A Field Guide to Unusual BAL Quasars & Other Oddities in SDSS Spectra

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ABSTRACT

The SDSS finds numerous examples of different types of unusual BAL quasars. I discuss how to recognize their spectra and estimate their redshifts. A few other oddities are also discussed.

1. Introduction

For detailed discussions of the categories of "odd BALs" discovered to date seeHall et al. (2002),[1] but note that a few objects are presented here for the first time. IRAF users may find my PHIST package useful for inspecting SDSS spectra: http://astro.princeton.edu/~pathall/PHIST/phist2.tar.gz

2. "Normal" BAL Quasars: HiBALs, LoBALs, FeLoBALs

BAL quasars are divided into three observational subtypes depending on what type of transitions are seen in absorption. Two of these three subtypes are illustrated and discussed in Fig. 1. (A list of relevant transitions with rest frame λ>1215 Å is given in Table 1 of Hall et al. 2002.)

High-ionization BAL quasars (*HiBALs*) show absorption from C IV $\lambda\lambda$1548,1550; N V $\lambda\lambda$1238,1242; Si IV λ1393,1402; and Lyα λ1215 (in order of decreasing typical strength). Low-ionization BAL quasars (*LoBALs*) exhibit the above high-ionization absorption and absorption in Mg II $\lambda\lambda$2796,2803, Al III $\lambda\lambda$1854,1862, Al II λ1670 and sometimes Fe II, Fe III and other low-ionization species, again roughly in order of decreasing strength. Note that the absorbing gas has a range of ionization states even in HiBALs. The observed range simply extends to lower ionization states in LoBALs. The rare Iron LoBALs (*FeLoBALs*) are LoBALs which also show absorption from excited fine-structure levels or excited atomic terms of Fe II or Fe III.

The SDSS pipeline does moderately well with identifying and assigning redshifts to HiBALs, and OK with LoBALs. But the pipeline doesn't know what to do with the more extreme examples. For example, Fig. 2a shows a BAL in which the emission lines appear completely absorbed, leaving only a reddish continuum and strong absorption. Because of such absorption, BAL quasar spectra are easy to identify, even in strange-looking cases like this one. So I will concentrate here on determining approximate redshifts.[2]

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[1]Available at http://www.astro.princeton.edu:81/pathall/SBALS/sb1submit1_11pt.ps

[2]Many of these objects' exact redshifts will be impossible to determine without detecting narrow emission or absorption from their host galaxies, via the near-IR and/or careful spatially resolved spectroscopy. What we're interested in here is redshifts good to $\pm$0.01, which is almost always possible.

Looking for the transitions listed two paragraphs ago is the best way to start. That's all you need to decipher Fig. 2a: a quick test shows that the 5600 & 6700 Å troughs are C IV & Al III respectively, so $z = 2.63$. Most of the unusual BAL quasars can be identified by just adding five strong Fe II lines to the search list: 2344, 2374/2382, 2586/2600 Å. Occasionally you must also consider excited Fe II absorption. The most common Fe II multiplets form troughs with red limits of 2414 Å (multiplets UV2,UV3), 2632 Å (UV1), and ∼2750 Å (UV32,62,63). For example, Fig. 2b shows a reddened FeLoBAL at $z = 2.33$: C IV is at ∼5000 Å, Al III at ∼6000 Å, and excited Fe II just blueward of 8000 Å.

The following sections illustrate the categories of unusual BAL quasars identified to date.

3. Extremely Reddened

Quasars are thought to have intrinsically blue spectra, but if sufficient dust is present along the line of sight they can be quite red. Not all extremely reddened quasars are BAL quasars, but there is a subset of extremely reddened BAL quasars with weak line emission at best, and sometimes with absorption at multiple redshifts (Fig. 3). For such objects, I use the red edges of the absorption troughs to estimate the systemic redshift. Obviously the highest-redshift trough should be used if more than one absorption system is present. Alternatively, the C III] λ1908 line can be used, if it is strong enough and not affected by absorption.

We have also found examples of extremely reddened BAL quasars with strong Fe II emission (Fig. 4). (Technically, the very narrow troughs make these *mini-BAL* quasars.)

4. Many-Narrow-Trough

Some BAL quasars have (relatively) narrow troughs which are present for dozens of transitions, mostly Fe II transitions (Fig. 5). But the strong transitions present in normal BAL quasars (C IV, Mg II, etc.) are still present, so determining a redshift is actually straightforward. Again, this can be done from the red edges of the absorption troughs, if no unabsorbed broad lines are present. And in some cases narrow emission and/or absorption from the host galaxy can be used to set the redshift (Fig. 7). (But don't be fooled by magnetic carbon (DQ) white dwarfs, which can resemble such BALs; see Fig. 6).

5. Overlapping-Trough

An overlapping-trough BAL quasar can be thought of as a many-narrow-trough quasar in which the gas has a higher terminal velocity, so that the troughs are no longer narrow, and in fact overlap to cause almost complete absorption below Mg II $\lambda\lambda$2796,2803 (Fig. 8). In some of these objects (including this one), associated narrow Mg II absorption is present, and can be used to set the redshift. In others, the troughs do not have sharp red edges, so that the redshifts estimated from the red edges of the troughs are more uncertain than usual. But Mg I λ2852 absorption is present in almost all of these objects, which can help confirm the redshift from Mg II $\lambda\lambda$2796,2803. Finally, if the BAL gas does not cover the continuum source (*partial covering*), the troughs can be saturated without reaching zero flux (Fig. 9).

6. Fe III Dominant

One luminous SDSS FeLoBAL has absorption from Mg II and Al III, but instead of Fe II absorption it shows Fe III absorption (Fig 10). The strongest common Fe III multiplets are the triplets UV34 $\lambda\lambda\lambda$ 1895.5,1914.056,1926.3 and UV48 $\lambda\lambda\lambda$ 2061.5,2068.2,2079.0. We also have a few fainter examples of Fe III-dominant BAL quasars. One is shown in Fig. 11; see Hall et al. (2002) for a few more.

7. Mysteries

The SDSS has discovered a few objects to date with strange continuum shapes that drop off steeply shortward of Mg II. Fig. 12 shows the first two of these; both have narrow Mg II which provides a good redshift,[3] and in SDSS 0105-0033 narrow [O II] emission confirms the Mg II absorption z.

Two possibly similar objects are shown in Fig. 13. The top one has a Mg II BAL trough just blueward of Mg II+Fe I+Fe II emission, as seen by comparision to Figs. 8 & 9 as well as Fig. 12. I estimate $z = 0.82$ from Mg II and possible Hβ. The bottom one is less certain, and begins to hit the limits of what we can estimate, even knowing that the object must be a quasar because it doesn't look like any known star or galaxy. But I would give $z = 1.24$ as a low-confidence redshift, based on weak C III] λ1908, the red edge of a possible Mg II BAL trough, and the 'notch' in the spectrum near 6800 Å which matches the gap between Fe II emission complexes seen at rest-frame 3050 Å in the top spectrum, in the spectra of the mystery objects, and in other Fe II-strong quasars.

8. Summary

If a spectrum you don't understand has absorption and you think it might be a BAL quasar:

1) Check for Mg II plus Fe II absorption: 2586/2600, 2374/2382, 2344.

2) If the wavelengths almost match, but not quite, consider excited Fe II absorption, which is most commonly seen in the form of troughs with red limits of 2414 Å, 2632 Å, and ~2750 Å.

3) Check for Mg II plus Fe III absorption: UV34: 1895/1914/1926 Å and/or UV48: 2061/2068/2079 Å.

4) If you have identified any of the above absorption, and there are no emission lines unaffected by absorption, consider using the red edges of the absorption troughs to define the object's redshift, using the highest-redshift trough if there is more than one. (You can also use narrow emission lines if they are present.)

Still no luck? Remain calm.

1) If there is narrow absorption near a broad emission line or a broad maximum in the spectrum, check to see if the absorption wavelengths match the Mg II or C IV doublets, or ground-state Fe II (§2). This is usable as a low-confidence redshift (cf. §7), though technically it is just a lower limit to the redshift.

2) Don't forget to compare to rare types of stars, particularly magnetic and/or C-rich WDs. In particular, late-type subdwarfs (Fig. 14a) can mimic the appearance of BAL quasars.

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[3]The redshift of 2204+0031 was later re-estimated by cross-correlation, which is why Mg II is "off" in the Figure.

3) Check if it could be a problem in the data or the reductions.

4) Check if it resembles anything on Scott Anderson's odd-objects web page: http://www.astro.washington.edu/anderson/sdss/serendip/odd_spectra.html ...this page keeps fairly complete notes on the various ideas that people have had of the identification of unusual objects.

5) If you find something unclassifiable or otherwise extreme, post to sdss-serendip; myself, Scott, and others interested in weird objects subscribe to that low-traffic group and can help try and figure it out.

Scott's page lists all the people who have contributed to understanding weird SDSS spectra. Thanks!

A. Non-BAL Oddities: Supernovae

Spectrum 438/51884-462 (Fig 14b) is clearly a galaxy (Ca II absorption, narrow [O II] & Hα+[N II] emission) but has strong broad features in the blue from a supernova. Other examples include 271/51883-171 and 304/51609-436.

B. Non-BAL Oddities: Superpositions

The spectrum 399/51817-245 (Fig. 15) is a superposition of a late K or early M star with a z=2.8215 quasar; the quasar is obvious because of the Lyα forest absorption. The spectrum 401/51788-550 (Fig. 16) is a superposed late M star and z=1.32 quasar. Note that the similar object 619/52056-437 is not a superposition, but rather an M dwarf in a binary system; the broad emission lines are cyclotron features and are variable. The spectrum 313/51673-481 (Fig. 17) is not a quasar, but an F + M star superposition.

C. Non-BAL Oddities: BL Lacs / Weak-Lined Quasars

Since their spectra are dominated by nonthermal continuum emission, by definition it is difficult to determine redshifts for BL Lacs. Nonetheless, in some cases stellar absorption features are seen, so a redshift can be assigned even though the spectrum may not look like a galaxy. Fig. 18a shows such a case, which is one of the reddest BL Lacs we've found. Fig. 18b shows one of the bluest, just for reference. I don't see how even the inspection part of the pipeline can say anything about this object: z is unknown, and I say it's probably a BL Lac rather than a hot hydrogen-free white dwarf only because it's a ROSAT source. Of course, WDs can be X-ray sources too, so only extensive study will conclusively show what this object is.[4]

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[4]I worry that we miss some interesting WDs by dismissing them as BL Lacs, as follows. Spectrum 668/52162-543 is 'clearly' a BL Lac, since it is a QSO, FIRST and ROSAT target with a featureless spectrum. But it appears to show absorption at 9000Å which is also seen in the BL Lac candidates 633/52079-518 and 584/52049-553, and weakly in 712/52199-123 (Fig. 18b) and 411/51817-138. If this is a real feature then these objects must all be stars. Many BL Lac candidates also show possible emission just redward of 6000Å: 584/52049-553, 281/51614-638, 668/52162-543, and possibly 411/51817-138. Again, if this is real it means these objects are stars; however, some known reduction artifacts are occasionally seen 6000Å. I am inclined to consider both the 6000Å and 9000Å features as artifacts, but someone may want to investigate this further. cf. weird BL Lacs from 2dF: http://www.noao.edu/perl/abstract?2002A-0070

By weak-lined quasars I refer to objects that seem to be extragalactic but are not radio or X-ray sources (and thus are not obviously BL Lacs) and whose continua show some weak broad features (some BL Lacs may also have features, so the division is not a sharp one). We know of a few high-redshift examples where the redshift is given by the onset of the Lyα forest (e.g. Fan et al. 1999), but at lower redshifts these objects can be just as puzzling as BL Lacs. For these objects' redshifts one must rely on broad continuum features and/or any narrow absorption lines present. The strongest broad continuum features are at $\sim$2300Å and $\sim$3200Å: Fe II emission is present redward of those wavelengths but not blueward; thus, as you move from blue to red around those wavelengths the continuum increases to a higher level (spectrum 278/51900-270 is a good example; if you removed this object's narrow Mg II emission you'd have a weak-lined quasar).

Examples of weak-lined quasars are shown in Fig. 19. Spectrum 535/51999-453 has narrow C IV doublet absorption at $z = 1.589$. This might suffice as a low-confidence redshift. Of course, it is only a lower limit since the absorption could be intervening. But I estimate $z = 1.66$ from a careful look at the spectrum, which is not far off the C IV redshift. Spectrum 512/51992-511 has $z = 1.707$ from Fe II absorption; there is also weak C IV emission just redward of 4000Å, and weak Mg II emission near 7600Å. The dip at 6000Å is the gap just blueward of the 2300Å Fe II emission complex. Spectrum 402/51793-400 (also 699/52202-518) is less of a success story. It has $z > 0.594$ from narrow Mg II doublet absorption, but no redshift fits particularly well. Optical colors are consistent with $z = 2.04$ or $z = 2.23$ (but 2MASS NIR colors are much bluer than normal quasars). Here is a case where a (low confidence) $z = 0.594$ based on Mg II absorption probably grossly underestimates the redshift, but where we don't really have a better guess we can stand behind.

Other possible weak-lined quasars include 288/52000-276 (probably a hot star similar to 503/51999-244 or 644/52149-348); 289/51990-434 (z=2.084); 364/52000-610 (z=1.06?); 395/51783-380 (z=2.06??); 584/52049-390 (z$\geq$1.685 from narrow absorption lines).

D. Non-BAL Oddities: Odd Quasars

If the wavelengths of numerous lines match, an object can be identified as a quasar even if the line ratios are strange, since quasars have a wide range of relative line strengths. For example (Fig. 20), 523/52025-431 at z=1.84 has Ne III] λ1750 Å $\gg$ C III] λ1908 Å, and 782/52320-351 at z=1.295 has extremely strong & narrow Fe II emission.

REFERENCES

Fan, X., Strauss, M. A., Gunn, J. E., Lupton, R. H., Carilli, C. L., Rupen, M. P., Schmidt, G. D., Moustakas, L. A., et al., 1999, ApJ, 526, L57

Hall, P. B., Anderson, S. F., Strauss, M. A., York, D. G., Richards, G. T., Fan, X., Knapp, G. R., Schneider, D. P., et al., 2002, ApJ, submitted

Schneider, D. P., Richards, G. T., Fan, X., Hall, P. B., Strauss, M. A., Vanden Berk, D. E., Gunn, J. E., Newberg, H. J., et al., 2001, AJ, in press (astro-ph/0110629)

White, R. L., Becker, R. H., Gregg, M. D., Laurent-Muehleisen, S. A., Brotherton, M. S., Impey, C. D., Petry, C. E., Foltz, C. B., et al., 2000, ApJS, 126, 133

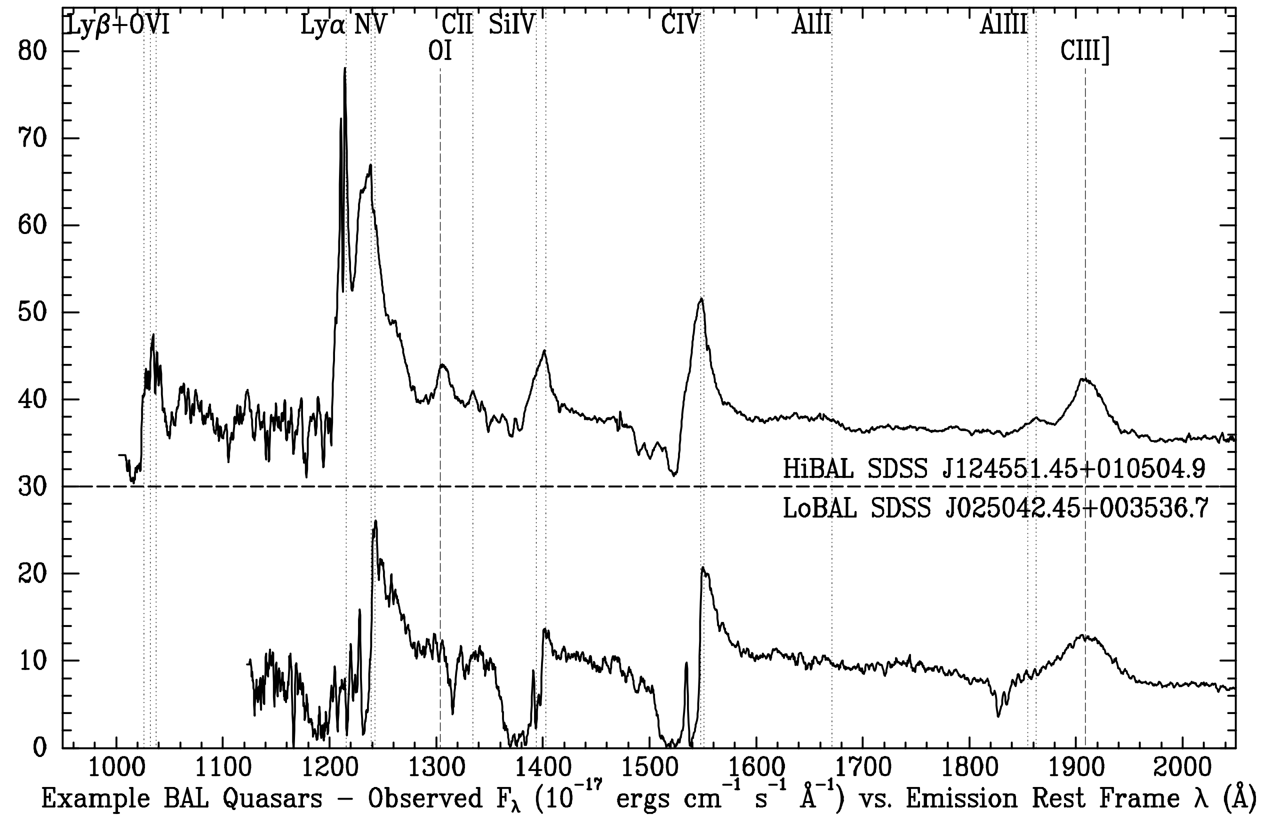


Fig. 1.— Rest-frame spectra of two illustrative BAL quasars from the SDSS Early Data Release quasar sample (Schneider et al. 2001). The top spectrum is the HiBAL SDSS J124551.45+010504.9 (LBQS 1243+0121), with absorption in C IV, O VI, N V, Si IV, and Lyα. The bottom spectrum is the LoBAL SDSS J025042.45+003536.7. Its spectral coverage does not include O VI, but all other species seen in absorption in the HiBAL are present, as well as Al III, C II, and possibly very weak Al II. (The spectral coverage does not include Mg II.) These spectra help illustrate the range of properties seen in BAL outflows. The absorption does not go to zero in either object (partial covering), though it does come close. In the HiBAL, the C IV and Si IV trough profiles are similar but not identical: both appear somewhat detached from the emission line, but C IV is deeper at the lowest outflow velocities. The weak Lyα absorption shows that the BAL outflow is highly ionized. In the LoBAL, the Al III and C II troughs are narrower and weaker than the C IV and Si IV troughs. Usually they appear weaker due to lower partial covering, but without high-resolution spectra the possibility of unsaturated low-ionization troughs cannot be ruled out. There appear to be two systems in the outflow: a narrow low-velocity system which is highly ionized (weak C II, strong N V) and a broad high-velocity system which includes the bulk of the low-ionization absorption, accompanied by strong Lyα absorption. This LoBAL is slightly unusual in that respect: low-ionization absorption is usually strongest at the lowest outflow velocities.

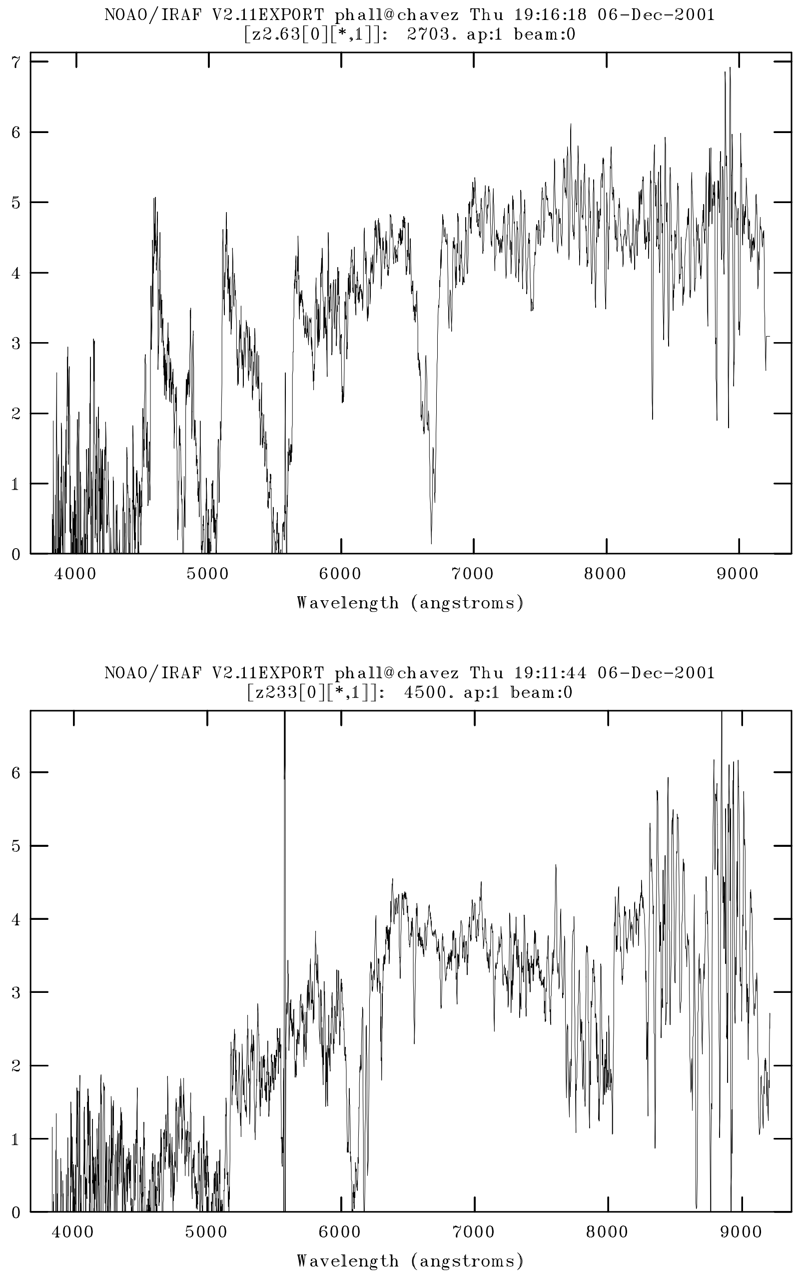


Fig. 2.— a) A reddened LoBAL at $z = 2.63$; the 5600 & 6700 Å troughs are C IV & Al III respectively. b) A reddened FeLoBAL at $z = 2.33$: C IV is at ∼5000 Å, Al III at ∼6000 Å, and excited Fe II just blueward of 8000 Å. There is more Fe II lost in the noise around 8700 Å, and Mg II at the very red end.

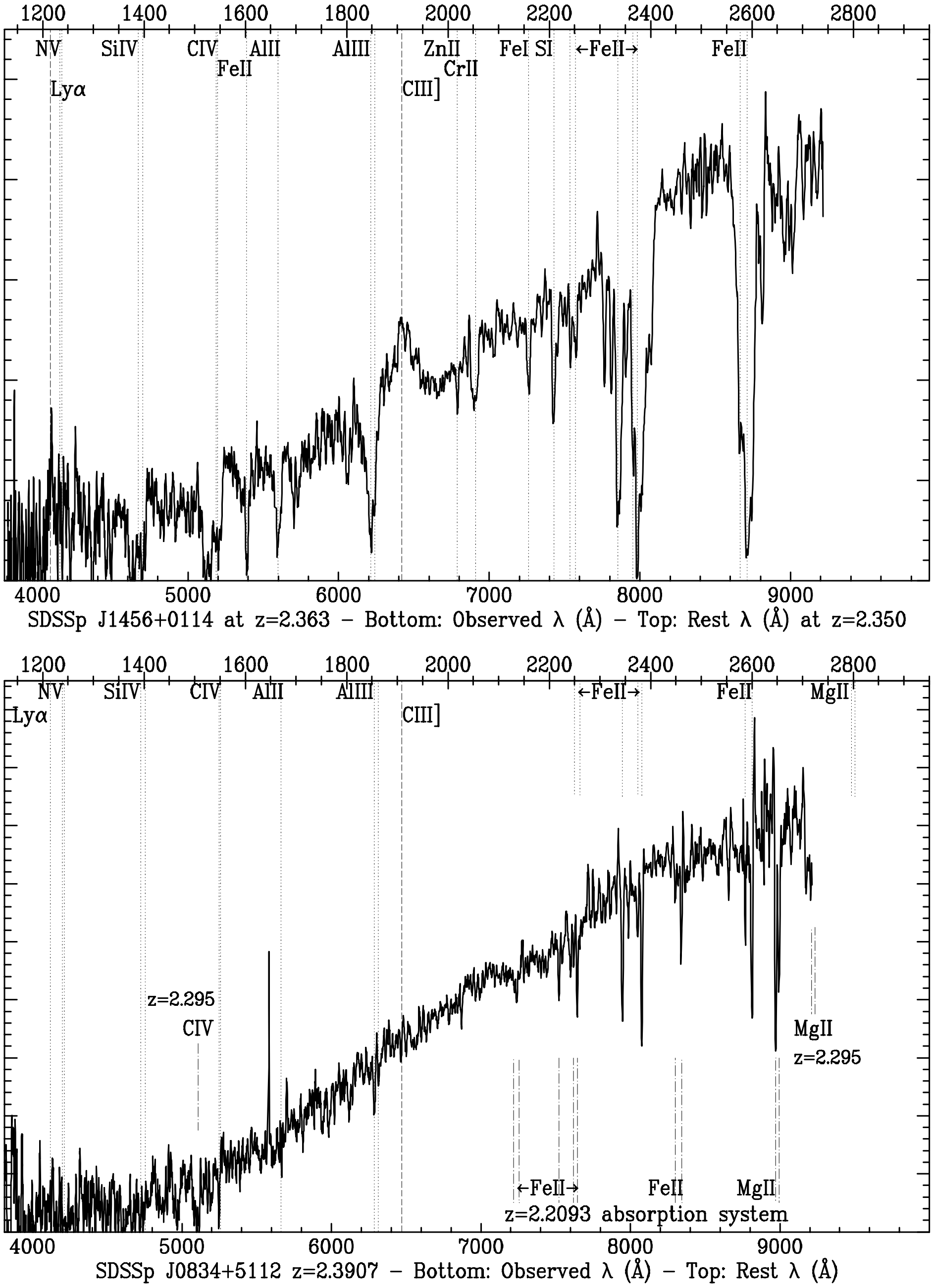


Fig. 3.— Extremely Reddened BAL quasar spectra, smoothed by a 7-pixel boxcar. Observed wavelengths are shown on the bottom axes, and rest frame on the top. Dashed lines show emission, and dotted lines absorption. a) SDSS 1456+0114 at $z = 2.363$. The absorption lines are identified at $z = 2.350$, the redshift of peak absorption. b) SDSS 0834+5112 at $z = 2.3907$. Absorption lines at this redshift are identified above the spectrum, while absorption lines from the $z = 2.295$ and $z = 2.2093$ systems are identified by dot-dashed lines in the bottom half of the figure.

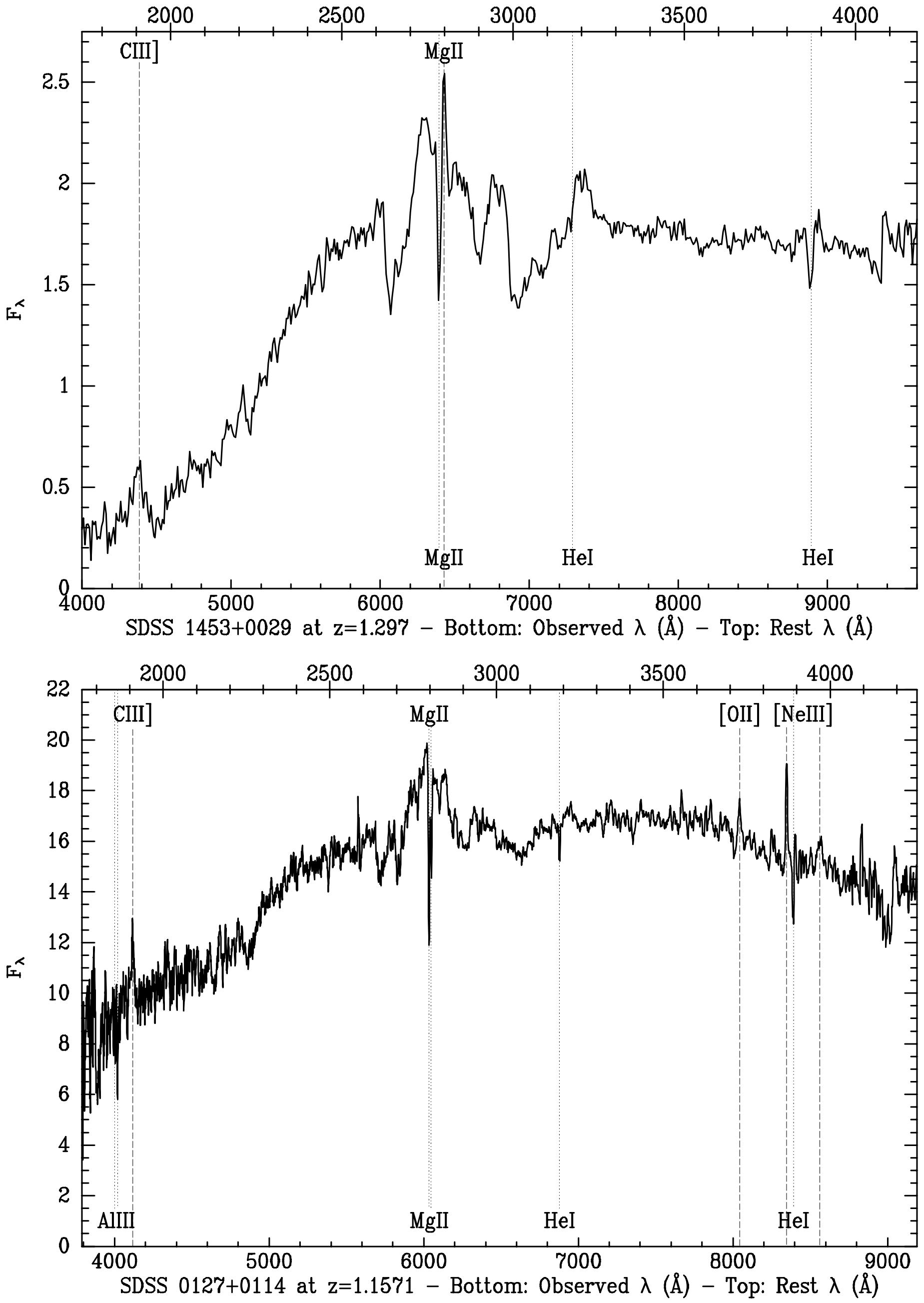


Fig. 4.— Extremely reddened BAL quasars with strong Fe II emission. a) SDSS 1453+0029, a mini-LoBAL quasar at $z = 1.297$. What look like absorption troughs at 2650, 2900, and 3000-3200 Å are actually gaps between Fe II emission complexes. b) SDSS 0127+0114, a mini-LoBAL quasar at $z = 1.1571$. In this object narrow emission lines help confirm the redshift. In both plots, dashed lines denote emission, and dotted lines absorption. The absorption lines are identified along the bottom of each plot and the emission lines along the top.

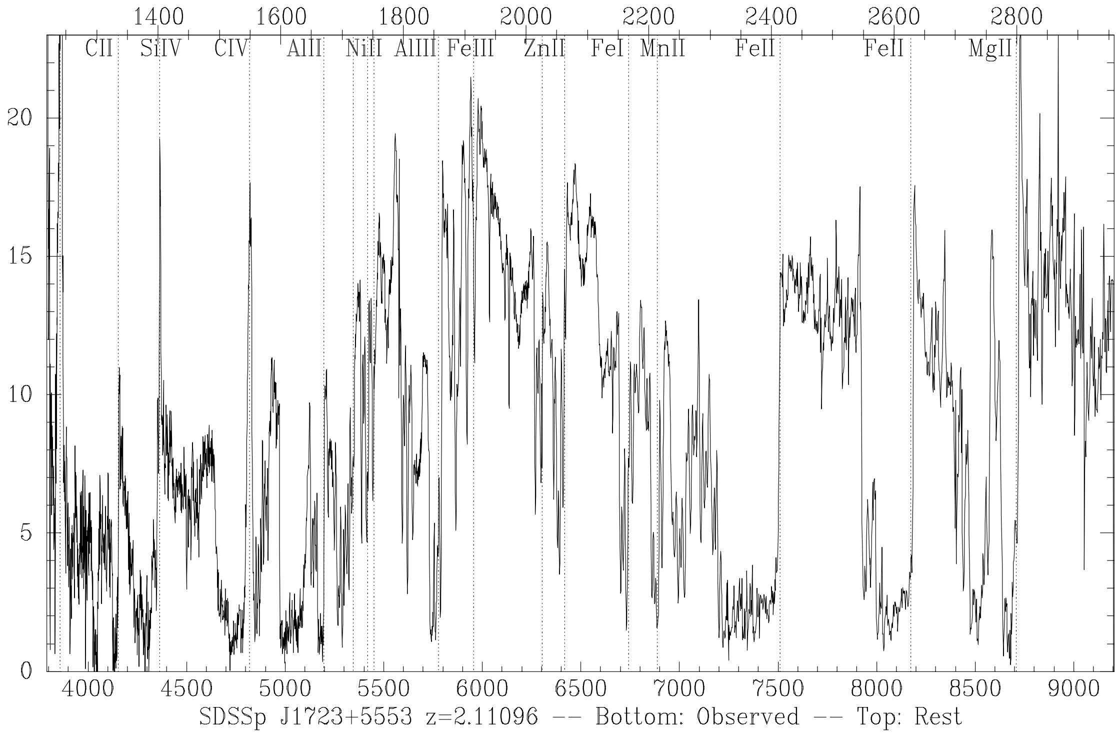


Fig. 5.— Many-Narrow-Trough BAL Quasar SDSS J1723+5553 at z=2.11. This initial redshift came simply from Fe II 2414 & 2632 plus Mg II. The final adopted redshift was $z = 2.1127$, from fitting the narrow Si IV and Mg II emission lines.

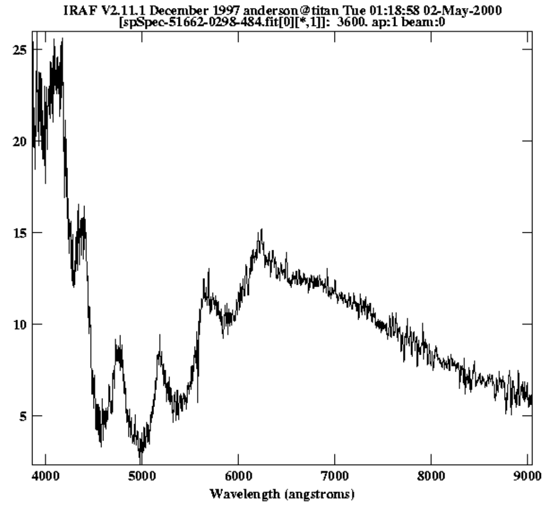


Fig. 6.— Spectrum 298/51662-484, a magnetic carbon (DQ) white dwarf, similar at first glance to the many-narrow-trough BALs on the next page.

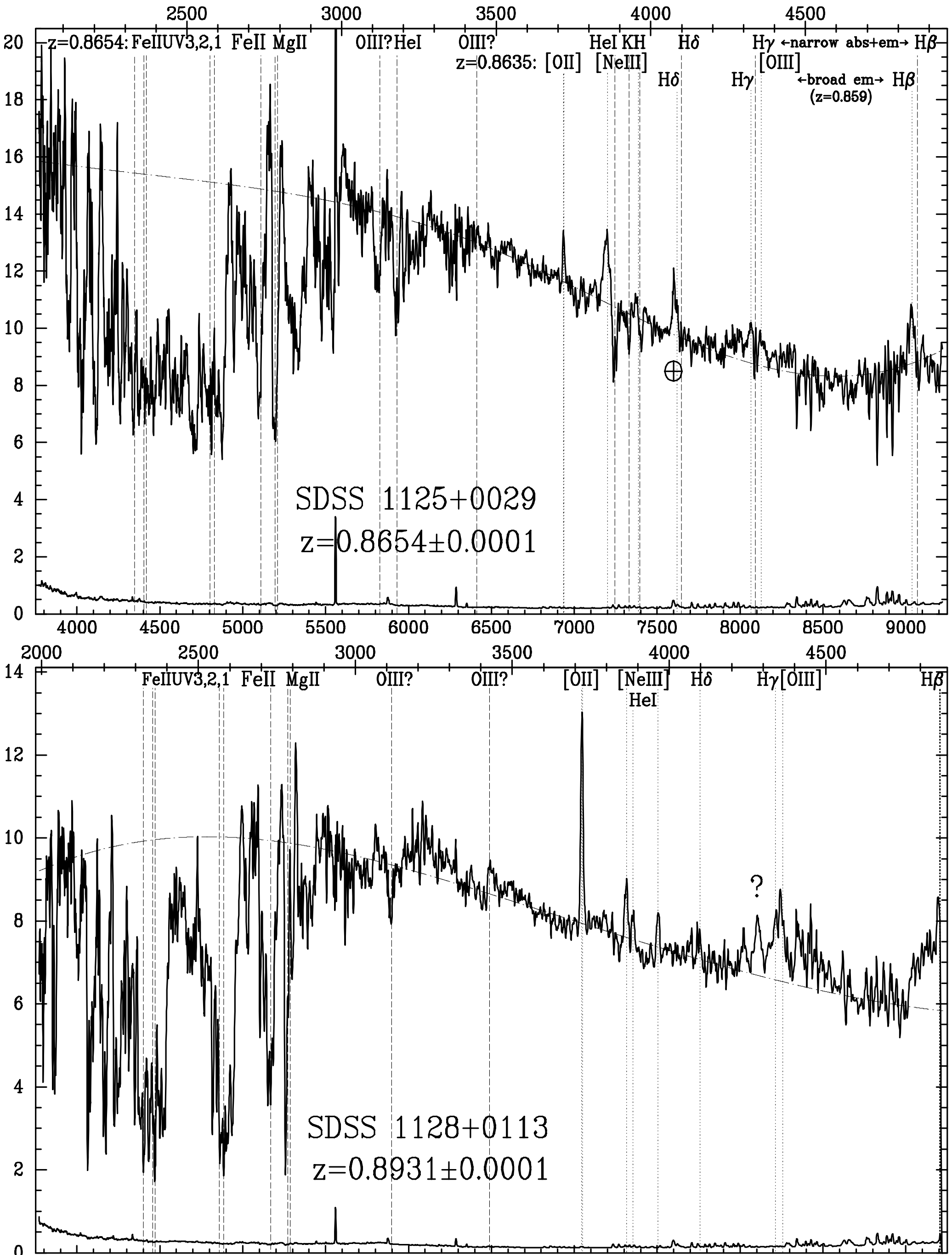


Fig. 7.— Many-Narrow-Trough BAL Quasars a) SDSS 1125+0029 and b) SDSS 1128+0113 (Observed F_λ vs. rest frame λ in Å at the top and observed frame λ at the bottom). All spectra and error arrays (lower curves) have been smoothed by a 5-pixel boxcar filter. For these objects, the [O II] and other emission & absorption lines from the host galaxies give good redshifts; the BAL absorption serves only to classify the objects as quasars. Dotted vertical lines show the wavelengths of emission lines and dashed vertical lines show the wavelengths of absorption lines. Between 2300−2600 Å rest frame, the strongest lines of Fe II multiplets UV1, UV2, and UV3 have been marked, but each is surrounded by many unmarked Fe II lines. The dot-dashed lines show the continuum fits used to calculate the balnicity index.

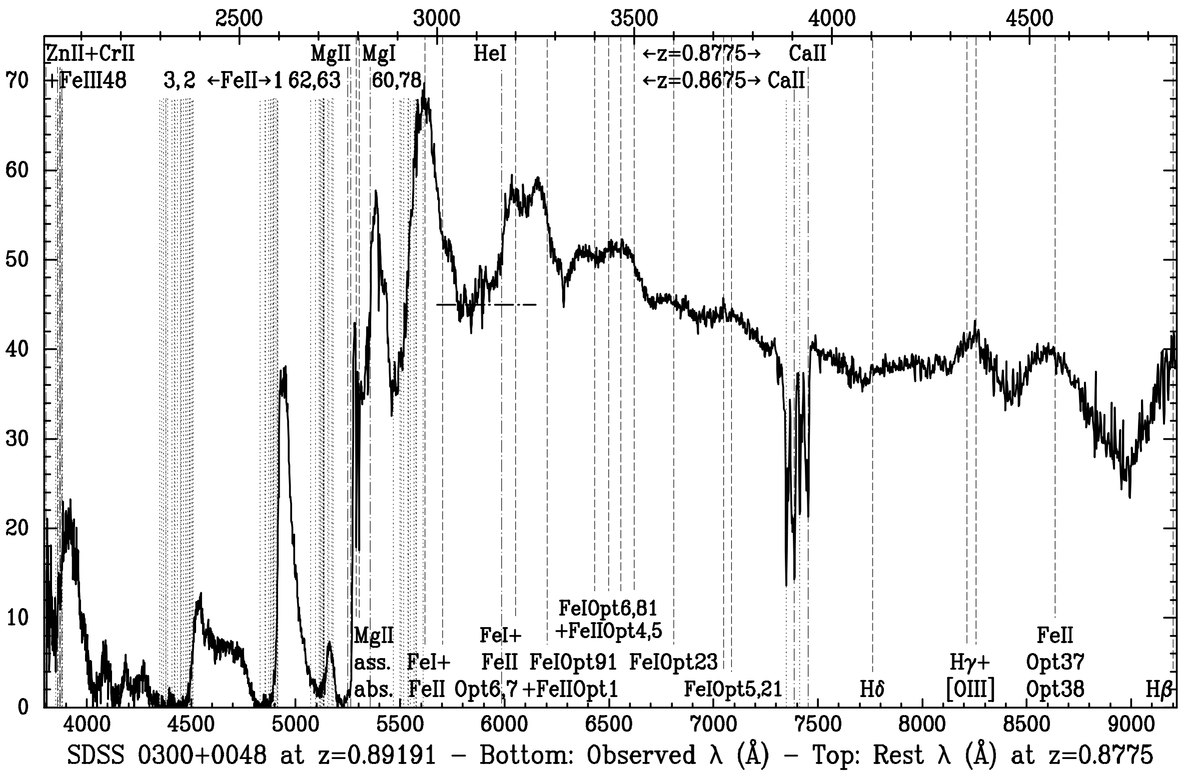


Fig. 8.— SDSS 0300+0048, an overlapping-trough FeLoBAL at $z = 0.89191 \pm 0.00005$. This assumed systemic redshift is taken from the associated Mg II system, but accurately predicts the wavelengths of broad emission features longward of Mg II (dashed lines labelled along the bottom of the plot).

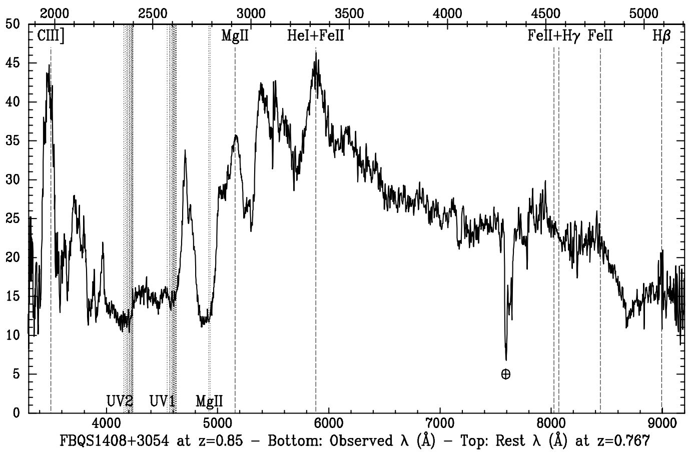


Fig. 9.— A non-SDSS spectrum of the overlapping-trough BAL quasar FBQS 1408+3054 (White et al. 2000), showing saturated troughs which do not reach zero flux.

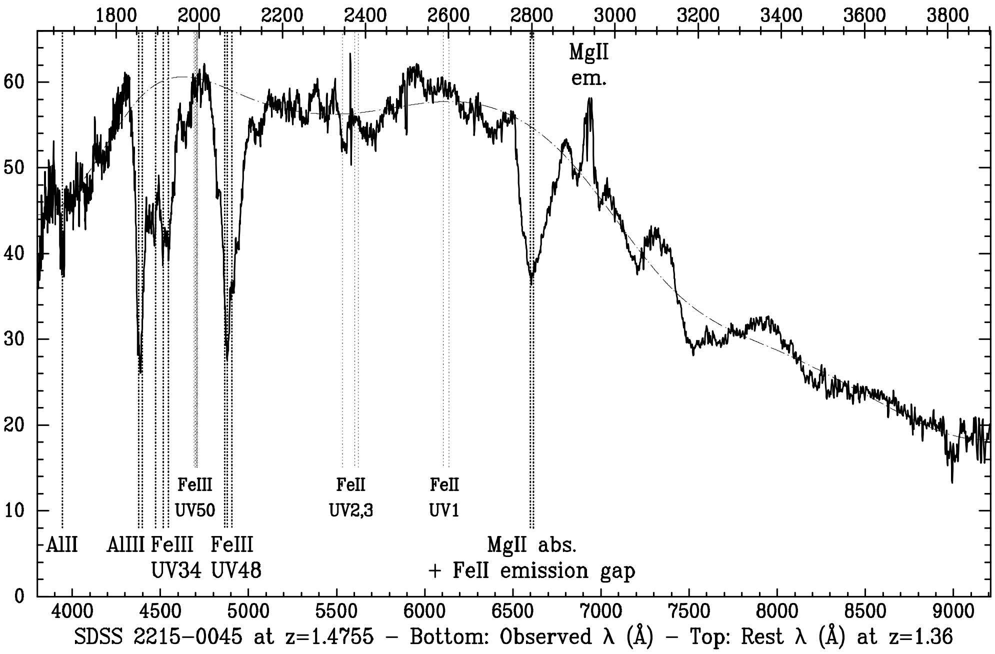


Fig. 10.— The Fe III-dominant BAL quasar SDSS 2215−0045 at $z = 1.4755$. The top axis plots rest wavelengths at the peak absorption trough $z = 1.36$, rather than this emission-line z, to demonstrate the absence of Fe II absorption at 2200−2600 Å. The thick dotted lines show detected absorption troughs, while the thin dotted lines show the expected positions of troughs that are not detected. The dot-dashed line shows the continuum fit used to normalize the spectrum for calculation of the balnicity index.

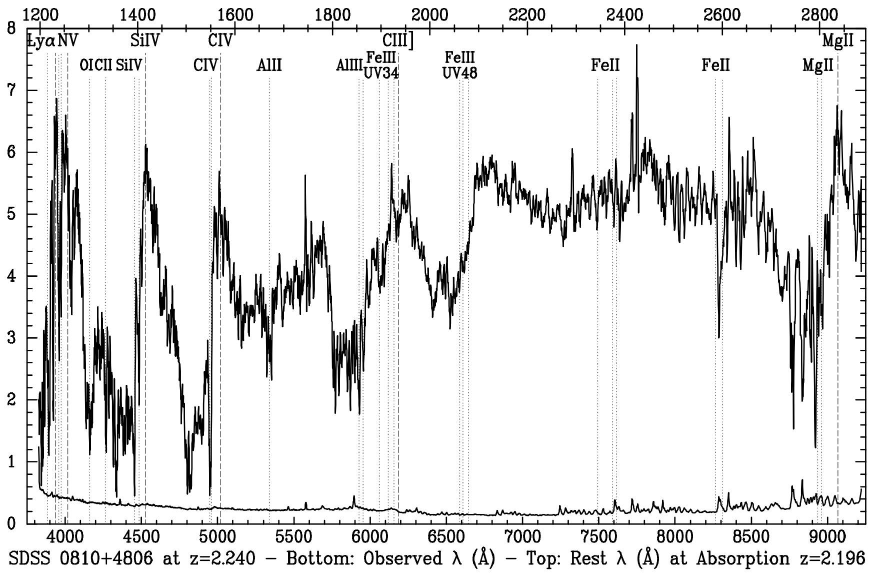


Fig. 11.— Fe III-dominant BAL quasar SDSS 0810+4806 at $z = 2.240 \pm 0.005$.

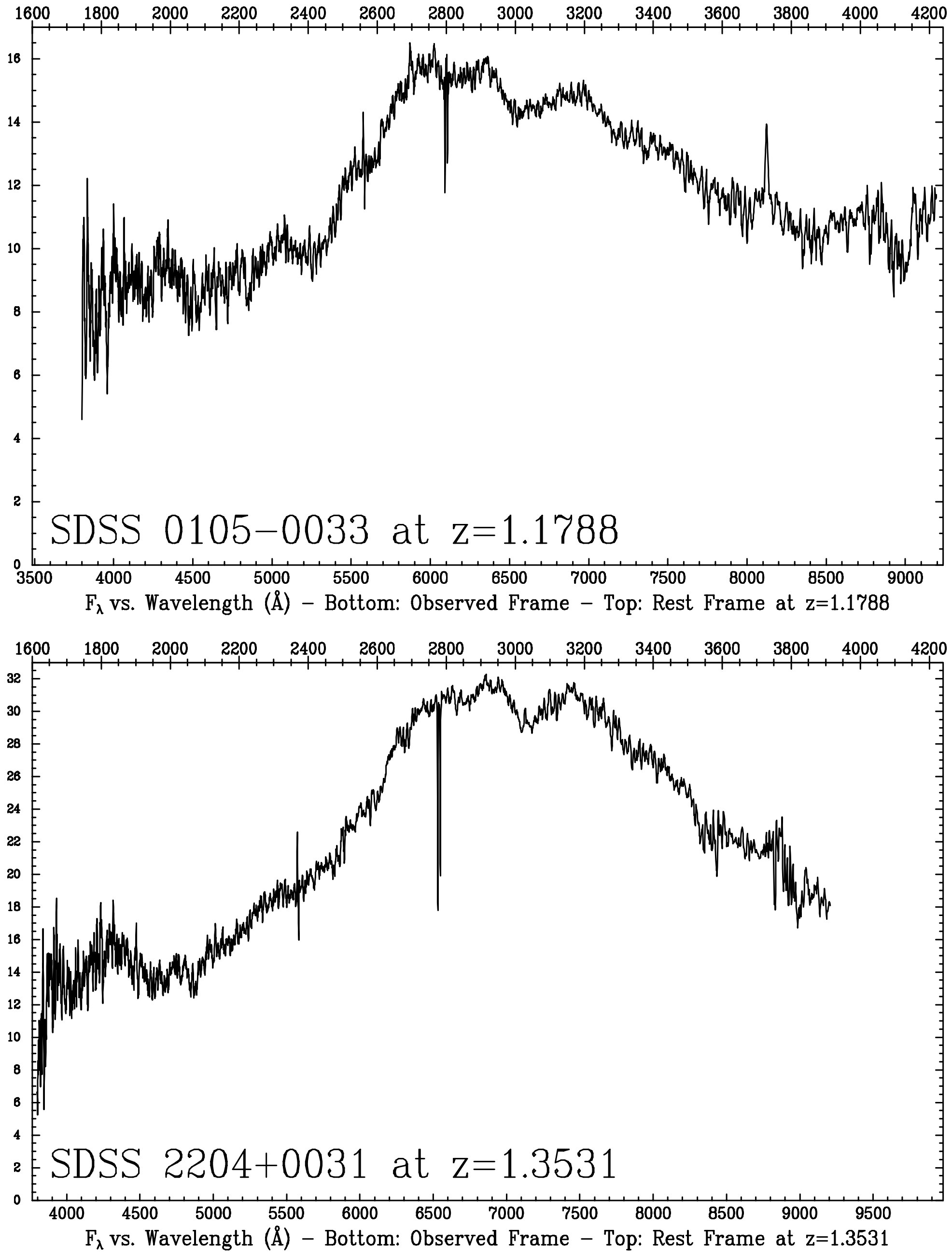


Fig. 12.— a) SDSS 0105−0033 at $z = 1.1788$ from Mg II absorption and [O II] emission. b) SDSS 2204+0031 at $z = 1.3531$ from cross-correlation with the spectrum of SDSS 0105−0033. Rest wavelengths are shown at the top and observed wavelengths at the bottom of each plot; both plots have the same rest frame wavelength limits. Both spectra have been smoothed by seven pixels everywhere except at the wavelengths of the associated Mg II absorption, in order to reduce the noise while illustrating the depth of the Mg II absorption at the original resolution of $R \sim 1950$.

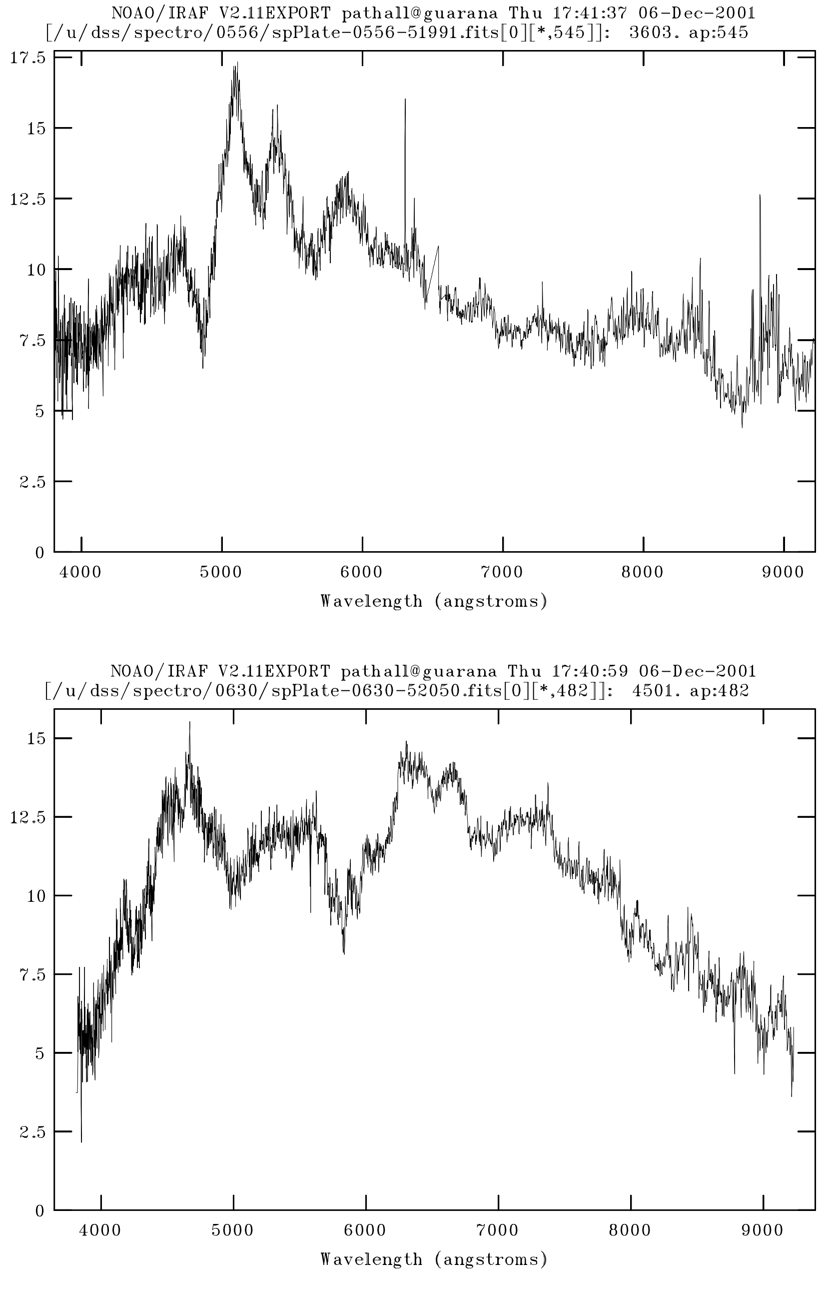
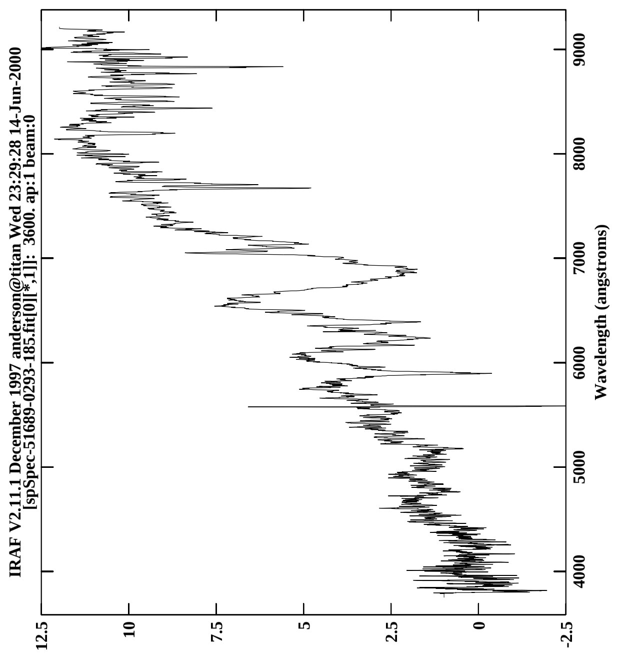


Fig. 13.— a) Spectrum 556/51991-545, a LoBAL quasar at $z = 0.82$. b) Spectrum 630/52050-482, a possible LoBAL quasar at $z = 1.24$?



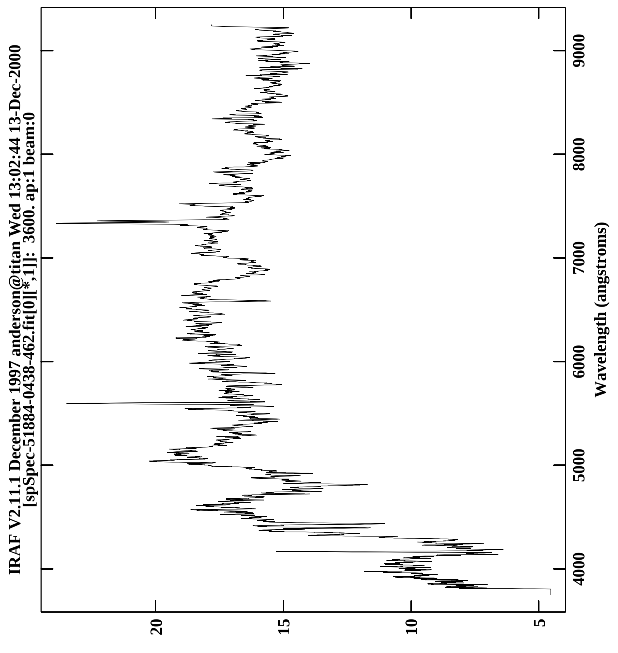


Fig. 14.— Spectrum 293/51689-185: a late-type subdwarf star. Spectrum 438/51884-462: galaxy with supernova.

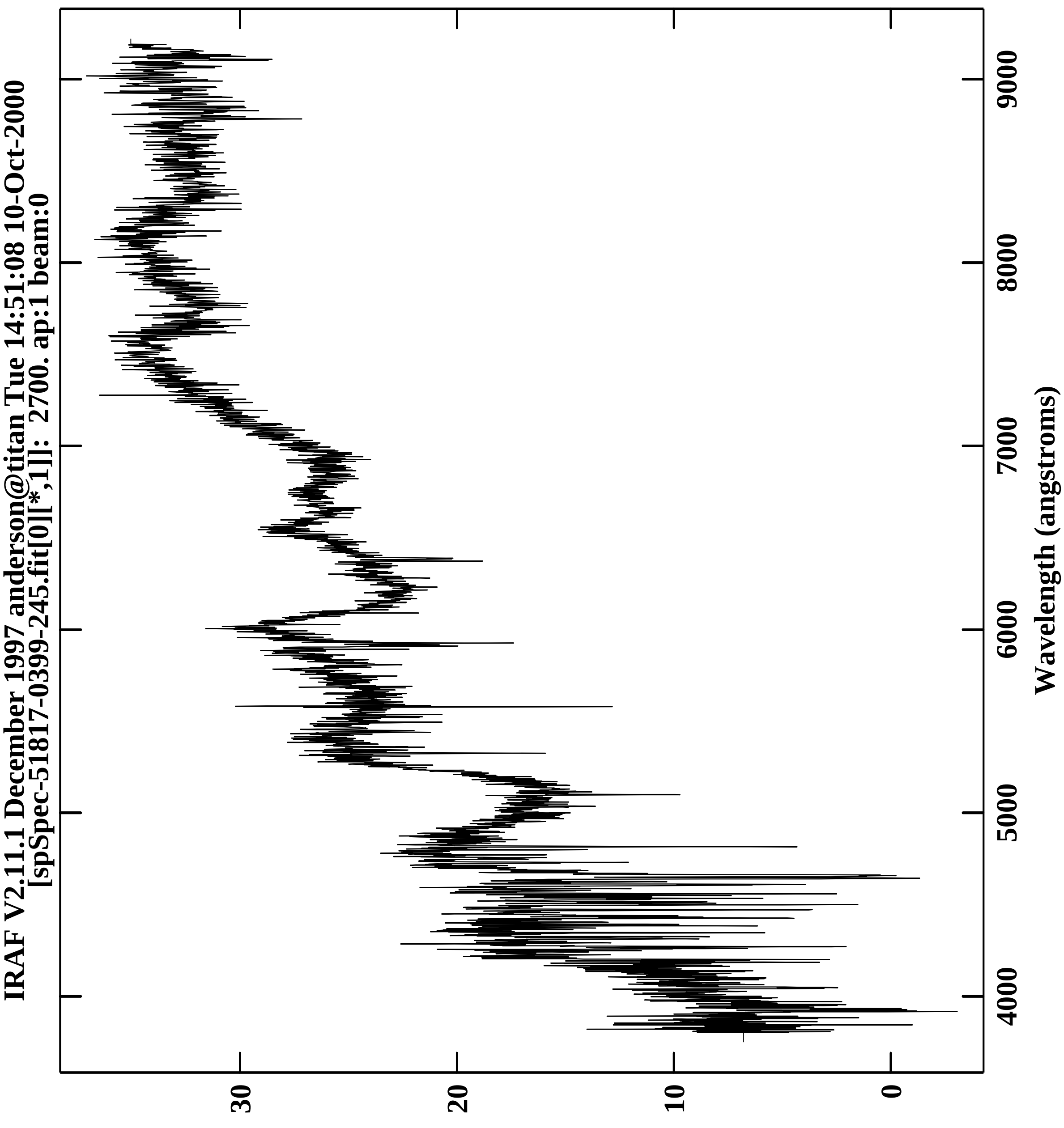


Fig. 15.— The spectrum 399/51817-245: a superposition of a late K or early M star with a z=2.8215 quasar. The quasar is obvious because of the Lyα forest absorption.

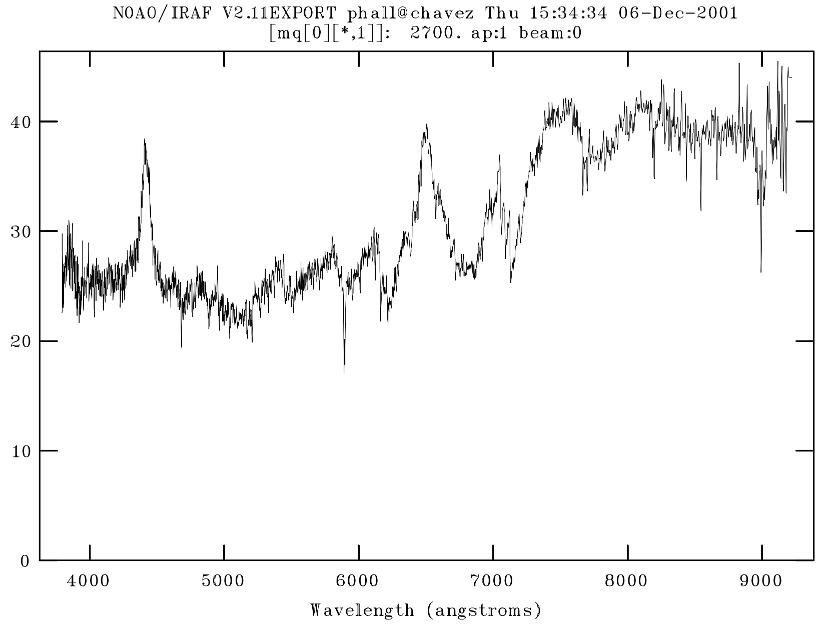


Fig. 16.— The spectrum 401/51788-550: a superposed late M star and z=1.32 quasar.

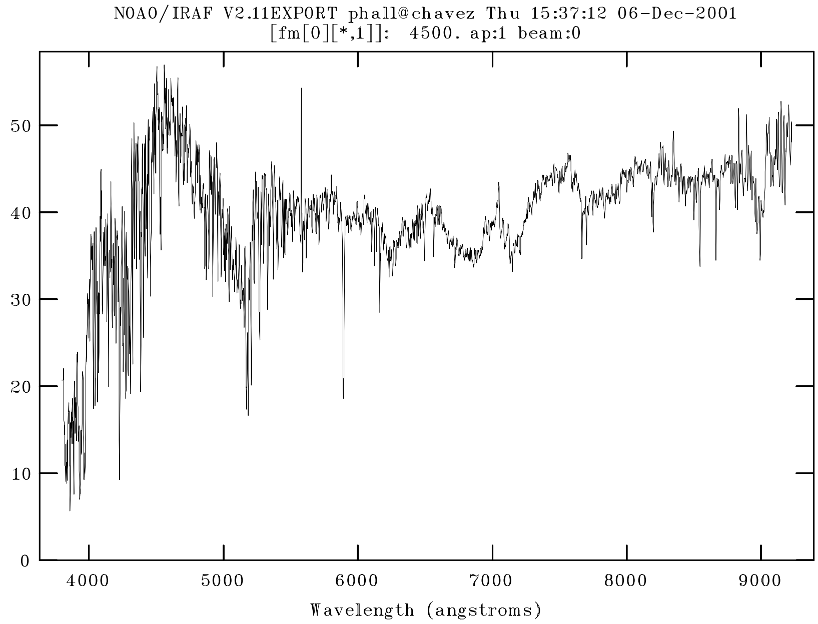
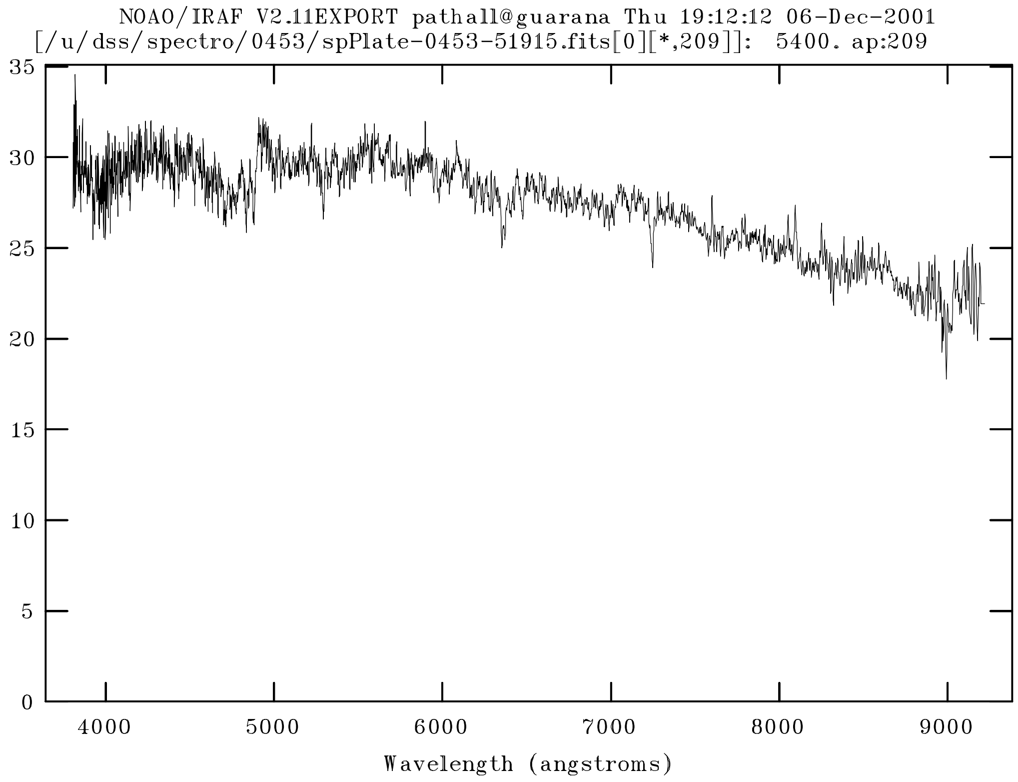


Fig. 17.— The spectrum 313/51673-481: an F star + M star superposition.



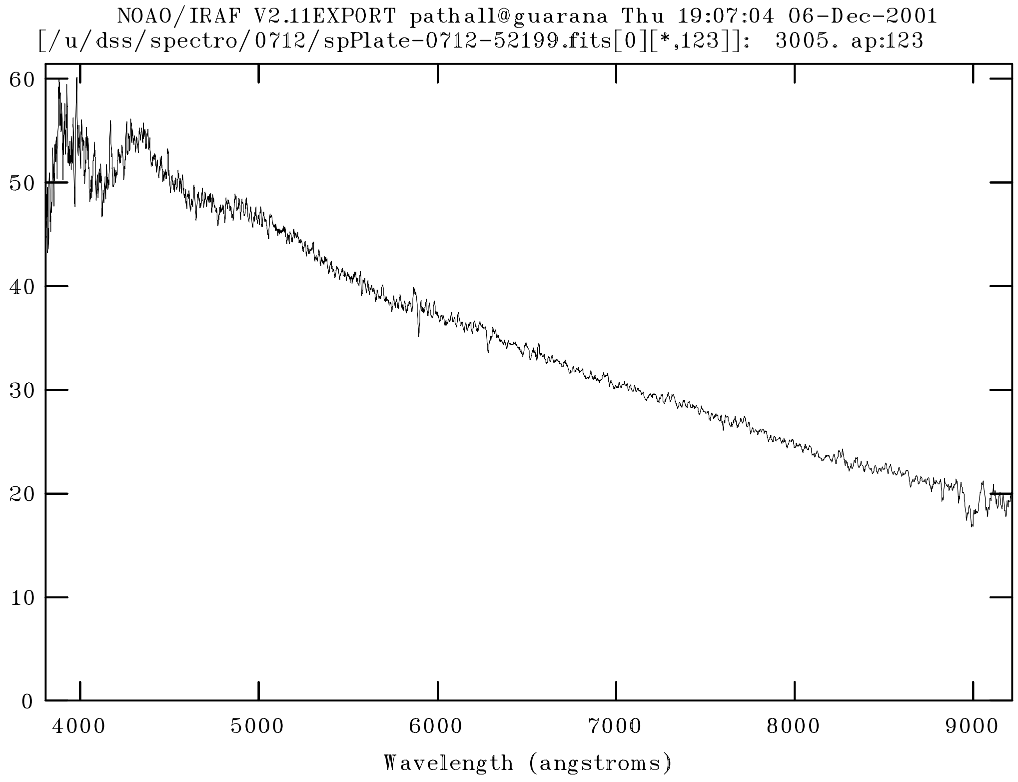


Fig. 18.— a) Spectrum 453/51915-209, a rather red BL Lac at $z = 0.2289$. b) Spectrum 712/52199-123, a rather blue BL Lac (probably) of unknown z.

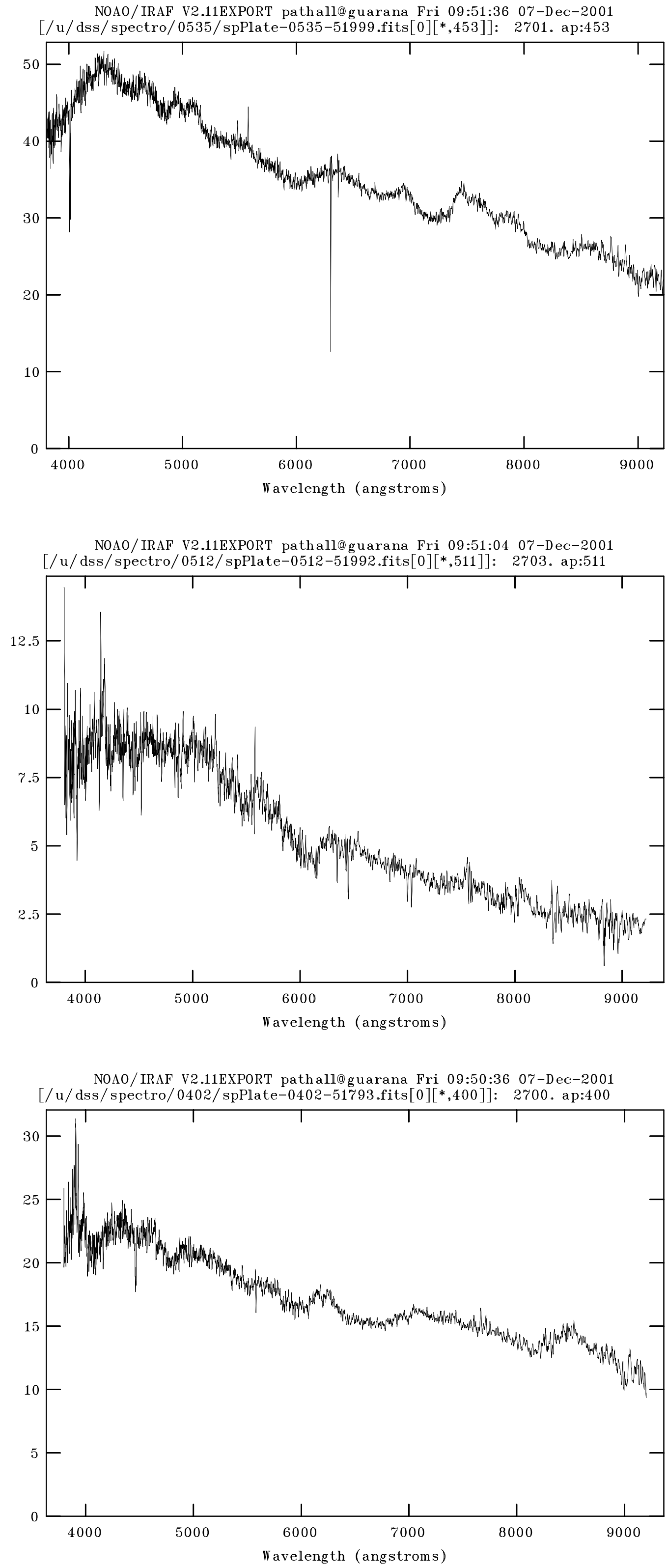
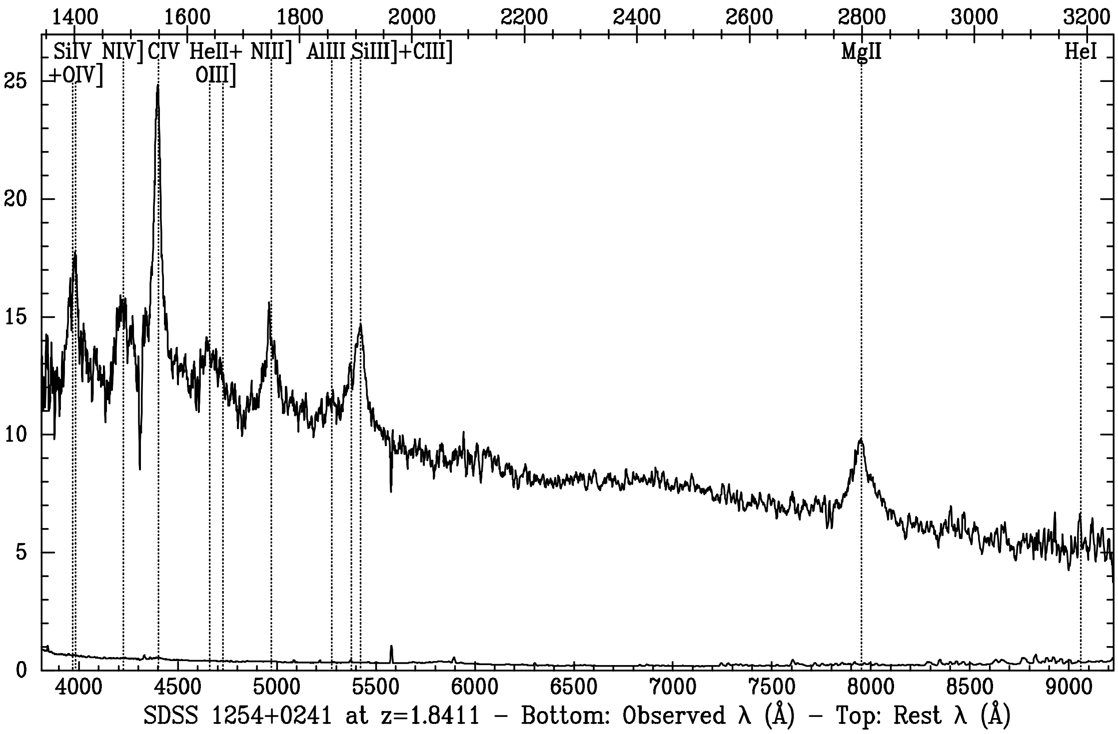


Fig. 19.— a) Spectrum 535/51999-453, z=1.589 from C IV or z=1.66 from weak emission features. b) Spectrum 512/51992-511, z=1.707 from Fe II absorption and weak C IV & Mg II emission. c) Spectrum 402/51793-400, $z > 0.594$ from Mg II.



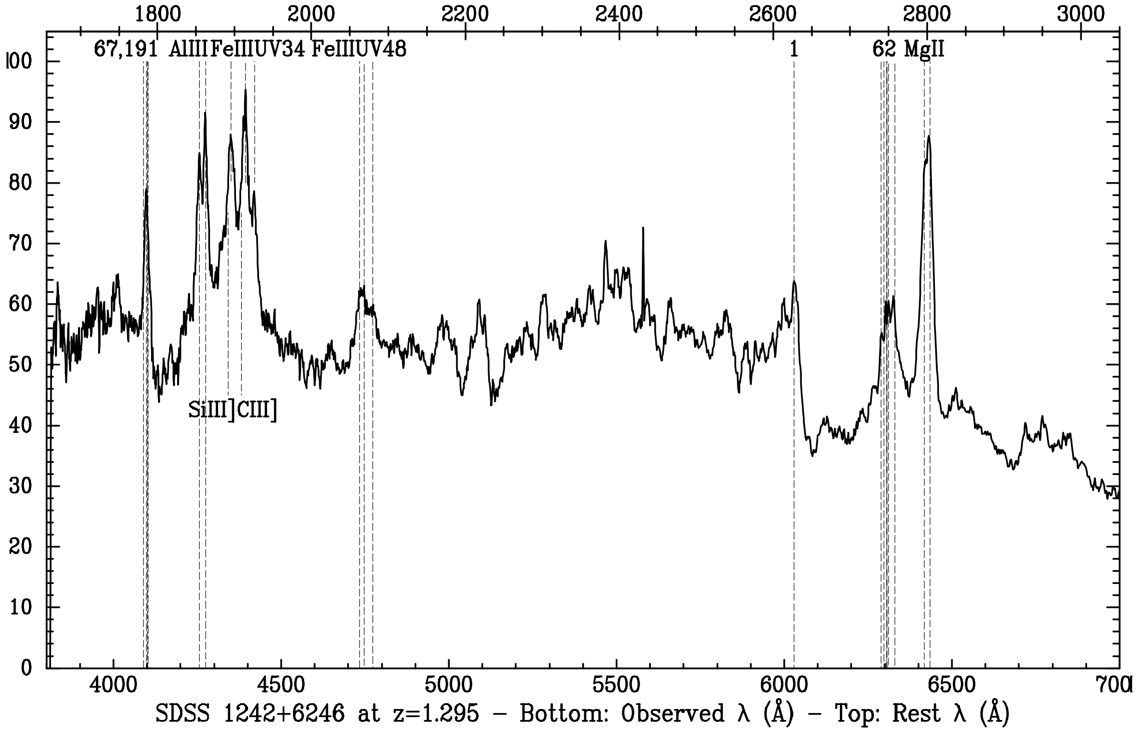


Fig. 20.— a) SDSS 1254+0241 (spectrum 523/52025-431), a nitrogen-strong quasar. b) SDSS 1242+6246 (spectrum 782/52320-351), an extreme Fe II-emitting quasar (partial spectrum).