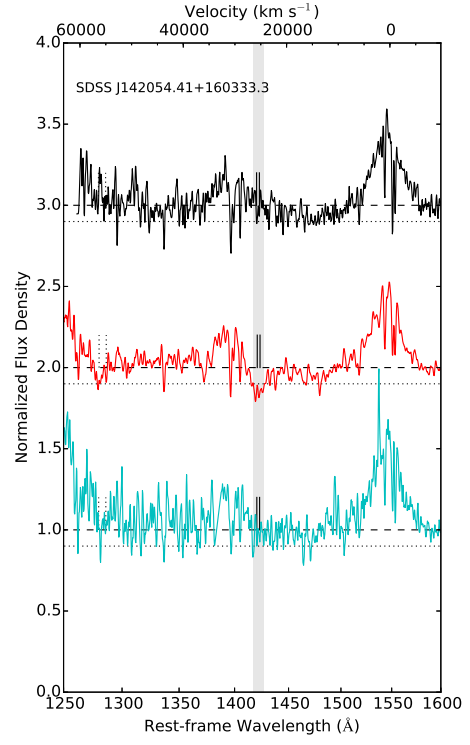
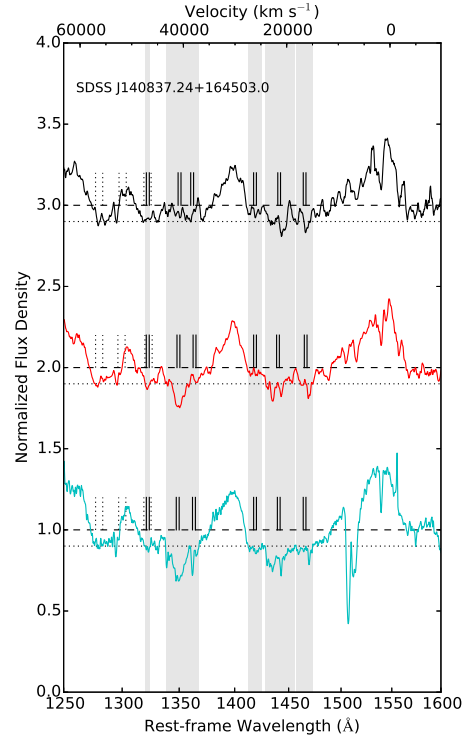


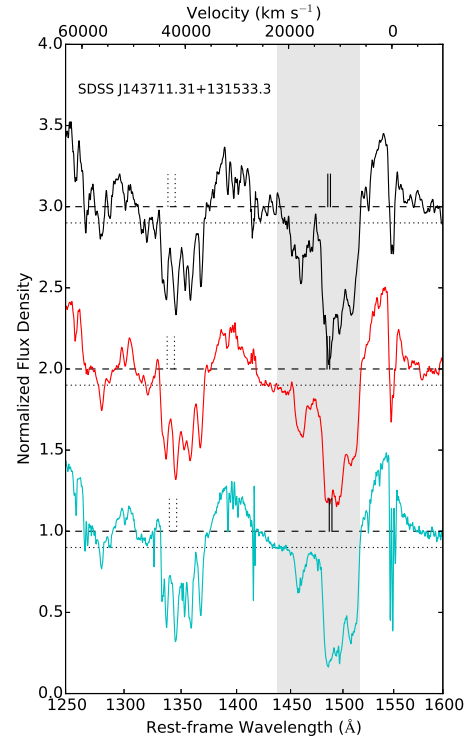
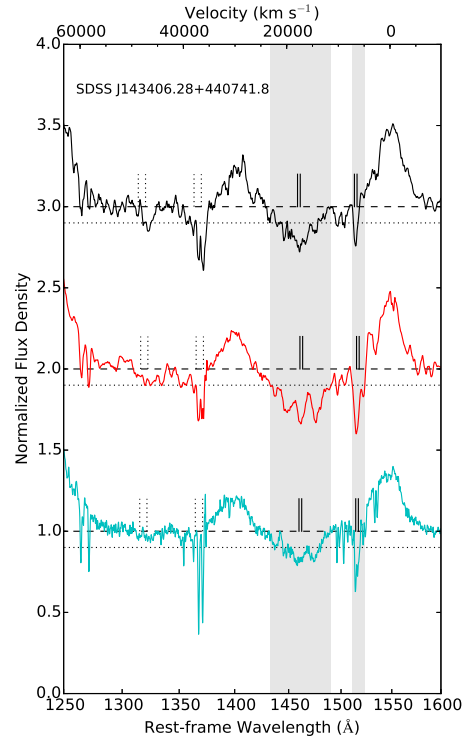
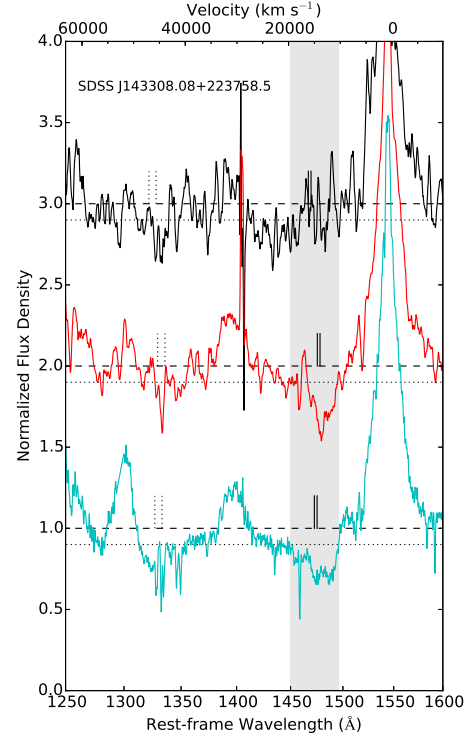
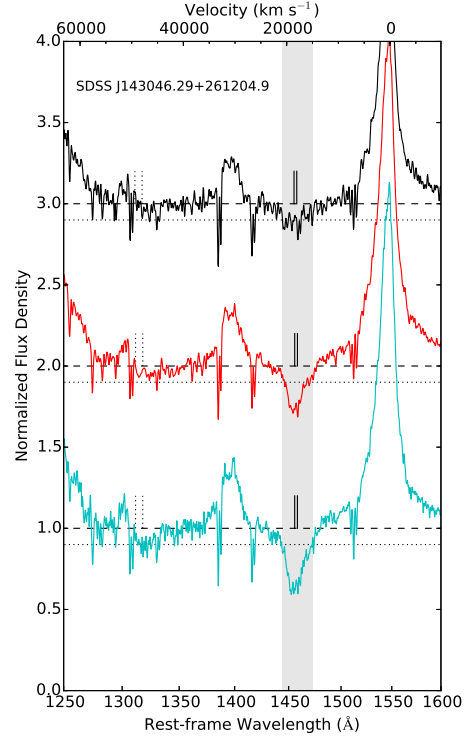


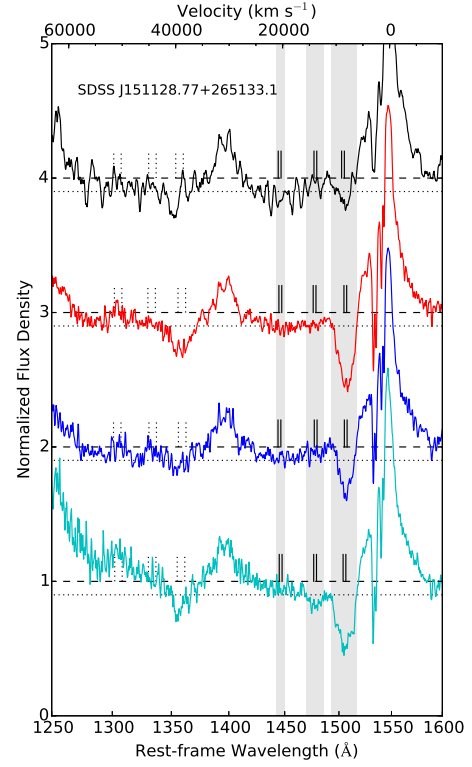
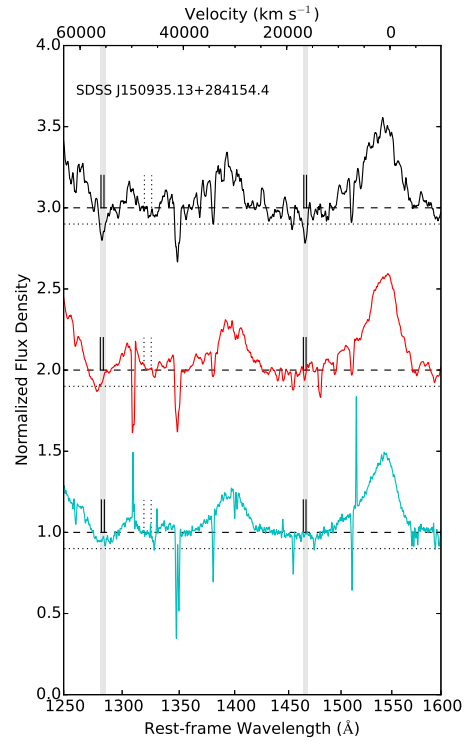
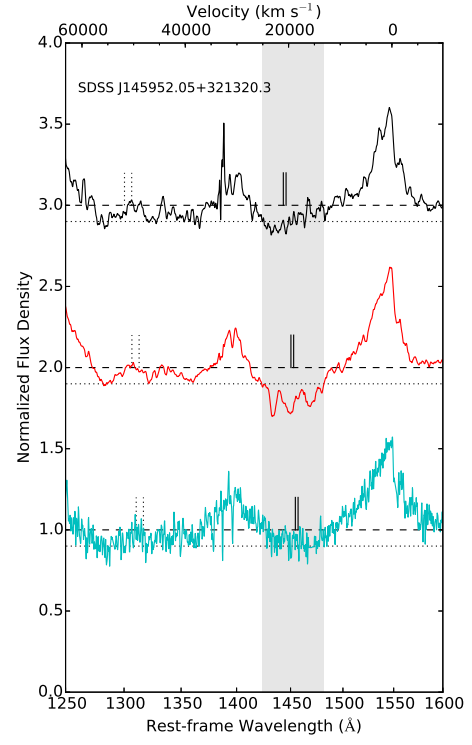
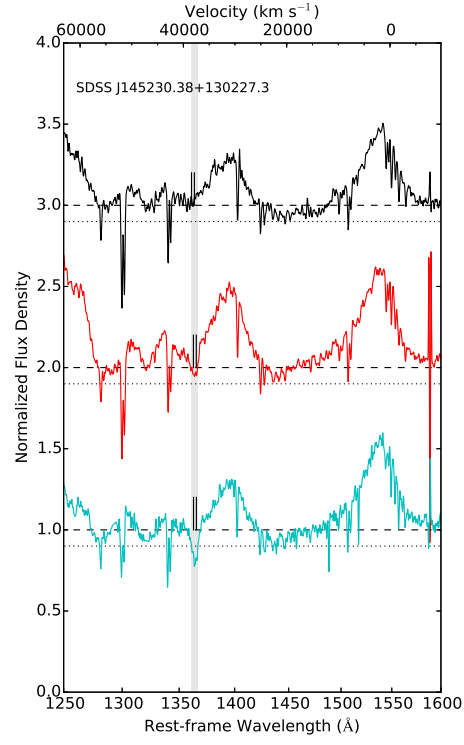


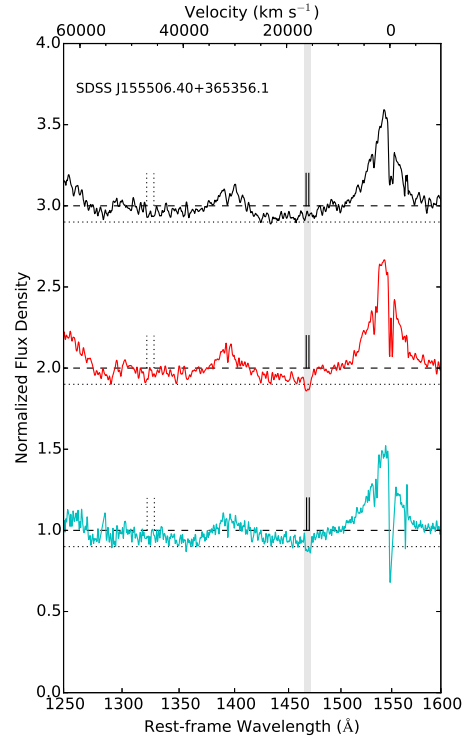
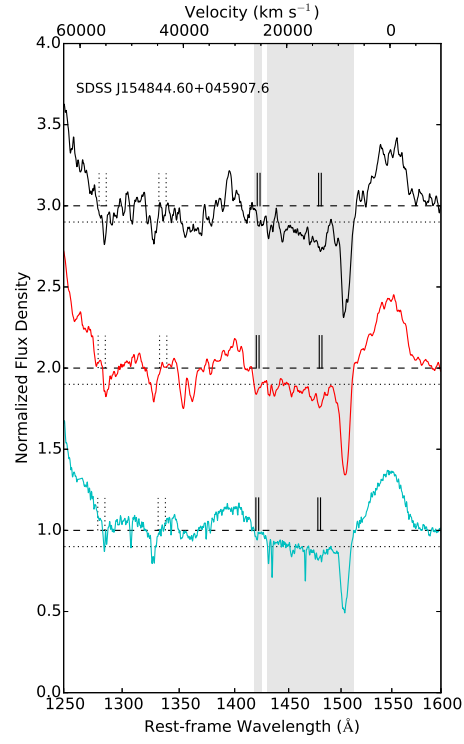
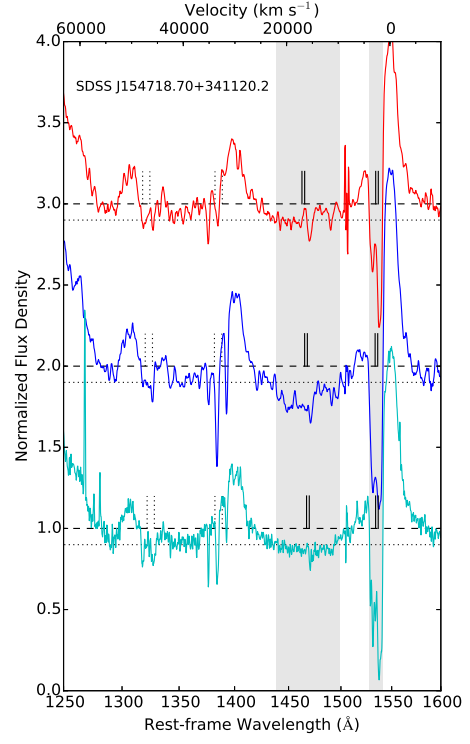
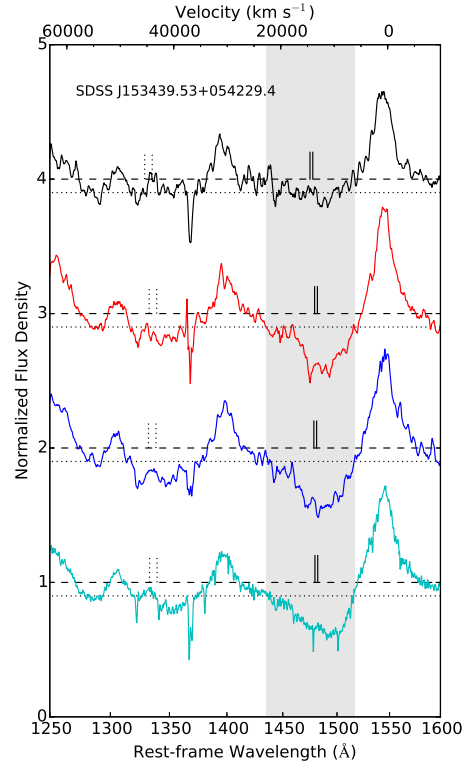


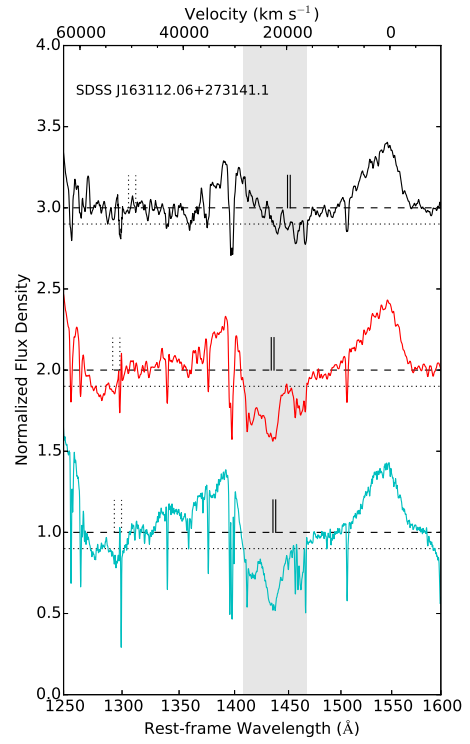
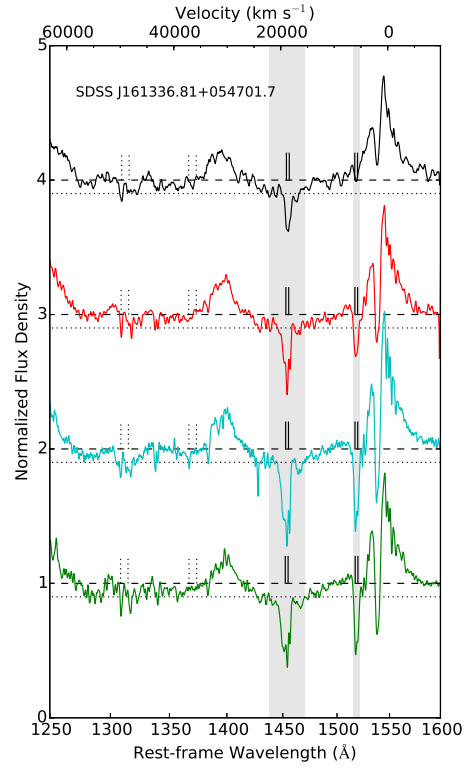
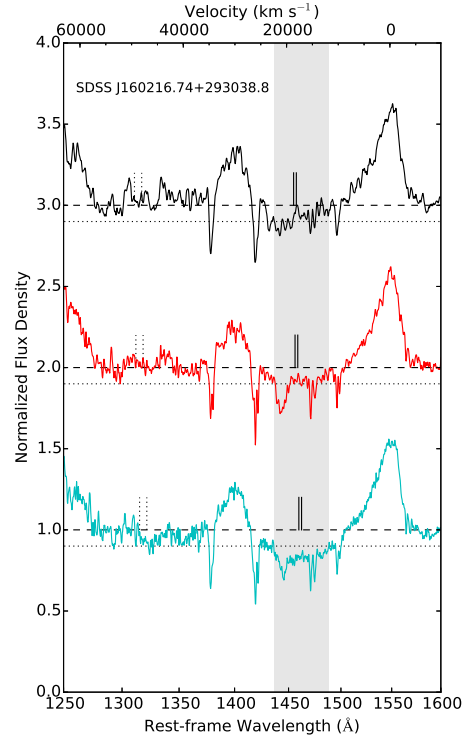
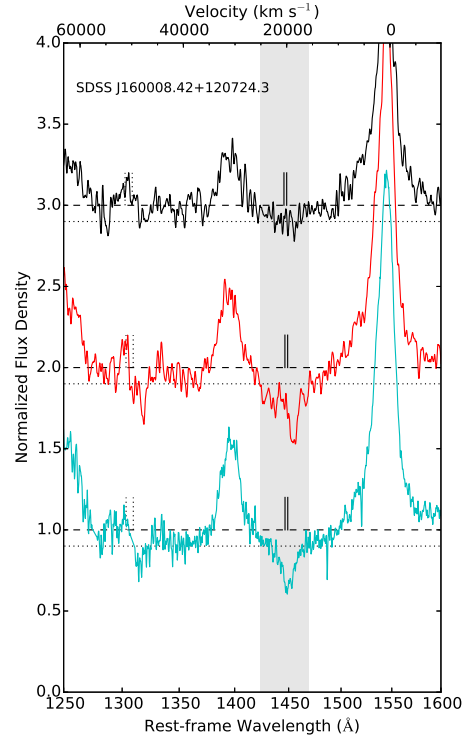


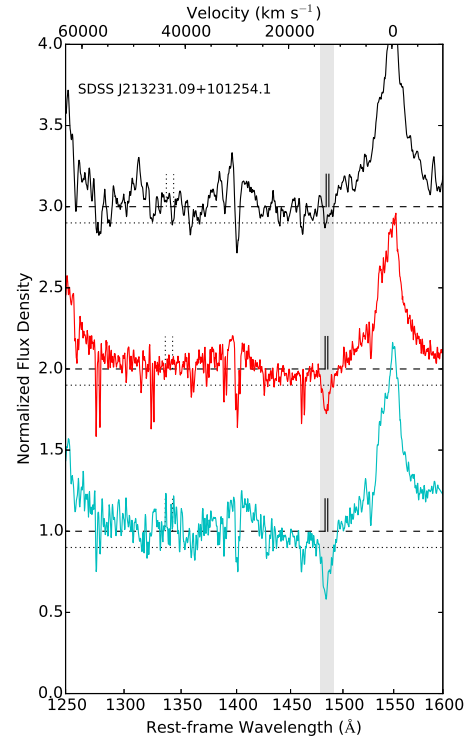
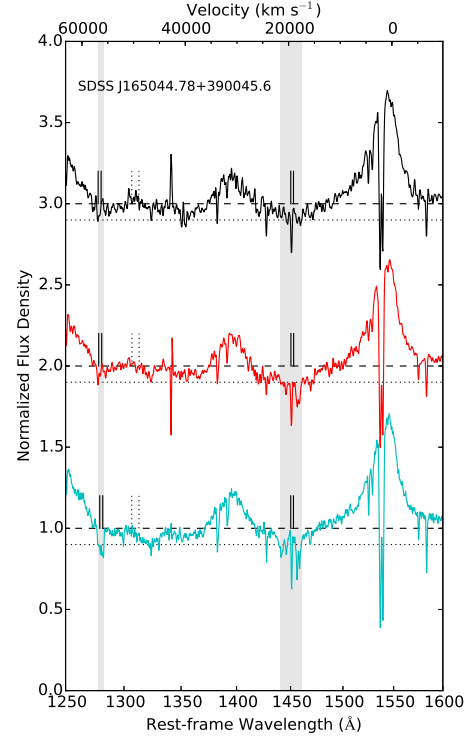
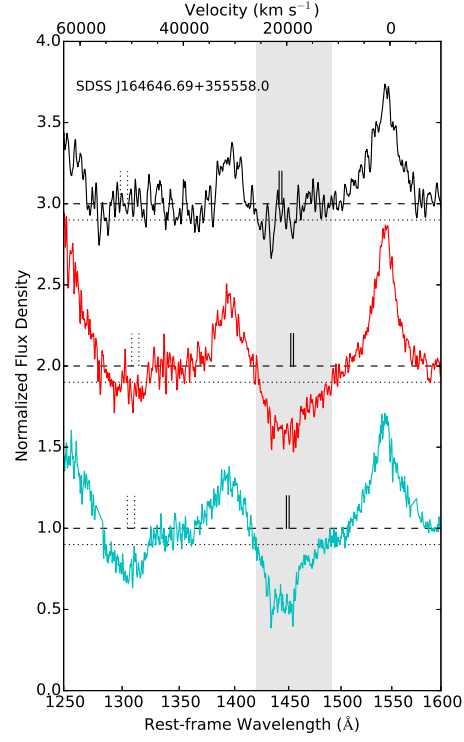


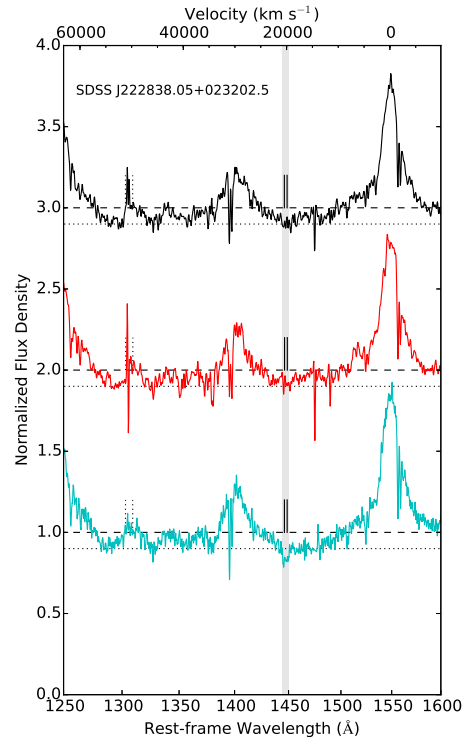
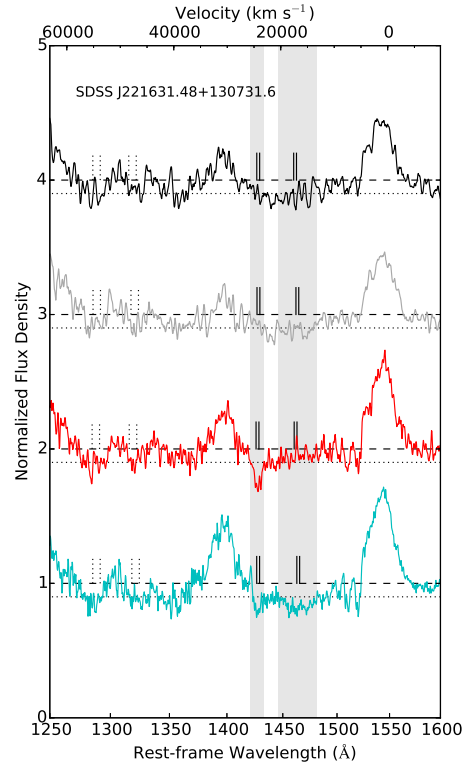
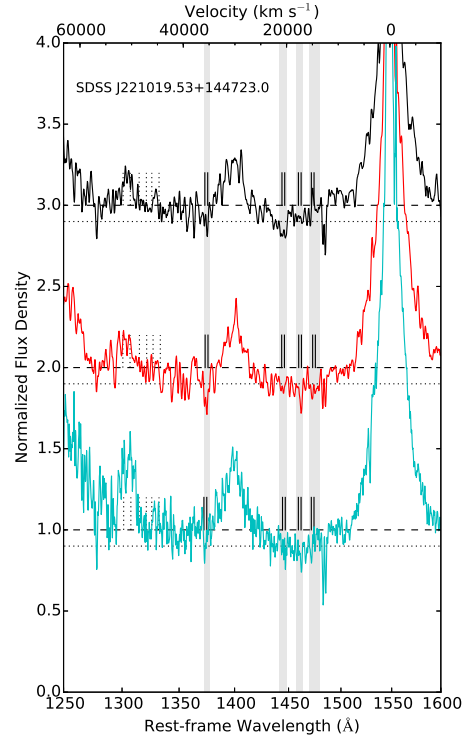
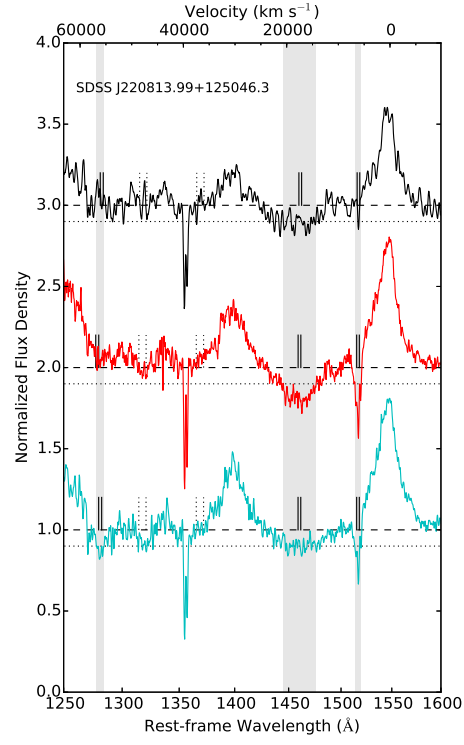


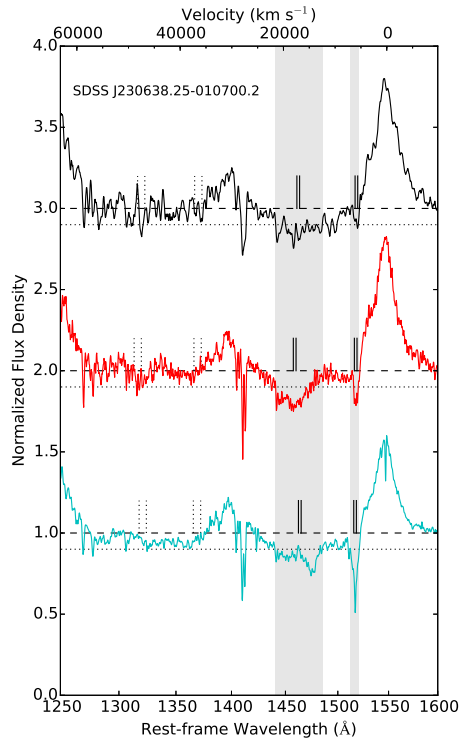












Bibliography

- Abazajian, K. N., Adelman-McCarthy, J. K., Agüeros, M. A., Allam, S. S., Allende Prieto, C., An, D., Anderson, K. S. J., Anderson, S. F., Annis, J., Bahcall, N. A., & et al. 2009, *Astrophys. J. Suppl. Ser.*, 182, 543
- Ahn, C. P., Alexandroff, R., Allende Prieto, C., Anders, F., Anderson, S. F., Anderton, T., Andrews, B. H., Aubourg, É., Bailey, S., Bastien, F. A., & et al. 2014, *Astrophys. J. Suppl. Ser.*, 211, 17
- Ahn, C. P., Alexandroff, R., Allende Prieto, C., Anderson, S. F., Anderton, T., Andrews, B. H., Aubourg, É., Bailey, S., Balbinot, E., Barnes, R., & et al. 2012, *Astrophys. J. Suppl. Ser.*, 203, 21
- Allen, J. T., Hewett, P. C., Maddox, N., Richards, G. T., & Belokurov, V. 2011, *Mon. Not. R. Astron. Soc.*, 410, 860
- Arav, N., Borguet, B., Chamberlain, C., Edmonds, D., & Danforth, C. 2013, *Mon. Not. R. Astron. Soc.*, 436, 3286
- Arav, N., Chamberlain, C., Kriss, G. A., Kaastra, J. S., Cappi, M., Mehdipour, M., Petrucci, P.-O., Steenbrugge, K. C., Behar, E., Bianchi, S., Boissay, R., Branduardi-Raymont, G., Costantini, E., Ely, J. C., Ebrero, J., di Gesu, L., Harrison, F. A., Kaspi, S., Malzac, J., De Marco, B., Matt, G., Nandra, K. P., Paltani, S., Peterson, B. M., Pinto, C., Ponti, G., Pozo Nuñez, F., De Rosa, A., Seta, H., Ursini, F., de Vries, C. P., Walton, D. J., & Whewell, M. 2015, *Astron. Astrophys.*, 577, A37
- Arav, N., Edmonds, D., Borguet, B., Kriss, G. A., Kaastra, J. S., Behar, E., Bianchi, S., Cappi, M., Costantini, E., Detmers, R. G., Ebrero, J., Mehdipour, M., Paltani, S., Petrucci, P. O., Pinto, C., Ponti, G., Steenbrugge, K. C., & de Vries, C. P. 2012, *Astron. Astrophys.*, 544, A33
- Arav, N., Korista, K. T., de Kool, M., Junkkarinen, V. T., & Begelman, M. C. 1999, *Astrophys. J.*, 516, 27
- Barlow, T. A. 1993, PhD thesis, California University
- Baskin, A., Laor, A., & Stern, J. 2014, *Mon. Not. R. Astron. Soc.*, 445, 3025

- Blackburne, J. A., Pooley, D., Rappaport, S., & Schechter, P. L. 2011, *Astrophys. J.*, 729, 34
- Bromage, G. E., Boksenberg, A., Clavel, J., Elvius, A., Penston, M. V., Perola, G. C., Pettini, M., Snijders, M. A. J., Tanzi, E. G., & Ulrich, M. H. 1985, *Mon. Not. R. Astron. Soc.*, 215, 1
- Capellupo, D. M., Hamann, F., Shields, J. C., Halpern, J. P., & Barlow, T. A. 2013, *Mon. Not. R. Astron. Soc.*, 429, 1872
- Capellupo, D. M., Hamann, F., Shields, J. C., Rodríguez Hidalgo, P., & Barlow, T. A. 2011, *Mon. Not. R. Astron. Soc.*, 413, 908
- . 2012, *Mon. Not. R. Astron. Soc.*, 422, 3249
- Chamberlain, C., Arav, N., & Benn, C. 2015, *Mon. Not. R. Astron. Soc.*, 450, 1085
- Chartas, G., Brandt, W. N., Gallagher, S. C., & Garmire, G. P. 2002, *Astrophys. J.*, 579, 169
- Dawson, K. S., Schlegel, D. J., Ahn, C. P., Anderson, S. F., Aubourg, É., Bailey, S., Barkhouser, R. H., Bautista, J. E., Beifiori, A., Berlind, A. A., Bhardwaj, V., Bizyaev, D., Blake, C. H., Blanton, M. R., Blomqvist, M., Bolton, A. S., Borde, A., Bovy, J., Brandt, W. N., Brewington, H., Brinkmann, J., Brown, P. J., Brownstein, J. R., Bundy, K., Busca, N. G., Carithers, W., Carnero, A. R., Carr, M. A., Chen, Y., Comparat, J., Connolly, N., Cope, F., Croft, R. A. C., Cuesta, A. J., da Costa, L. N., Davenport, J. R. A., Delubac, T., de Putter, R., Dhital, S., Ealet, A., Ebelke, G. L., Eisenstein, D. J., Escoffier, S., Fan, X., Filiz Ak, N., Finley, H., Font-Ribera, A., Génova-Santos, R., Gunn, J. E., Guo, H., Haggard, D., Hall, P. B., Hamilton, J.-C., Harris, B., Harris, D. W., Ho, S., Hogg, D. W., Holder, D., Honscheid, K., Huehnerhoff, J., Jordan, B., Jordan, W. P., Kauffmann, G., Kazin, E. A., Kirkby, D., Klaene, M. A., Kneib, J.-P., Le Goff, J.-M., Lee, K.-G., Long, D. C., Loomis, C. P., Lundgren, B., Lupton, R. H., Maia, M. A. G., Makler, M., Malanushenko, E., Malanushenko, V., Mandelbaum, R., Manera, M., Maraston, C., Margala, D., Masters, K. L., McBride, C. K., McDonald, P., McGreer, I. D., McMahon, R. G., Mena, O., Miralda-Escudé, J., Montero-Dorta, A. D., Montesano, F., Muna, D., Myers, A. D., Naugle, T., Nichol, R. C., Noterdaeme, P., Nuza, S. E., Olmstead, M. D., Oravetz, A., Oravetz, D. J., Owen, R., Padmanabhan, N., Palanque-Delabrouille, N., Pan, K., Parejko, J. K., Pâris, I., Percival, W. J., Pérez-Fournon, I., Pérez-Ràfols, I., Petitjean, P., Pfaffenberger, R., Pforr, J., Pieri, M. M., Prada, F., Price-Whelan, A. M., Raddick, M. J., Rebolo, R., Rich, J., Richards, G. T., Rockosi, C. M., Roe, N. A., Ross, A. J., Ross, N. P., Rossi, G., Rubiño-Martin, J. A., Samushia, L., Sánchez, A. G., Sayres, C., Schmidt, S. J., Schneider, D. P., Scóccola, C. G., Seo, H.-J., Shelden, A., Sheldon, E., Shen, Y., Shu, Y., Slosar, A., Smee, S. A., Snedden, S. A., Stauffer, F., Steele, O., Strauss, M. A., Streblyanska, A., Suzuki, N., Swanson, M. E. C., Tal, T., Tanaka, M., Thomas, D., Tinker, J. L., Tojeiro, R., Tremonti, C. A., Vargas Magaña, M., Verde, L., Viel, M., Wake, D. A., Watson, M., Weaver, B. A., Weinberg, D. H., Weiner, B. J., West, A. A., White, M., Wood-Vasey, W. M., Yèche, C., Zehavi, I., Zhao, G.-B., & Zheng, Z. 2013, *Astron. J.*, 145, 10

- Dere, K. P., Landi, E., Mason, H. E., Monsignori Fossi, B. C., & Young, P. R. 1997, *Astron. Astrophys. Suppl. Ser.*, 125, 149
- Dexter, J. & Agol, E. 2011, *Astrophys. J. Lett.*, 727, L24
- Drake, A. J., Djorgovski, S. G., Mahabal, A., Beshore, E., Larson, S., Graham, M. J., Williams, R., Christensen, E., Catelan, M., Boattini, A., Gibbs, A., Hill, R., & Kowalski, R. 2009, *Astrophys. J.*, 696, 870
- Dunn, J. P., Bautista, M., Arav, N., Moe, M., Korista, K., Costantini, E., Benn, C., Ellison, S., & Edmonds, D. 2010, *Astrophys. J.*, 709, 611
- Edelson, R., Gelbord, J. M., Horne, K., McHardy, I. M., Peterson, B. M., Arévalo, P., Breeveld, A. A., De Rosa, G., Evans, P. A., Goad, M. R., Kriss, G. A., Brandt, W. N., Gehrels, N., Grupe, D., Kennea, J. A., Kochanek, C. S., Nousek, J. A., Papadakis, I., Siegel, M., Starkey, D., Uttley, P., Vaughan, S., Young, S., Barth, A. J., Bentz, M. C., Brewer, B. J., Crenshaw, D. M., Dalla Bontà, E., De Lorenzo-Cáceres, A., Denney, K. D., Dietrich, M., Ely, J., Fausnaugh, M. M., Grier, C. J., Hall, P. B., Kaastra, J., Kelly, B. C., Korista, K. T., Lira, P., Mathur, S., Netzer, H., Pancoast, A., Pei, L., Pogge, R. W., Schimoia, J. S., Treu, T., Vestergaard, M., Villforth, C., Yan, H., & Zu, Y. 2015, *Astrophys. J.*, 806, 129
- Elvis, M. 2000, *ApJ*, 545, 63
- Faucher-Giguère, C.-A., Quataert, E., & Murray, N. 2012, *Mon. Not. R. Astron. Soc.*, 420, 1347
- Filiz Ak, N., Brandt, W. N., Hall, P. B., Schneider, D. P., Anderson, S. F., Gibson, R. R., Lundgren, B. F., Myers, A. D., Petitjean, P., Ross, N. P., Shen, Y., York, D. G., Bizyaev, D., Brinkmann, J., Malanushenko, E., Oravetz, D. J., Pan, K., Simmons, A. E., & Weaver, B. A. 2012, *Astrophys. J.*, 757, 114
- Filiz Ak, N., Brandt, W. N., Hall, P. B., Schneider, D. P., Anderson, S. F., Hamann, F., Lundgren, B. F., Myers, A. D., Pâris, I., Petitjean, P., Ross, N. P., Shen, Y., & York, D. 2013, *Astrophys. J.*, 777, 168
- Foltz, C. B., Weymann, R. J., Morris, S. L., & Turnshek, D. A. 1987, *Astrophys. J.*, 317, 450
- Foltz, C. B., Weymann, R. J., Peterson, B. M., Sun, L., Malkan, M. A., & Chaffee, Frederic H., J. 1986, *ApJ*, 307, 504
- Foltz, C. B., Wilkes, B., Weymann, R., & Turnshek, D. 1983, *PASP*, 95, 341
- Gibson, R. R., Brandt, W. N., Gallagher, S. C., Hewett, P. C., & Schneider, D. P. 2010, *Astrophys. J.*, 713, 220

- Gibson, R. R., Brandt, W. N., Schneider, D. P., & Gallagher, S. C. 2008, *Astrophys. J.*, 675, 985
- Gibson, R. R., Jiang, L., Brandt, W. N., Hall, P. B., Shen, Y., Wu, J., Anderson, S. F., Schneider, D. P., Vanden Berk, D., Gallagher, S. C., Fan, X., & York, D. G. 2009, *Astrophys. J.*, 692, 758
- Grier, C. J., Hall, P. B., Brandt, W. N., Trump, J. R., Shen, Y., Vivek, M., Filiz Ak, N., Chen, Y., Dawson, K. S., Denney, K. D., Green, P. J., Jiang, L., Kochanek, C. S., McGreer, I. D., Pâris, I., Peterson, B. M., Schneider, D. P., Tao, C., Wood-Vasey, W. M., Bizyaev, D., Ge, J., Kinemuchi, K., Oravetz, D., Pan, K., & Simmons, A. 2015, *Astrophys. J.*, 806, 111
- Gunn, J. E., Carr, M., Rockosi, C., Sekiguchi, M., Berry, K., Elms, B., de Haas, E., Ivezić, Ž., Knapp, G., Lupton, R., Pauls, G., Simcoe, R., Hirsch, R., Sanford, D., Wang, S., York, D., Harris, F., Annis, J., Bartozek, L., Boroski, W., Bakken, J., Haldeman, M., Kent, S., Holm, S., Holmgren, D., Petravick, D., Prosapio, A., Rechenmacher, R., Doi, M., Fukugita, M., Shimasaku, K., Okada, N., Hull, C., Siegmund, W., Mannery, E., Blouke, M., Heidtman, D., Schneider, D., Lucinio, R., & Brinkman, J. 1998, *Astron. J.*, 116, 3040
- Gunn, J. E., Siegmund, W. A., Mannery, E. J., Owen, R. E., Hull, C. L., Leger, R. F., Carey, L. N., Knapp, G. R., York, D. G., Boroski, W. N., Kent, S. M., Lupton, R. H., Rockosi, C. M., Evans, M. L., Waddell, P., Anderson, J. E., Annis, J., Barentine, J. C., Bartoszek, L. M., Bastian, S., Bracker, S. B., Brewington, H. J., Briegel, C. I., Brinkmann, J., Brown, Y. J., Carr, M. A., Czarapata, P. C., Drennan, C. C., Dombeck, T., Federwitz, G. R., Gillespie, B. A., Gonzales, C., Hansen, S. U., Harvanek, M., Hayes, J., Jordan, W., Kinney, E., Klaene, M., Kleinman, S. J., Kron, R. G., Kresinski, J., Lee, G., Limmongkol, S., Lindenmeyer, C. W., Long, D. C., Loomis, C. L., McGehee, P. M., Mantsch, P. M., Neilsen, Jr., E. H., Neswold, R. M., Newman, P. R., Nitta, A., Peoples, Jr., J., Pier, J. R., Prieto, P. S., Prosapio, A., Rivetta, C., Schneider, D. P., Snedden, S., & Wang, S.-i. 2006, *Astron. J.*, 131, 2332
- Haggard, D., Arraki, K. S., Green, P. J., Aldcroft, T., & Anderson, S. F. 2012, in *Astronomical Society of the Pacific Conference Series*, Vol. 460, AGN Winds in Charleston, ed. G. Chartas, F. Hamann, & K. M. Leighly, 98
- Hall, P. B., Anderson, S. F., Strauss, M. A., York, D. G., Richards, G. T., Fan, X., Knapp, G. R., Schneider, D. P., Vanden Berk, D. E., Geballe, T. R., Bauer, A. E., Becker, R. H., Davis, M., Rix, H.-W., Nichol, R. C., Bahcall, N. A., Brinkmann, J., Brunner, R., Connolly, A. J., Csabai, I., Doi, M., Fukugita, M., Gunn, J. E., Haiman, Z., Harvanek, M., Heckman, T. M., Hennesy, G. S., Inada, N., Ivezić, Ž., Johnston, D., Kleinman, S., Krolik, J. H., Krzesinski, J., Kunszt, P. Z., Lamb, D. Q., Long, D. C., Lupton, R. H., Miknaitis, G., Munn, J. A., Narayanan, V. K., Neilsen, E., Newman, P. R., Nitta, A., Okamura, S., Pentericci, L., Pier, J. R., Schlegel, D. J., Snedden, S., Szalay, A. S., Thakar, A. R., Tsvetanov, Z., White, R. L., & Zheng, W. 2002, *Astrophys. J. Suppl. Ser.*, 141, 267

- Hall, P. B., Anosov, K., White, R. L., Brandt, W. N., Gregg, M. D., Gibson, R. R., Becker, R. H., & Schneider, D. P. 2011, *Mon. Not. R. Astron. Soc.*, 411, 2653
- Hall, P. B., Noordeh, E. S., Chajet, L. S., Weiss, E., & Nixon, C. J. 2013, *ArXiv e-prints*
- Hall, P. B., Sadavoy, S. I., Hutsemekers, D., Everett, J. E., & Rafiee, A. 2007, *Astrophys. J.*, 665, 174
- Hamann, F., Barlow, T. A., Beaver, E. A., Burbidge, E. M., Cohen, R. D., Junkkarinen, V., & Lyons, R. 1995, *Astrophys. J.*, 443, 606
- Hamann, F., Barlow, T. A., Junkkarinen, V., & Burbidge, E. M. 1997, *Astrophys. J.*, 478, 80
- Hamann, F., Kaplan, K. F., Rodríguez Hidalgo, P., Prochaska, J. X., & Herbert-Fort, S. 2008, *Mon. Not. R. Astron. Soc.*, 391, L39
- He, Z.-C., Bian, W.-H., Ge, X., & Jiang, X.-L. 2015, *Mon. Not. R. Astron. Soc.*, 454, 3962
- Hewett, P. C. & Wild, V. 2010, *Mon. Not. R. Astron. Soc.*, 405, 2302
- Hogg, D. W. 1999, *ArXiv Astrophysics e-prints*
- Ivezić, Ž., Menou, K., Knapp, G. R., Strauss, M. A., Lupton, R. H., Vanden Berk, D. E., Richards, G. T., Tremonti, C., Weinstein, M. A., Anderson, S., Bahcall, N. A., Becker, R. H., Bernardi, M., Blanton, M., Eisenstein, D., Fan, X., Finkbeiner, D., Finlator, K., Frieman, J., Gunn, J. E., Hall, P. B., Kim, R. S. J., Kinkhabwala, A., Narayanan, V. K., Rockosi, C. M., Schlegel, D., Schneider, D. P., Strateva, I., SubbaRao, M., Thakar, A. R., Voges, W., White, R. L., Yanny, B., Brinkmann, J., Doi, M., Fukugita, M., Hennessy, G. S., Munn, J. A., Nichol, R. C., & York, D. G. 2002, *Astron. J.*, 124, 2364
- Jannuzi, B. T., Hartig, G. F., Kirhakos, S., Sargent, W. L. W., Turnshek, D. A., Weymann, R. J., Bahcall, J. N., Bergeron, J., Boksenberg, A., Savage, B. D., Schneider, D. P., & Wolfe, A. M. 1996, *ApJL*, 470, L11
- Jiménez-Vicente, J., Mediavilla, E., Muñoz, J. A., & Kochanek, C. S. 2012, *Astrophys. J.*, 751, 106
- Kallman, T. R. & McCray, R. 1982, *Astrophys. J. Suppl. Ser.*, 50, 263
- Kaspi, S., Brandt, W. N., George, I. M., Netzer, H., Crenshaw, D. M., Gabel, J. R., Hamann, F. W., Kaiser, M. E., Koratkar, A., Kraemer, S. B., Kriss, G. A., Mathur, S., Mushotzky, R. F., Nandra, K., Peterson, B. M., Shields, J. C., Turner, T. J., & Zheng, W. 2002, *Astrophys. J.*, 574, 643
- Krolik, J. H. 1999, *Active galactic nuclei : from the central black hole to the galactic environment*
- Landi, E., Young, P. R., Dere, K. P., Del Zanna, G., & Mason, H. E. 2013, *Astrophys. J.*, 763, 86

- Landolt, A. U. 1992, *Astron. J.*, 104, 340
- Laor, A. & Brandt, W. N. 2002, *Astrophys. J.*, 569, 641
- Leighly, K. M., Halpern, J. P., Jenkins, E. B., & Casebeer, D. 2007, *Astrophys. J. Suppl. Ser.*, 173, 1
- Leighly, K. M., Hamann, F., Casebeer, D. A., & Grupe, D. 2009, *Astrophys. J.*, 701, 176
- Leighly, K. M., Terndrup, D. M., Baron, E., Lucy, A. B., Dietrich, M., & Gallagher, S. C. 2014, *Astrophys. J.*, 788, 123
- Lundgren, B. F., Willhite, B. C., Brunner, R. J., Hall, P. B., Schneider, D. P., York, D. G., Vanden Berk, D. E., & Brinkmann, J. 2007, *Astrophys. J.*, 656, 73
- Luo, B., Brandt, W. N., Hall, P. B., Wu, J., Anderson, S. F., Garmire, G. P., Gibson, R. R., Plotkin, R. M., Richards, G. T., Schneider, D. P., Shemmer, O., & Shen, Y. 2015, *Astrophys. J.*, 805, 122
- Lynds, C. R. 1967, *Astrophys. J.*, 147, 396
- MacLeod, C. L., Ivezić, Ž., Kochanek, C. S., Kozłowski, S., Kelly, B., Bullock, E., Kimball, A., Sesar, B., Westman, D., Brooks, K., Gibson, R., Becker, A. C., & de Vries, W. H. 2010, *Astrophys. J.*, 721, 1014
- McDowell, J. C., Canizares, C., Elvis, M., Lawrence, A., Markoff, S., Mathur, S., & Wilkes, B. J. 1995, *Astrophys. J.*, 450, 585
- Moe, M., Arav, N., Bautista, M. A., & Korista, K. T. 2009, *Astrophys. J.*, 706, 525
- Morgan, C. W., Kochanek, C. S., Morgan, N. D., & Falco, E. E. 2010, *Astrophys. J.*, 712, 1129
- Morton, D. C. 1991, *Astrophys. J. Suppl. Ser.*, 77, 119
- Murray, N. & Chiang, J. 1997, *ApJ*, 474, 91
- Murray, N., Chiang, J., Grossman, S. A., & Voit, G. M. 1995, *Astrophys. J.*, 451, 498
- Narayanan, D., Hamann, F., Barlow, T., Burbidge, E. M., Cohen, R. D., Junkkarinen, V., & Lyons, R. 2004, *Astrophys. J.*, 601, 715
- Netzer, H. 2013, *The Physics and Evolution of Active Galactic Nuclei*
- Ostriker, J. P., Choi, E., Ciotti, L., Novak, G. S., & Proga, D. 2010, *Astrophys. J.*, 722, 642
- Pâris, I., Petitjean, P., Aubourg, É., Bailey, S., Ross, N. P., Myers, A. D., Strauss, M. A., Anderson, S. F., Arnau, E., Bautista, J., Bizyaev, D., Bolton, A. S., Bovy, J., Brandt, W. N., Brewington, H., Browstein, J. R., Busca, N., Capellupo, D., Carithers, W., Croft, R. A. C., Dawson, K., Delubac,

- T., Ebelke, G., Eisenstein, D. J., Engelke, P., Fan, X., Filiz Ak, N., Finley, H., Font-Ribera, A., Ge, J., Gibson, R. R., Hall, P. B., Hamann, F., Hennawi, J. F., Ho, S., Hogg, D. W., Ivezić, Ž., Jiang, L., Kimball, A. E., Kirkby, D., Kirkpatrick, J. A., Lee, K.-G., Le Goff, J.-M., Lundgren, B., MacLeod, C. L., Malanushenko, E., Malanushenko, V., Maraston, C., McGreer, I. D., McMahon, R. G., Miralda-Escudé, J., Muna, D., Noterdaeme, P., Oravetz, D., Palanque-Delabrouille, N., Pan, K., Perez-Fournon, I., Pieri, M. M., Richards, G. T., Rollinde, E., Sheldon, E. S., Schlegel, D. J., Schneider, D. P., Slosar, A., Shelden, A., Shen, Y., Simmons, A., Snedden, S., Suzuki, N., Tinker, J., Viel, M., Weaver, B. A., Weinberg, D. H., White, M., Wood-Vasey, W. M., & Yèche, C. 2012, *Astron. Astrophys.*, 548, A66
- Pâris, I., Petitjean, P., Aubourg, É., Ross, N. P., Myers, A. D., Streblyanska, A., Bailey, S., Hall, P. B., Strauss, M. A., Anderson, S. F., Bizyaev, D., Borde, A., Brinkmann, J., Bovy, J., Brandt, W. N., Brewington, H., Brownstein, J. R., Cook, B. A., Ebelke, G., Fan, X., Filiz Ak, N., Finley, H., Font-Ribera, A., Ge, J., Hamann, F., Ho, S., Jiang, L., Kinemuchi, K., Malanushenko, E., Malanushenko, V., Marchante, M., McGreer, I. D., McMahon, R. G., Miralda-Escudé, J., Muna, D., Noterdaeme, P., Oravetz, D., Palanque-Delabrouille, N., Pan, K., Perez-Fournon, I., Pieri, M., Riffel, R., Schlegel, D. J., Schneider, D. P., Simmons, A., Viel, M., Weaver, B. A., Wood-Vasey, W. M., Yèche, C., & York, D. G. 2014, *Astron. Astrophys.*, 563, A54
- Pietrini, P. & Krolik, J. H. 1995, *Astrophys. J.*, 447, 526
- Plotkin, R. M., Anderson, S. F., Brandt, W. N., Diamond-Stanic, A. M., Fan, X., Hall, P. B., Kimball, A. E., Richmond, M. W., Schneider, D. P., Shemmer, O., Voges, W., York, D. G., Bahcall, N. A., Snedden, S., Bizyaev, D., Brewington, H., Malanushenko, V., Malanushenko, E., Oravetz, D., Pan, K., & Simmons, A. 2010, *Astron. J.*, 139, 390
- Pounds, K. A., King, A. R., Page, K. L., & O'Brien, P. T. 2003, *Mon. Not. R. Astron. Soc.*, 346, 1025
- Rafiee, A. & Hall, P. B. 2011, *Astrophys. J. Suppl. Ser.*, 194, 42
- Richards, G. T., Lacy, M., Storrie-Lombardi, L. J., Hall, P. B., Gallagher, S. C., Hines, D. C., Fan, X., Papovich, C., Vanden Berk, D. E., Trammell, G. B., Schneider, D. P., Vestergaard, M., York, D. G., Jester, S., Anderson, S. F., Budavári, T., & Szalay, A. S. 2006, *ApJS*, 166, 470
- Rodríguez Hidalgo, P., Hamann, F., & Hall, P. 2011, *MNRAS*, 411, 247
- Rogerson, J. A., Hall, P. B., Rodríguez Hidalgo, P., Pirkola, P., Brandt, W. N., & Filiz Ak, N. 2016, *Mon. Not. R. Astron. Soc.*, 457, 405
- Rogerson, J. A., Hall, P. B., Snedden, S. A., Brotherton, M. S., & Anderson, S. F. 2011, *New Astron.*, 16, 128

- Savitzky, A. & Golay, M. J. E. 1964, *Analytical Chemistry*, 36, 1627
- Schneider, D. P., Richards, G. T., Hall, P. B., Strauss, M. A., Anderson, S. F., Boroson, T. A., Ross, N. P., Shen, Y., Brandt, W. N., Fan, X., Inada, N., Jester, S., Knapp, G. R., Krawczyk, C. M., Thakar, A. R., Vanden Berk, D. E., Voges, W., Yanny, B., York, D. G., Bahcall, N. A., Bizyaev, D., Blanton, M. R., Brewington, H., Brinkmann, J., Eisenstein, D., Frieman, J. A., Fukugita, M., Gray, J., Gunn, J. E., Hibon, P., Ivezić, Ž., Kent, S. M., Kron, R. G., Lee, M. G., Lupton, R. H., Malanushenko, E., Malanushenko, V., Oravetz, D., Pan, K., Pier, J. R., Price, III, T. N., Saxe, D. H., Schlegel, D. J., Simmons, A., Snedden, S. A., SubbaRao, M. U., Szalay, A. S., & Weinberg, D. H. 2010, *Astron. J.*, 139, 2360
- Shakura, N. I. & Sunyaev, R. A. 1973, *Astron. Astrophys.*, 24, 337
- Smee, S. A., Gunn, J. E., Uomoto, A., Roe, N., Schlegel, D., Rockosi, C. M., Carr, M. A., Leger, F., Dawson, K. S., Olmstead, M. D., Brinkmann, J., Owen, R., Barkhouser, R. H., Honscheid, K., Harding, P., Long, D., Lupton, R. H., Loomis, C., Anderson, L., Annis, J., Bernardi, M., Bhardwaj, V., Bizyaev, D., Bolton, A. S., Brewington, H., Briggs, J. W., Burles, S., Burns, J. G., Castander, F. J., Connolly, A., Davenport, J. R. A., Ebelke, G., Epps, H., Feldman, P. D., Friedman, S. D., Frieman, J., Heckman, T., Hull, C. L., Knapp, G. R., Lawrence, D. M., Loveday, J., Mannery, E. J., Malanushenko, E., Malanushenko, V., Merrelli, A. J., Muna, D., Newman, P. R., Nichol, R. C., Oravetz, D., Pan, K., Pope, A. C., Ricketts, P. G., Shelden, A., Sandford, D., Siegmund, W., Simmons, A., Smith, D. S., Snedden, S., Schneider, D. P., SubbaRao, M., Tremonti, C., Waddell, P., & York, D. G. 2013, *Astron. J.*, 146, 32
- Smith, L. J. & Penston, M. V. 1988, *Mon. Not. R. Astron. Soc.*, 235, 551
- Trump, J. R., Hall, P. B., Reichard, T. A., Richards, G. T., Schneider, D. P., Vanden Berk, D. E., Knapp, G. R., Anderson, S. F., Fan, X., Brinkman, J., Kleinman, S. J., & Nitta, A. 2006, *Astrophys. J. Suppl. Ser.*, 165, 1
- Vanden Berk, D. E., Richards, G. T., Bauer, A., Strauss, M. A., Schneider, D. P., Heckman, T. M., York, D. G., Hall, P. B., Fan, X., Knapp, G. R., Anderson, S. F., Annis, J., Bahcall, N. A., Bernardi, M., Briggs, J. W., Brinkmann, J., Brunner, R., Burles, S., Carey, L., Castander, F. J., Connolly, A. J., Crocker, J. H., Csabai, I., Doi, M., Finkbeiner, D., Friedman, S., Frieman, J. A., Fukugita, M., Gunn, J. E., Hennessy, G. S., Ivezić, Ž., Kent, S., Kunszt, P. Z., Lamb, D. Q., Leger, R. F., Long, D. C., Loveday, J., Lupton, R. H., Meiksin, A., Merelli, A., Munn, J. A., Newberg, H. J., Newcomb, M., Nichol, R. C., Owen, R., Pier, J. R., Pope, A., Rockosi, C. M., Schlegel, D. J., Siegmund, W. A., Smee, S., Snir, Y., Stoughton, C., Stubbs, C., SubbaRao, M., Szalay, A. S., Szokoly, G. P., Tremonti, C., Uomoto, A., Waddell, P., Yanny, B., & Zheng, W. 2001, *Astron. J.*, 122, 549

- Wang, T., Yang, C., Wang, H., & Ferland, G. 2015, *Astrophys. J.*, 814, 150
- Weymann, R. J., Morris, S. L., Foltz, C. B., & Hewett, P. C. 1991, *Astrophys. J.*, 373, 23
- York, D. G., Adelman, J., & Anderson, Jr., J. E. e. a. 2000, *Astron. J.*, 120, 1579
- Zoghbi, A., Miller, J. M., Walton, D. J., Harrison, F. A., Fabian, A. C., Reynolds, C. S., Boggs, S. E., Christensen, F. E., Craig, W., Hailey, C. J., Stern, D., & Zhang, W. W. 2015, *Astrophys. J. Lett.*, 799, L24