The author on the catwalk surrounding the 3m Shane telescope at Lick Observatory

Orbital Velocities in the Broad Line Region of Seyfert 1 Galaxies

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Abstract:

Active galactic nuclei (AGNs) are among the most energetic objects in the Universe and are believed to be powered by supermassive black holes. By studying optical spectra of these AGNs, information can be acquired about the central black hole and its surroundings. Specifically the broad component of the Hβ emission line can be used to find the velocity of gas in the broad line region, a necessary step in determining the mass of the central black hole. In this thesis, I present the results of using a python code to measure the broad component of Hβ in the spectra of 78 AGNs. This broad component was found to occur in a wide range of widths and shapes, and to apparently disappear in four objects that previously had shown a broad component.

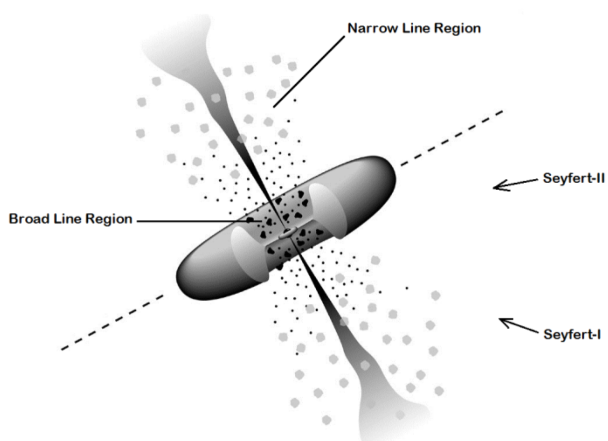
1. An Introduction to Galaxies and Their Black Holes

Active galactic nuclei (AGNs) are among the most energetic objects in our universe. They reside in the center of galaxies and are similar in size to our solar system, but produce as much or more radiation as the entire rest of their host galaxy. Because of this huge amount of energy being released, they are believed to be powered by supermassive black holes. The gravitational potential in the vicinity of the black hole is very large. In order for material, in the form of gas, dust, and possibly even larger objects like stars, to fall into a black hole, it has to lose a lot of angular momentum. Due to angular momentum preservation, the material falling toward a black hole forms an accretion disk in which the potential energy is converted into radiation. Because of that large potential difference, it should not even require that much material: a few stellar masses per year of gas and dust is all it takes to fuel the average AGN. A detailed description of AGNs can be found in Peterson (2003), and I have summarized the parts most relevant to my project here.

The optical spectra of AGNs are characterized by a number of emission lines, similar to those found in emission nebulae, with both so-called 'permitted' and 'forbidden' lines present. Lines in any emission spectrum are designated 'permitted' and forbidden' based on the quantum-mechanical lifetimes of the excited state. If the state has a short lifetime, chances are an atom will de-excite by photon emission at its natural decay rate, but if the lifetime is longer, it is more likely that the atom will de-excite in a collision first, unless the density of the environment is extremely low. The fact that AGN spectra have forbidden lines suggests that the area around the black hole probably contains low-density ionized gas, again similar to a nebula. What makes the spectra of AGNs particularly interesting, however, is the assortment of widths associated with the emission lines. In AGN spectra, forbidden lines are broader than their natural widths, but they are narrow relative to the permitted lines, which have both a 'narrow' component like the forbidden lines, as well as a typically distinct 'broad' component. This led to the idea of the gas in an AGN being split up into two distinct regions: the broad line region (BLR) and narrow line region (NLR). The gas of the NLR has the low densities necessary for forbidden lines to appear in addition to the permitted lines, but is far from the black hole so has low velocities (hundreds of km/s) associated with it. That means that lines coming from it have narrower widths, because they are not Doppler-broadened much by the bulk motion of the gas. The BLR is denser, so emits only permitted lines, but the gas is closer to the black hole so it is moving faster (thousands of km/s) and, therefore, the emissions are more Doppler-broadened.

Figure 1: Differences between the Spectra of a Seyfert-1 and Seyfert-2 Galaxy

Not every AGN is the same, however. Some AGNs have broad lines in their spectra, but some do not. Some are very luminous at radio wavelengths and are called ‘radio-loud’; others are radio-quiet instead. Some AGNs are only as bright as their host galaxy, where others are so bright they nearly drown out their host in images. This has led to a whole list of AGN classes. One of the earliest known classes of AGN are quasars. They were discovered by radio astronomers who went looking for the optical counterpart to some loud radio sources, but found objects that looked like stars aside from them having emission lines in their spectra that suggested they were extremely far away. Now we know quasars are really distant, extremely luminous, radio loud AGNs, and we’ve found quasar-like objects that are radio-quiet instead, called QSOs. Another class of AGN are Seyfert galaxies. They are AGNs that are nearby, only about as bright as their host galaxy, radio quiet, and usually occur in spiral galaxies. But even Seyfert galaxies are split up further: Seyfert 1 galaxies have broad lines in their spectra, as can be seen in figure 1, while Seyfert 2 galaxies do not!



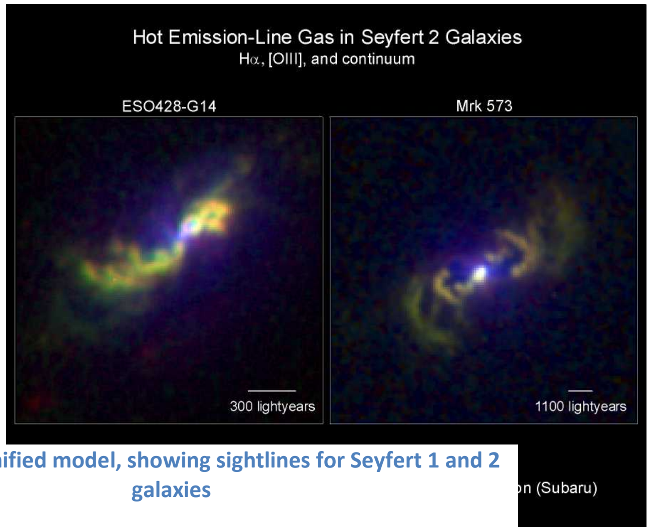


Figure 2: The unified model, showing sightlines for Seyfert 1 and 2 galaxies

Figure 3: Image showing NLR emissions for two Seyfert 2 galaxies, supporting the unified model

The fact that some types of AGN, like the two types of Seyfert galaxy, are nearly the same aside from one trait has gotten astronomers studying the possibility of a unified model that explains all AGNs as different versions of the same object. Figure 2 is a diagram of the suspected object geometry. In the center is the black hole and its accretion disk. Slightly further out is the BLR surrounded by a thick dust torus. Where light from the accretion disk can escape through the hole in the torus, it ionizes gas in two cone-shaped regions, forming the NLR. Figure 3 shows two images suggesting this cone of light. To turn this unified model into all the different types of AGN, it just requires a few tweaks. To get the high luminosity of a quasar, the black hole just needs to be accreting more material. Similarly, the difference between the Seyfert galaxies is just a matter of what angle the dust torus it tilted relative to our point of view. If we see the dust torus edge on, then the BLR is shielded from view, and we classify the galaxy as a Seyfert 2. If the view gets skewed a little, however, we can see the BLR and we see a Seyfert 1.

Having a single type of object visible all across the universe, from modern day to some of the most distant objects we can see, actually comes in rather useful in learning about their evolution, and the evolution of galaxies in general. The group I have been working with is particularly interested in how the black hole and its host galaxy are connected. An empirical relation has been found between the mass of a galaxy and the mass of its central black hole, with bigger galaxies hosting bigger black holes. Figure 4 shows where several galaxies fall on a plot of central black hole mass versus the galaxy's luminosity (which is related to the galaxy's mass). While it makes sense intuitively, that if a galaxy has more material, its black hole will also have more material, it is not obvious how the two are linked. The black hole's gravitational sphere of influence is several orders of magnitude smaller than the galaxy itself, so how do the two stay connected? Does the galaxy grow, and in turn feed the black

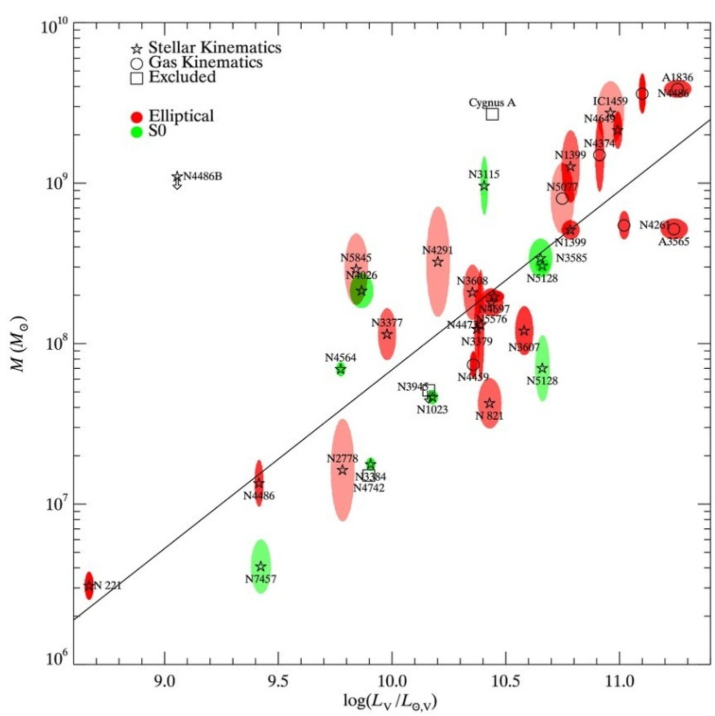


Figure 4: Graph showing the relationship between the mass of black holes and luminosity of their host galaxies

hole some of the extra material, or does a bigger black hole somehow help the galaxy gather or hold onto more material despite being so much smaller? It's a cosmological chicken-and-egg problem. Which element is leading the growth—the galaxy or the black hole—is what we hope to figure out. We want to study the relationship between the masses of galaxies and their black holes over time, since if earlier black holes tend to be heavier relative to their galaxies, this would suggest they lead the growth of the galaxy. If, instead, the earlier black holes are lighter, that would mean the galaxies grew first. The chicken and egg problem is summed up humorously in figure 5.

We can measure the masses of nearby black holes by observing the dynamics of gas and stars in their vicinity, but for black holes in the distant universe, even the best telescopes cannot resolve their spheres of influence. That's where AGNs come in. They can be seen both locally as Seyfert galaxies and in the early universe as QSOs, so we can see examples from a wide range of times. Before we can look at changes in the relationship between the masses of active galaxies and their black hole nuclei, we need to know what the relationship looks like now. This means we need to weigh some local black holes from active galaxies.

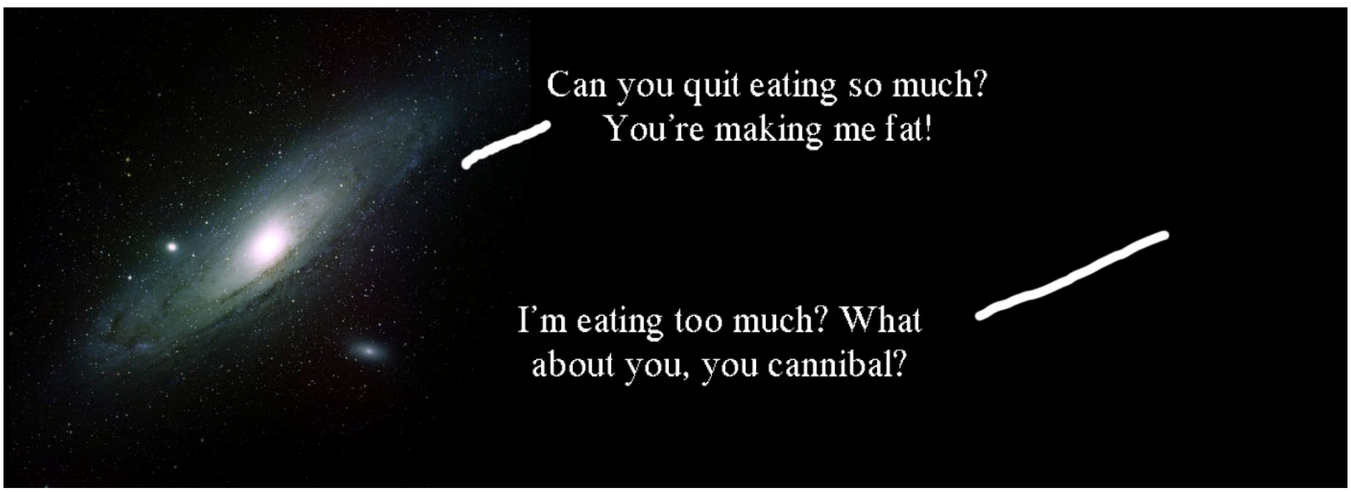


Figure 5: Which Came First, the Galaxy or the Black Hole?

2. The Theory of Weighing Black Holes

Despite the complex description of what happens near the center of a black hole, finding the mass of one is relatively easy:

$$M = \frac{v^2 r}{G}$$

Since G is the gravitational constant, to find the black hole's mass (M), you only need to know two things about a small object orbiting it: the small object's velocity (v), and how far away it is from the center of the black hole(r). Actually, this formula holds true for any system where most of the mass is in the middle, whether that center is a black hole, or even our sun.

One reason we decided to study Seyfert 1 galaxies is that they can tell us both v and r for the gas in their BLR.

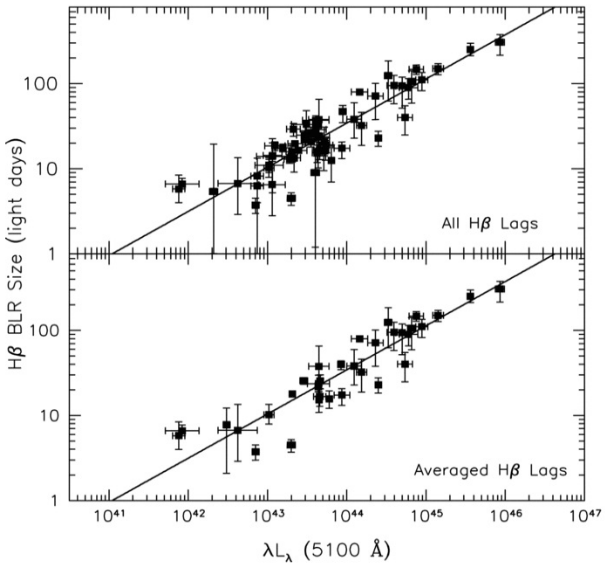


Figure 6: Data demonstrating the relationship between AGN luminosity and BLR size

Since the amount of material being accreted varies with time, the luminosity of the accretion disk also varies over time. One piece of evidence for the unified model of AGNs is how those changes in luminosity propagate, with different parts of the spectrum changing at different times. For example, in a Seyfert 1 galaxy, the continuum will be the first to increase in luminosity, it will then be followed by the broad components of emission lines getting brighter, and then the narrow lines will get brighter. This occurs because light takes time to travel. The time between the continuum luminosity increasing and the broad lines getting brighter depends on how far apart the two regions are. One hour between the changes? The BLR is, on average, one light-hour away from the accretion disk. This method of watching light propagate through the gas of an AGN is called reverberation mapping, and it is one way to get an orbital radius, in this case the radius of the BLR. I say one way, because reverberation mapping is not without issues. These changes happen over the course of several hours, which means that trying to use reverberation mapping on a large number of AGNs will require a large amount of observing time. At many telescopes, getting weeks of consecutive observing time is just not practical. Luckily, studies found that the radius of the BLR is closely related to the AGN's continuum luminosity, a relation that can be seen in graphical for in figure 6. That relation replaces many exposures with just one.

The velocity can be found from the broad emission lines that give the broad line region its name. In section 1 I mentioned that the reason the BLR emits broad emission lines is because the gas that makes it up is moving quickly. We can find out how fast the BLR gas is orbiting the hole by measuring the width of the broad component of the lines that have it. Wider broad lines means the emissions are getting red and blue shifted more, so the gas must be orbiting the black hole faster. Though it does take a good spectrograph to do well, this can also be done with one exposure, so it is also a good method for use on many black holes.


Figure 7: The Keck Telescopes on Mauna Kea

3. The Project

To build a local baseline for the relationship between the mass of galaxies and their black holes, around 100 Seyfert 1 galaxies were selected for their

broad Hβ lines in Sloan Digital Sky Survey spectra. Seyfert 1 galaxies were chosen because they are a common type of nearby AGN that show broad line emissions, and where the AGN doesn't drown out the host galaxy so severely that the galaxy can't be weighed as well. Once the objects were chosen, Keck spectra were obtained for each one. The telescope used can be seen in figure 7. A pilot sample of 25 objects has been published in Bennert et al. (2011). For the entire sample, the stellar velocity dispersions have been published in Harris et al. (2012). The goal of this thesis is to measure the velocity of the Hβ broad line for 78 objects not included in the pilot sample. Hydrogen is the most common element in the universe, so its emission lines reliably show up in all our AGN spectra. In addition, the Balmer series of lines, of which Hβ is one, consists entirely of permitted lines, so Hβ will have a broad component. Ideally, we would use Hα instead, since it is the brightest of the Balmer lines, but two facts make using that one more difficult. First, as we look at galaxies further and further away, all the emission lines from the AGNs will get shifted further into the red and infrared. Because Hα is the 'reddest' of the Balmer series, it will be the first to get redshifted into wavelength ranges that are difficult to detect from the ground. Second, and more importantly, Hα is surrounded closely by several other emission lines, so it becomes very difficult to separate the broad component of the Hα emissions from emissions in any of those other lines. Hβ is the second strongest of the Balmer series lines, and only has two strong neighboring lines that are ~50Å away rather than ~10Å, so this line is the preferred one instead.

To fit the Hβ emission line, I used one of four computer programs written in the Python programming language. All four programs fit a Gaussian to the narrow Hβ line and fit Gauss Hermite polynomials to each of the broad Hβ line and the two neighboring [OIII] lines that occurred in all of our spectra. Gauss Hermite polynomials, an expansion to a simple Gaussian profile, were used for those lines because their profiles are noticeably non-Gaussian in most of our spectra. For details on Gauss-Hermite polynomials see e.g. McGill et al. (2007) and van der Marel & Franx (1993). The difference between the four programs came from how they handled any additional lines. "hbeta_simple.py" was just that, simple. It fit the broad and narrow Hβ emissions and the [OIII] lines, and only those. "hbeta_he.py" was useful when HeII, another broadened line, was present and either overlapping Hβ or close enough to confuse hbeta_simple into fitting it as part of the broad Hβ emissions. "hbeta_fear.py" had nothing to do with being afraid of noisy spectra, though it would sometimes help with those. Normally, it helped with iron (Fe) and argon (Ar) lines that are near the Hβ line in the same way "hbeta_he.py" helped with the helium. "hbeta_force.py" is a return to just fitting the three main lines, but it lets the user put restrictions on the fit. At first it was built to deal with a handful of objects that the computer gave a broader narrow Hβ component than appeared to exist, but most of those objects turned out to have another problem with them (see below) and so I used a different solution. In the end, it was only needed on one object.

4. Results and Discussion

Below, I present the results of my measurements, broken up into groups based on large-scale difficulties in fitting the broad component of their Hβ lines. The first two 'oddball' groups are mostly qualitatively chosen examples of the wide variety of broad lines that occurred in our data, and there is some overlap between the two groups and the 'normal' spectra. I will first discuss why the group got set apart from the others and possible sources of the differences, then present plots showing the fits, and finish with tables showing the results.

A Guide to the Table Columns:

Names:

ob: Object Number, an internal index number used to call up spectra
Short RA/Dec: Hours and minutes of right ascension followed by degrees and arc minutes of declination for the object location. The full location and other object data can be found in the final section.

Output:

Model 2mom σ: a measure of the width of the broad Hβ fit from the model. The width of a line can be measured in different ways, either using the Full Width at Half Maximum (FWHM) or the second moment sigma. FWHM is the full width of the line at half of the peak value. For a Gaussian profile, FHWM relates to sigma as follows: sigma = FWHM / 2.35.However, for non-Gaussian profiles, there is no simple relationship. Taken as the velocity of gas in the BLR. Units: km/s
Data 2mom σ: a measure of the width of the broad Hβ section of the data. Units: km/s
2mom Difference: difference between the two 2mom values. A measure of the accuracy of the broad Hβ fit and used as the error*. Units: km/s
Hβ/OIII: ratio of the narrow Hβ flux to the flux of the taller [OIII] line

Input Parameters:

Special Fitter?: Was something other than hbeta_simple.py used for the fit
lo, hi: set the start and end wavelengths for the whole fit. If there was data outside this range, the program did not see it at all. Units: Angstroms
wl, wh: set the start and end wavelength for the broad Hβ fit used in the calculation of the line's width. Units: Angstroms
Horder, HorderOiii: set the order of Gauss Hermite polynomial that was used for the broad Hβ fit and the [OIII] line fits respectively.

*In many cases, 2mom Difference is a good measure of the error from the fitting process, but in the cases where it is less than 1% of the velocity (Model 2mom), difficulties in setting the fit parameters precisely outweigh the fitting error, making that the major contributor to error. If 2mom Difference is less than 1% of Model 2mom, then a 1% error was assumed.

Normal Spectra

First off are the straightforward ones. They were not always the easiest to fit, but it was easy to tell when the computer was doing a bad job, and easy to trust the computer's answer when a good fit was found. In each spectrum, black represents the data, red is the overall fit, green is the section of the broad Hβ fit used for finding the width, and blue is the result of subtracting the overall fit from the data.

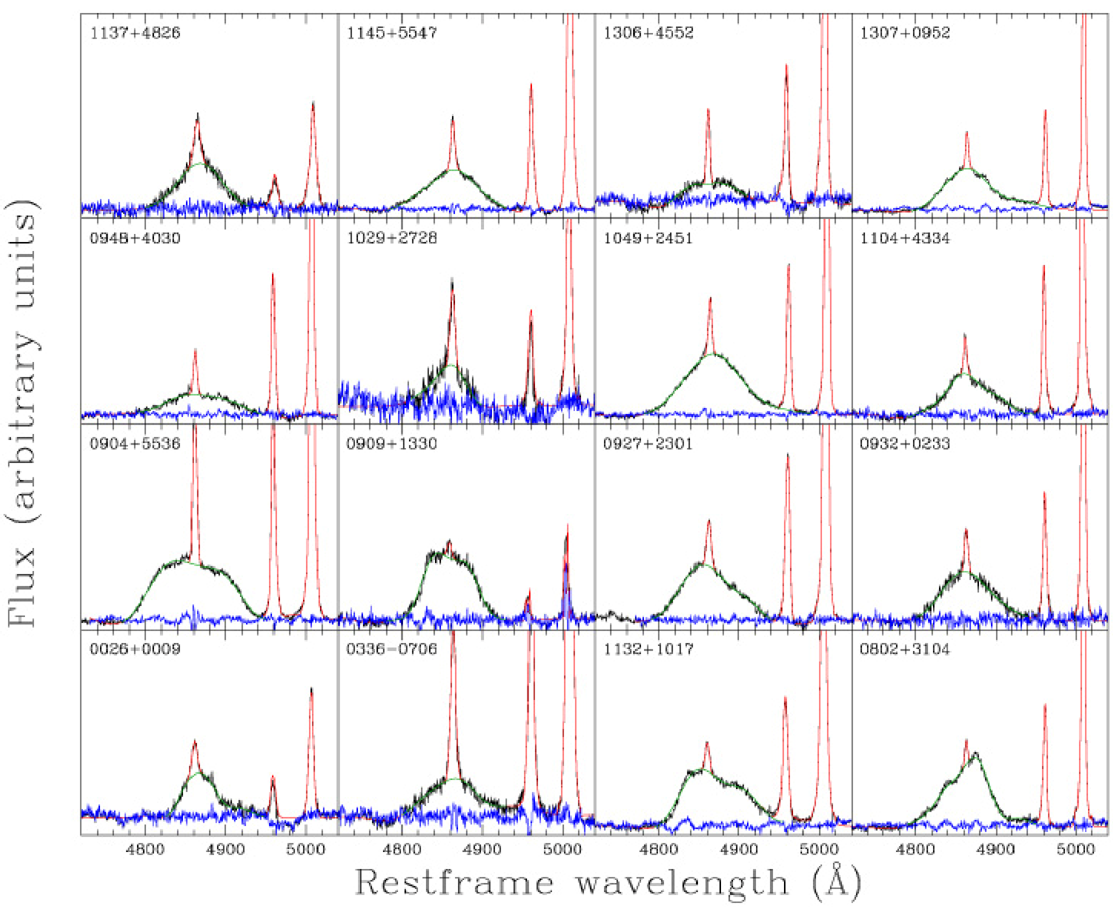


Figure 8: Fits of 'normal' spectra, part 1

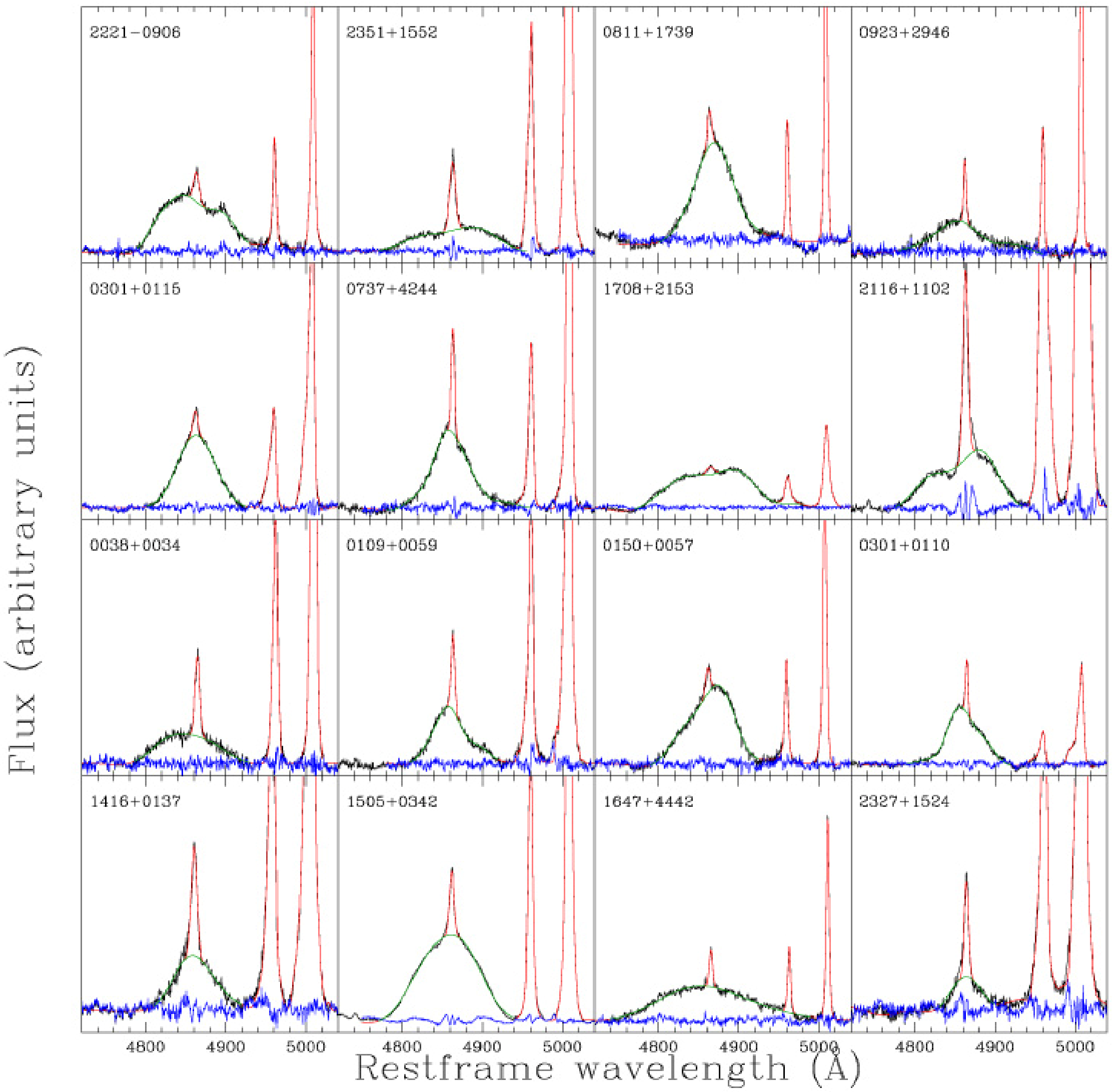


Figure 9: Fits of 'normal' spectra, part 2

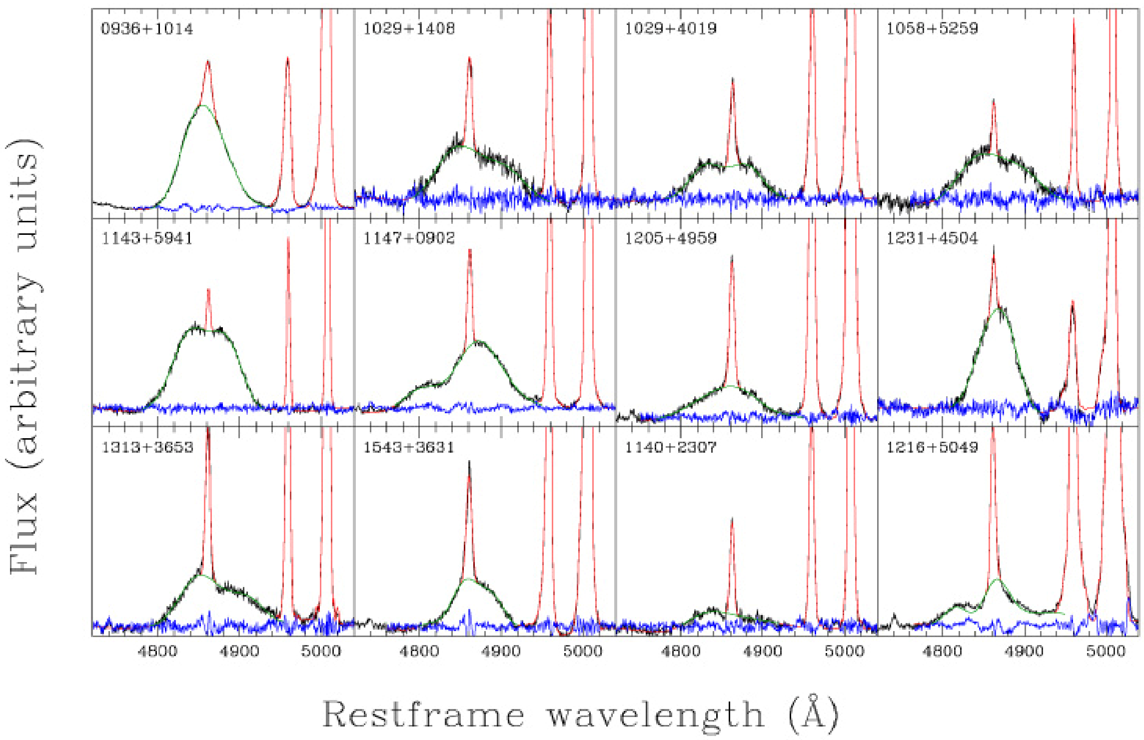


Figure 10: Fits of 'normal' spectra, part 3

Table 1: Numerical results of fitting the 'Normal' spectra, as well as parameter values used

ob	Short RA/Dec	lo	hi	wl	wh	Horder	HorderOIII	Special Fitter?	Model 2mom σ	Data 2mom σ	2mom Difference	Hβ/OIII
5	0026+0009	4600	5150	4825	4950	7	10	.	1477.2	1531.6	54.4	0.28260220
9	0336-0706	4700	5150	4800	4930	5	18	.	1742.4	1739.6	2.8	0.14959593
14	1132+1017	4720	5150	4795	4955	7	12	.	2042.0	2058.9	16.9	0.05645766
16	0802+3104	4710	5150	4790	4950	9	12	.	1776.8	1798.7	21.9	0.04392911
20	0904+5536	4730	5100	4770	4950	9	16	.	2096.1	2081.1	15	0.21186591
21	0909+1330	4600	5150	4780	4930	9	8	He	1467.1	1460.5	6.6	0.31833899
24	0927+2301	4770	5120	4790	4940	7	14	.	1881.6	1883.5	1.9	0.07990297
26	0932+0233	4600	5150	4800	4940	3	10	.	1755.8	1734.6	21.2	0.09578221
29	0948+4030	4700	5150	4790	4945	5	12	.	2112.9	2124.0	11.1	0.10274737
31	1029+2728	4600	5150	4810	4900	3	14	.	1167.3	1136.1	31.2	0.27568191
34	1049+2451	4710	5100	4780	4990	5	12	.	2227.5	2243.9	16.4	0.12262283
36	1104+4334	4600	5150	4790	4950	7	16	He	1624.6	1653.7	29.1	0.07392621
39	1137+4826	4710	5100	4800	4930	3	16	.	1593.2	1603.1	9.9	0.39147449
41	1145+5547	4600	5150	4780	4930	7	12	He	1828.5	1802.2	26.3	0.11854871
47	1306+4552	4600	5100	4810	4910	5	12	.	1388.1	1358.3	29.8	0.13361914
48	1307+0952	4710	5150	4795	4970	5	10	.	2049.1	2015.3	33.8	0.11021373
52	1416+0137	4700	5100	4810	4920	3	18	.	1440.8	1422.8	18	0.07514392
56	1505+0342	4750	5150	4770	4940	5	18	.	1958.1	1938.5	19.6	0.07198511
64	1647+4442	4600	5150	4740	4990	3	4	.	3197.5	3110.4	87.1	0.19974458
70	2327+1524	4720	5120	4830	4900	7	12	.	899.8	879.2	20.6	0.05043803
73	0038+0034	4700	5150	4785	4930	5	14	.	1846.7	1845.6	1.1	0.10643581
74	0109+0059	4780	5070	4810	4920	7	18	.	1311.0	1309.9	1.1	0.06570013
76	0150+0057	4600	5150	4790	4925	5	18	.	1589.4	1578.6	10.8	0.09752512
78	0301+0110	4730	5130	4790	4920	7	12	.	1311.9	1329.0	17.1	0.23087332
79	0301+0115	4700	5150	4800	4925	5	12	.	1368.3	1356.3	12	0.06435610
83	0737+4244	4750	5100	4780	4960	7	18	.	1615.2	1553.8	61.4	0.14112959
91	1708+2153	4600	5150	4770	4980	11	14	.	2508.9	2514.1	5.2	0.10520259
96	2116+1102	4760	5150	4775	4935	5	14	.	1952.8	1943.9	8.9	0.06986470
102	2221-0906	4700	5090	4790	4930	13	10	.	1918.9	1916.4	2.5	0.14471363
109	2351+1552	4700	5150	4770	4955	7	12	.	2423.5	2389.2	34.3	0.11352626
114	0811+1739	4750	5150	4800	4930	5	6	.	1508.9	1496.9	12	0.12265246
138	0923+2946	4720	5100	4780	4960	7	14	.	2259.8	2272.2	12.4	0.14506978
143	0936+1014	4770	5070	4790	4940	5	12	.	1477.1	1501.6	24.5	0.10071901
155	1029+1408	4700	5150	4790	4960	5	12	.	2031.8	2050.7	18.9	0.14291206
156	1029+4019	4700	5150	4780	4930	9	12	.	1815.4	1847.8	32.4	0.11737405
162	1058+5259	4760	5150	4790	4950	5	12	.	1939.9	1989.3	49.4	0.08573178
177	1143+5941	4600	5150	4780	4930	9	12	He	1772.4	1783.9	11.5	0.07369620
180	1147+0902	4730	5150	4770	4950	7	18	.	2278.1	2297.3	19.2	0.09656363
187	1205+4959	4750	5130	4770	4950	5	14	.	2093.0	2143.5	50.5	0.08845919
196	1231+4504	4600	5150	4810	4920	5	12	.	1167.0	1180.2	13.2	0.10603745
213	1313+3653	4695	5150	4790	4955	7	14	.	2084.1	2119.0	34.9	0.12686225
214	1543+3631	4760	5150	4800	4920	11	16	.	1513.7	1470.4	43.3	0.07785899
44	1216+5049	4765	5100	4785	4950	7	18	.	2064.9	2219.5	154.6	0.05883449
40	1140+2307	4700	5100	4800	4920	5	16	.	1837.4	1824.5	12.9	0.11076480

<u>Type A Oddballs: No Narrow/Broad Division</u>

The first two 'oddball' groups are mostly qualitatively chosen examples of the wide variety of broad lines that occurred in our data, and there is some overlap between the two groups and the 'normal' spectra. The type A oddballs are characterized by a lack of definition for where the narrow component of the Hβ line ends and the broad component begins. In most of the normal spectra, the broad component flattens out, and the narrow component shows up as a peak breaking through that flatness. In type A oddballs, the broad line just keeps on rising, blending into the narrow line aside from the occasional side-bumps. This makes it more difficult to find the width of just the broad component, as you have to trust that the computer fit the line properly, so you trust the results less. The fact that there is such a small difference between the broad and narrow lines could actually hold some interesting science in it, however. Because the broad section of the narrow component is nearly as broad as the narrow section of the broad component, it could be that the gap between the NLR and BLR is smaller in these objects than in the ones above. It could also be the result of viewing the AGN from a different angle.

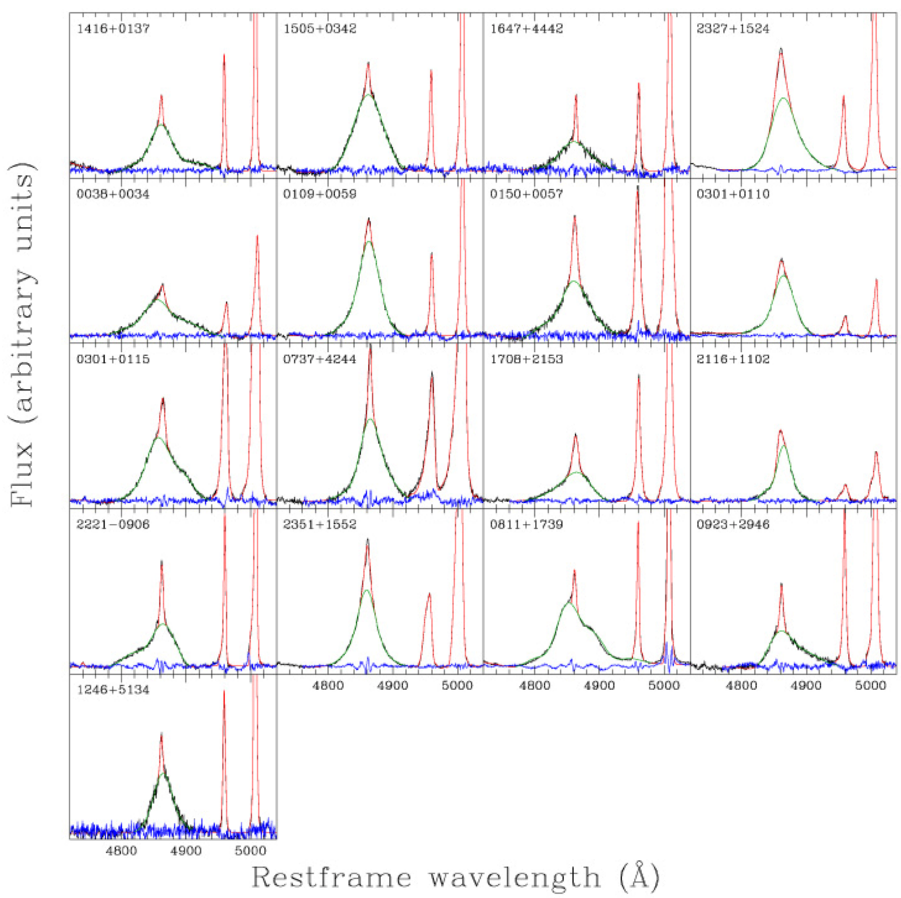


Figure 11: Fits of the type A oddballs

Table 2: Numerical results of fitting the type A oddballs, as well as parameter values used

ob	Short RA/Dec	lo	hi	wl	wh	Horder	HorderOIII	Special Fitter?	Model 2mom σ	Data 2mom σ	2mom Difference	Hβ/OIII
10	0813+4608	4600	5100	4790	4950	7	10	He	1662.3	1703.1	40.8	0.08820382
19	0857+0528	4750	5150	4790	4930	5	8	Force Width < 4	1926.1	1875.2	50.9	1.78532232
22	0921+1017	4600	5150	4800	4930	5	12	.	1458.6	1481.8	23.2	0.12420940
23	0923+2254	4760	5150	4800	4950	5	16	.	1385.0	1420.3	35.3	0.37389787
71	0013-0951	4600	5150	4780	4960	11	8	.	2003.4	1999.9	3.5	0.19131201
77	0212+1406	4740	5100	4795	4920	5	12	.	1178.3	1176.2	2.1	0.10237861
81	0731+4522	4600	5150	4780	4930	7	10	He	1592.9	1581.5	11.4	0.13141329
99	2140+0025	4700	5150	4800	4910	7	12	.	1109.2	1100.7	8.5	0.43711213
100	2215-0036	4700	5150	4790	4940	7	14	.	1536.3	1544.8	8.5	0.06722908
103	2222-0819	4760	5130	4800	4930	5	16	.	1328.8	1323.4	5.4	0.08824432
106	2233+1312	4760	5150	4785	4915	3	14	.	1481.9	1488.2	6.3	0.12526658
108	2254+0046	4600	5150	4810	4920	5	12	.	927.4	940.1	12.7	0.34238969
126	0845+3409	4600	5150	4780	4905	7	16	Fe+Ar	24.5	24.5	0	0.15569781
130	0854+1741	4760	5150	4800	4920	5	16	.	1169.5	1157.7	11.8	0.16459173
174	1139+5911	4600	5130	4770	4980	7	8	He	1985.3	1933.1	52.2	0.09298249
197	1241+3722	4770	5150	4825	4950	3	18	.	1549.3	1616.4	67.1	0.09688718
202	1246+5134	4720	5150	4820	4910	5	12	.	994.5	990.2	4.3	0.08183505

Type B Oddballs: Dents and Dings

These spectra stand out because they all show an odd dent in the broad Hβ component right next to the narrow line. This dent is significantly smaller in width than any of the other features of the broad Hβ, so it is unlikely to be just another odd shape in the broad line. It is possible that the "dents" we observe in some objects are caused by residuals when subtracting the underlying Hβ absorption lines from stars in the host galaxy. For these objects, I picked fits in which the computer ignored the dent as much as possible, hoping that the fit is a good representation of the width of the Hβ emission line.

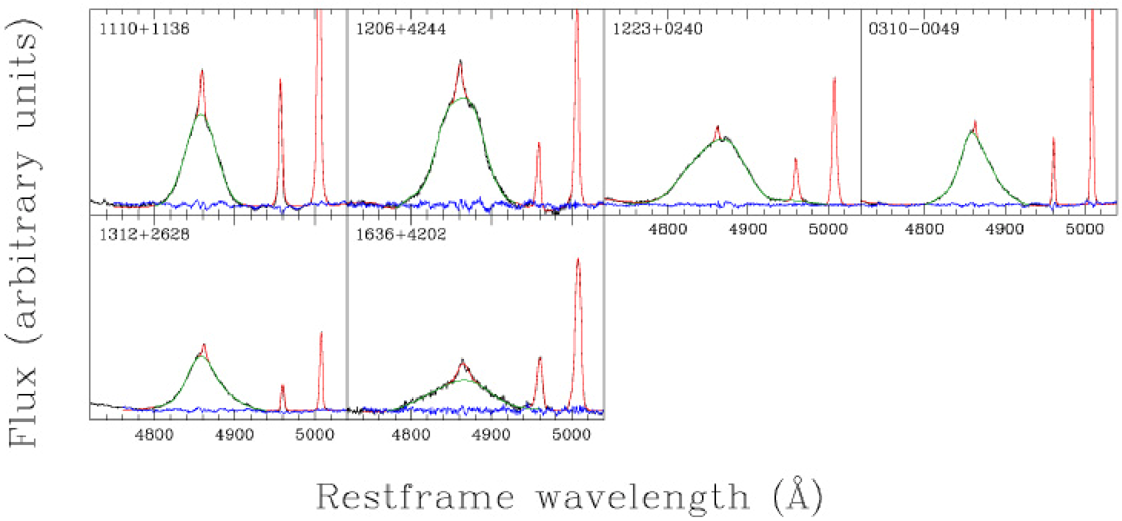


Figure 12: Fits of the type B oddballs

Table 3: Numerical results of fitting the type B oddballs, as well as parameter values used

ob	Short RA/Dec	lo	hi	wl	wh	Horder	HorderOIII	Special Fitter?	Model 2mom σ	Data 2mom σ	2mom Difference	Hβ/OIII
37	1110+1136	4750	5150	4800	4910	3	12	.	1151.4	1151.9	0.5	0.10961945
42	1206+4244	4600	5150	4780	4930	11	12	He	1569.7	1559.4	10.3	0.24528562
45	1223+0240	4600	5150	4750	5000	7	16	He	2256.1	2256.2	0.1	0.07366320
80	0310-0049	4600	5150	4800	4930	9	6	He	1310.3	1299.3	11	0.05895118
204	1312+2628	4760	5150	4800	4940	5	12	.	1433.0	1400.2	32.8	0.21403595
205	1636+4202	4740	5100	4770	4960	5	6	.	2184.9	2201.9	17	0.20032459

Type C Oddballs: Broad Line?

On most of the spectra, the broad Hβ line was very obvious, mostly because during sample selection, that was what we were looking for. However, when looking through the high-resolution spectra I was using for analysis, a few of the AGNs had broad lines that appeared to be just barely there. On these objects it was difficult to know how much of the bump under the narrow Hβ was BLR emissions and how much was noise, and with the bump just barely out of the noise, the fitting program has a lot of difficulty finding the width. Because of this, all widths listed in the table here have to be taken with caution..

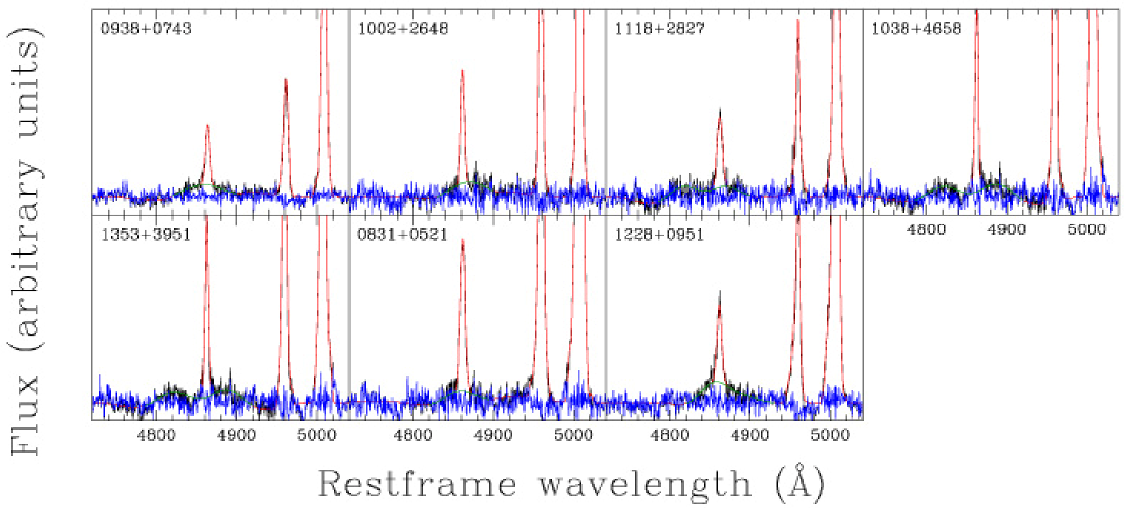


Figure 13: Fits of the type C oddballs

Table 4: Numerical results of fitting the type C oddballs, as well as parameter values used

ob	Short RA/Dec	lo	hi	wl	wh	Horder	HorderOIII	Special Fitter?	Model 2mom σ	Data 2mom σ	2mom Difference	Hβ/OIII
28	0938+0743	4600	5150	4820	4900	5	12	.	1151.1	1181.9	30.8	0.14619036
30	1002+2648	4600	5150	4830	4900	5	12	.	970.9	1020.8	49.9	0.10330833
38	1118+2827	4600	5150	4785	4900	5	12	.	1458.1	1533.2	75.1	0.15144439
157	1038+4658	4600	5150	4785	4920	5	12	.	1870.0	1573.7	296.3	0.09527951
207	1353+3951	4600	5150	4775	4895	5	12	.	1149.9	695.6	454.3	0.17916649
208	0831+0521	4600	5150	4820	4895	3	12	.	719.4	125.4	594.0	0.10322122
210	1228+0951	4600	5150	4820	4930	3	12	.	1314.1	1482.8	168.7	0.09456667

<u>Type D Oddballs: They *Had* a Broad Line</u>

These objects are the extreme versions of the type C oddballs. On these, there appears to be no broad line whatsoever. When selecting targets, all of the objects chosen had a broad Hβ line, but several years passed between the time the SDSS spectra that were used to select objects were taken, and the time the Keck spectra I have been analyzing were taken. Somehow, in that time some of the objects appeared to lose a good chunk of their BLR emissions. If the telescope wasn't properly centered on the AGN, that would result in there being no broad line emissions visible, but if it wasn't a pointing error, this is a really interesting find because it gives us an idea of the time scale on which these AGNs can change. There could be lots of dust that moved in between the AGN and Earth, blocking light from the BLR, the galaxies could now be acting like Seyfert 2 galaxies, or maybe there is much less, or no gas left in the BLR. Bryan Scott will be looking into all these possibilities in his senior thesis.

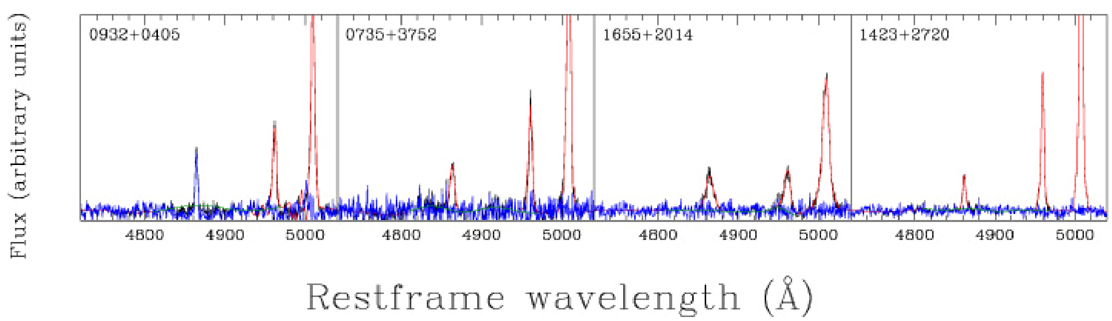


Figure 14: Attempts at fitting the type D oddballs. Note the leftmost object where the narrow Hβ line was fit as noise.

5. Conclusion:

In the end I was able to measure the velocities of gas in 74 different Seyfert 1 BLRs, but just as interesting was the simple wide variety of broad lines that are represented by my data. No two spectra are alike, and they do not seem to stay constant either. The project started with Keck spectra of 78 Seyfert 1 galaxies that had seemed to have prominent broad lines in their spectra. Out of those, four AGNs had apparently lost their broad lines in the time between their selection from SDSS spectra and the collection of the Keck spectra, and seven more might have as well. Is this a sign of a conversion from a Seyfert 1 galaxy to a Seyfert 2, a dip in the luminosity of the BLR below the sensitivity of our instruments, or simply a matter of not having the telescope pointed at the AGN? There is also more AGN science hiding in the shapes of the lines themselves. Why are some broad lines fairly Gaussian while others are almost 'm' shaped, and still others are completely lopsided? What broad line shapes stem from the geometry of the BLR or the dust torus, and what differences are the result of different viewing angles? That is for later though. Now I just have to wait for the continuum luminosity/BLR radius measurements, and then we can find some black hole masses!

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Figure 2: Figure 5 from Torres, D. F., and Anchordoqui, L. A. 2004, Reports on Progress in Physics, 67, 1663
Figure 3: http://www.astro.ru.nl/~falcke/pictures.html
Figure 4: Figure 4 from Gültekin, K., Richstone, D. O., Gebhardt, K., et al. 2009 The Astrophysical Journal, 698, 198
Figure 5: Adapted from http://www.noao.edu/image_gallery/html/im0424.html Credit: Bill Schoening, Vanessa Harvey/REU program/NOAO/AURA/NSF
Figure 6: Figure 5 from Bentz, M. C. Peterson, B. M., Netzer, H., Pogge, R. W., and Vestergaard, M., 2009, The Astrophysical Journal, 697, 160
Figure 7: http://wordlesstech.com/2010/10/29/keck-observatory-hawaii-one-in-four-sun-like-stars-should-host-an-earth-mass-planet/