Emergence of a BAL flow in the Narrow-line Seyfert 1 Galaxy WPVS 007

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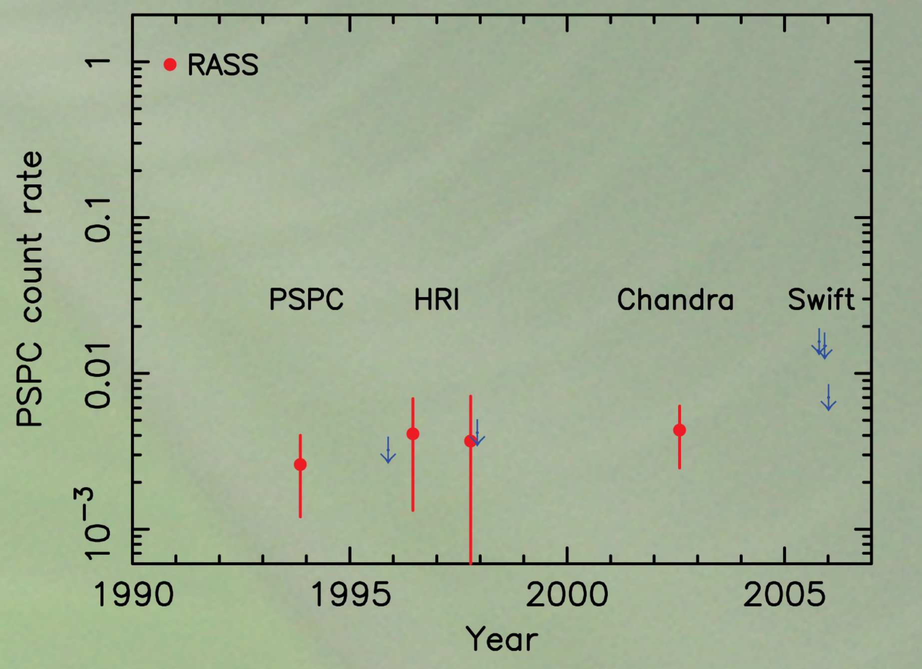
ABSTRACT

We report emergence of a broad absorption-line (BAL) flow in the peculiar narrow-line Seyfert 1 Galaxy WPVS 007 (z=0.0288). WPVS 007 was observed to have normal X-ray luminosity in the ROSAT All Sky Survey, but in subsequent X-ray observations from 1993 to 2005, it nearly disappeared from the X-ray sky. Most NLS1s are bright soft X-ray sources, and the origin of this X-ray weakness was unknown until now. Observed to have a miniBAL with maximum velocity v_{max}~1000 km s^{-1} in an *HST* observation from 1996, it was discovered to have developed an additional BAL flow by the time of the *FUSE* observation seven years later. The BAL flow has a maximum velocity of ~6,000 km s^{-1}, and the unambiguous presence of PV indicates that it is very optically thick. BALQSOs are notoriously X-ray weak and X-ray spectroscopy from other BALQSOs indicates that this is because they are absorbed. Thus, the change in X-ray flux is plausibly a result of absorption due to the development of the BAL flow.

Variability in broad absorption lines are generally confined to changes in optical depth, and the emergence of a BAL flow has never been observed before. Furthermore, the observation of a BAL flow in an object with such low luminosity (M_V=-19.7) is unprecedented. However, these two properties may be connected. WPVS 007 has a small black hole mass (1.2 x 10^6 solar masses based on the Kaspi relationship) so size scales are small and time scales are short. Similar changes on a 7-year time scale might be impossible in a more typical BAL quasar which may be 1000 times more luminous with correspondingly larger emission regions and longer time scales.

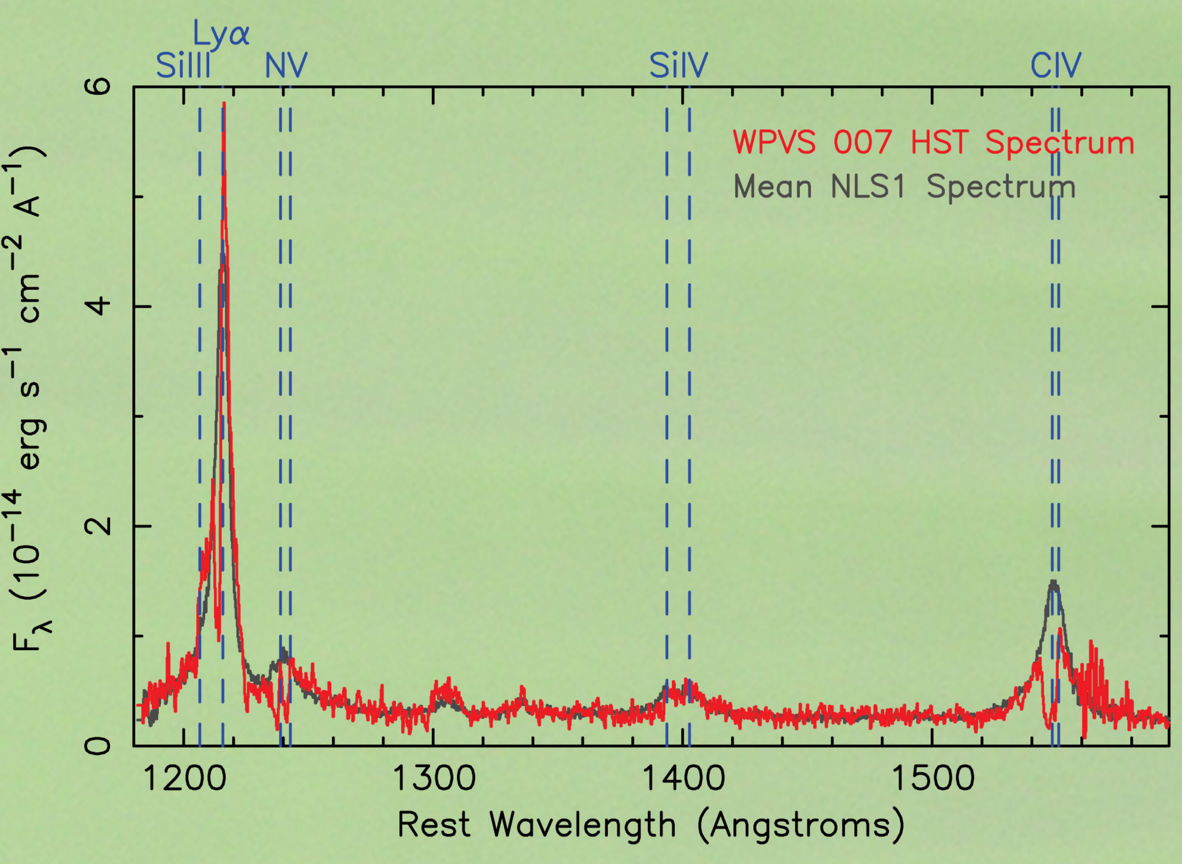
X-Ray History

WPVS 007 is a Narrow-line Seyfert 1 (z=0.028, m_V=15.7) with an unusual X-ray flux history. It was first observed in the *ROSAT* All Sky Survey with a typical flux for an AGN of its UV luminosity, although it had an unusually soft X-ray spectrum (inferred power law energy index of -7.3). However, subsequent observations between 1993 and 2005 found that its X-ray emission had decreased by a factor of ~400 (Grupe et al. 1995). Now it is significantly underluminous for a AGN; the inferred luminosity from 10 photons detected in a 9.8ks *Chandra* observation is 2x10^{40} erg s^{-1} (Vaughan et al. 2004) about the luminosity of a normal or starburst galaxy (e.g., David, Jones & Forman 1992). (Right: red points show detections and blue arrows show upper limits.)



1996 *HST* Spectrum

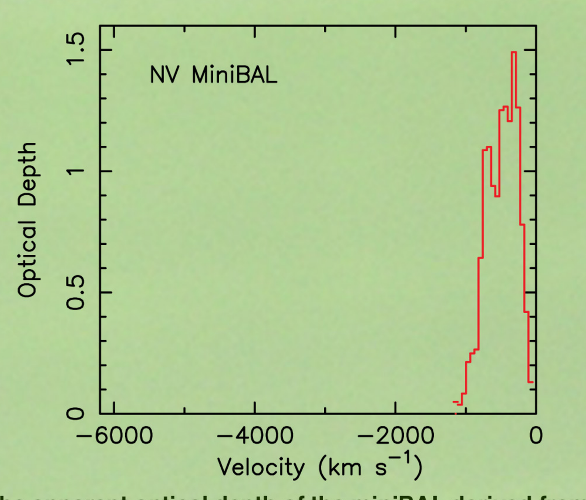
In 1996, WPVS 007 was observed using *HST*. The UV spectrum (right) shows strong, rather narrow emission lines. Its spectrum is similar to that of other low-luminosity NLS1s such as Mrk 335 and Mrk 493 (average spectrum is shown in grey). There are low-velocity broad trough absorption lines (miniBALs) present on the UV resonance lines SiIII, NV, SiIV, and CIV.



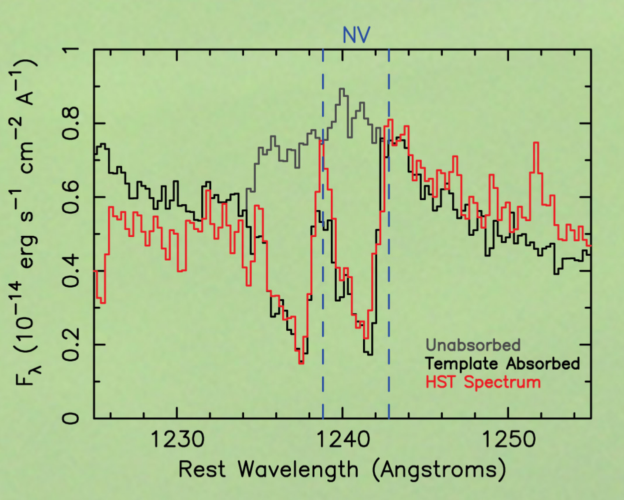
MiniBAL Analysis

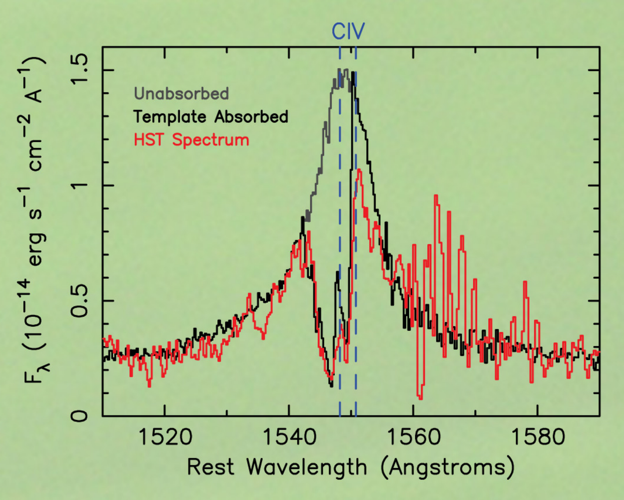
The doublet components of NV are sufficiently separated that the miniBAL appears to be resolved. We first estimate the spectrum before absorption using the mean of the *HST* spectra from low-luminosity NLS1s Mrk 335 and Mrk 493. The oscillator strengths predict that the 1239 Angstrom component should be twice as deep as the 1243 Angstrom component. They appear to be the same strength in the normalized spectrum, implying that the absorber is optically thick and only partially covers the emission regions. Therefore, we derive the optical depth profile as a function of velocity assuming 1:1 doublet ratio (right). To check our result, we apply the optical depth profile to the assumed unabsorbed spectrum. The figures below show that we are able to model both the NV and CIV absorption profiles rather well. Integrating over the optical depth yields a minimum column density for N^{+4} of log(N)=15.5. Assuming an [O/H] ratio of -3.31, and a peak ion fraction for N^{+4} of 0.4 (Hamann 1997) we infer a lower limit on the equivalent hydrogen column of log(N_H)=19.2.

The non-black troughs imply that the absorber partially covers the emission. The miniBAL is suffiecently deep that it must cover both the continuum and emission line regions.



The apparent optical depth of the miniBAL derived from NV as a function of velocity.

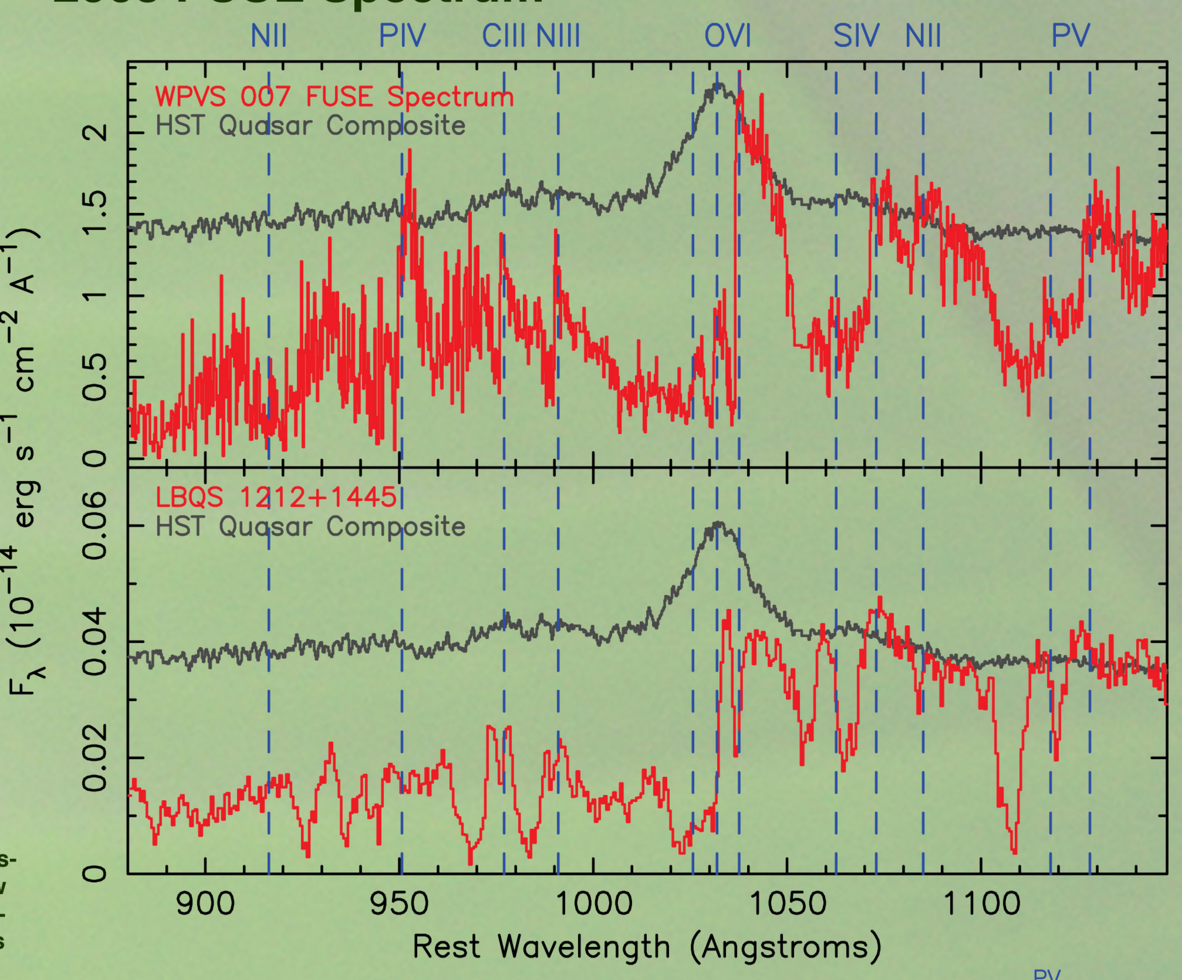




Testing the miniBAL template. Light grey: the mean spectrum from the low-luminosity NLS1s Mrk 335 and Mrk 493. Black: the mean spectrum folded with the template absorption. Red: the *HST* spectrum of WPVS 007. Left: applying the miniBAL template to NV. Right: applying the miniBAL template to CIV.

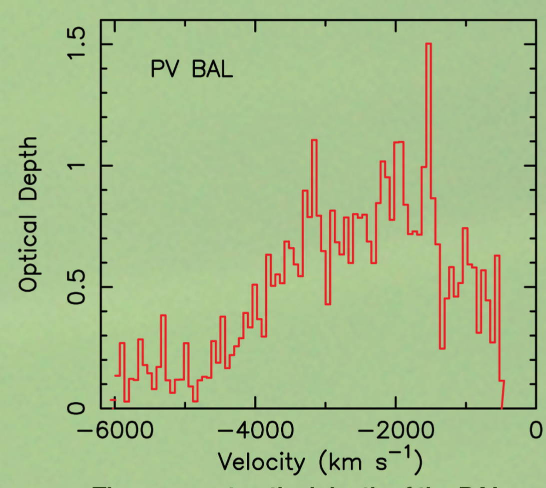
2003 FUSE Spectrum

In 2003, *FUSE* observed WPVS 007, and found that it had developed a broad absorption line flow in addition to the miniBAL that can still be seen in OVI. The figure (right) shows the spectrum in comparison with the *HST* quasar composite (Zheng et al. 1997), and with the BAL quasar LBQS 1212+1445, which has similar absorption lines but is 100 times more luminous. Rest wavelengths of prominent absorption lines are marked.

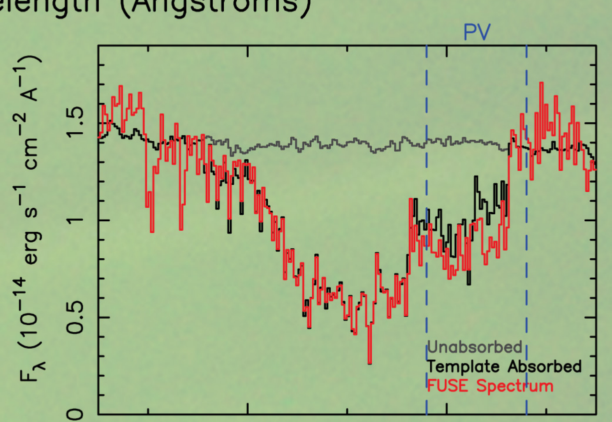


BAL Analysis

Notable in the spectrum is the BAL in PV. Phosphorus is an odd-numbered element, and has low abundance ([P/H]=-6.50) compared with other elements (e.g., [C/H]=-3.61, [O/H]=-3.31). Thus, PV is less likely to be saturated than other lines. We compare the WPVS 007 spectrum with the *HST* quasar composite (Zheng et al. 1997) to determine the continuum, and derive the optical depth as a function of velocity in the BAL. The 1118 angstrom component is expected to be twice as deep as the 1128 angstrom component, so we force a 2:1 ratio in the analysis. The resulting profile shows that v_{max}~5000 km s^{-1}. To check the results, we apply the model profile to the *HST* composite spectrum, and compare that with the *FUSE* spectrum. The model is good but not perfect. Integrating over the optical depth profile yields an inferred P^{+4} column of log(N)=15.3.



The apparent optical depth of the BAL derived from PV as a function of velocity.



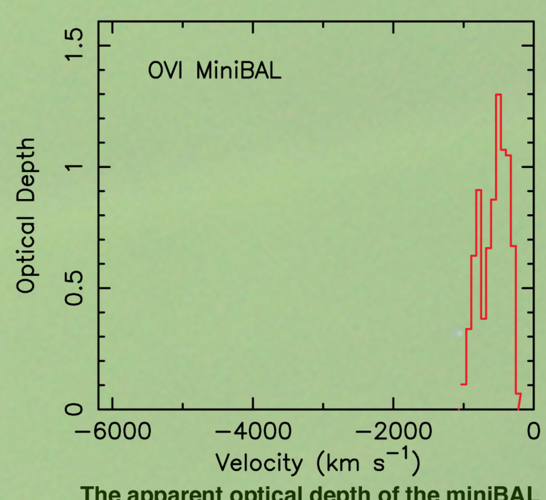
Testing the BAL template: Light grey: the *HST* quasar composite spectrum. Black: the mean spectrum folded with the template absorption. Red: the *FUSE* spectrum of WPVS 007.

MiniBAL Analysis

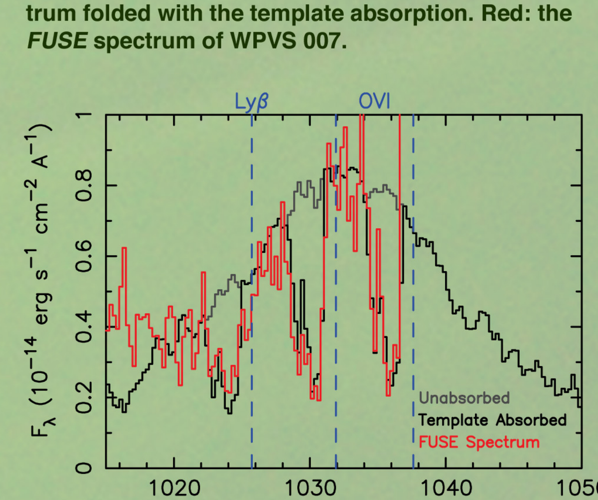
The miniBAL does not appear to be present in PV perhaps implying that the column of the miniBAL is not large enough to produce appreciable opacity in PV. However, it is clearly present in OVI.

Because oxygen is much more abundant than phosphorus, the OVI BAL is plausibly saturated. It is not black because the trough is filled in. Interestingly, the bottom of the BAL trough near OVI is not flat but rather resembles the OVI emission line from the composite spectrum. Thus the absorption trough may be filled in at least partially by the emission line, which may mean that the BAL flow is interior to the broad-line region.

We analyze the miniBAL by assuming that the unabsorbed residual continuum in the trough has the shape of the composite emission line. We develop the template from the average of the OVI doublet components. We apply the template to the emission line, assuming absorption in both OVI doublet components, and also in Lybeta. We assume that the miniBAL is optically thick and has a 1:1 ratio in all three lines. We find a good correspondence (right).



The apparent optical depth of the miniBAL drive from OVI as a function of velocity.



Testing the miniBAL template: Light grey: the *HST* quasar composite spectrum rescaled to model the flux filling the BAL trough. Black: the mean spectrum

Equivalent Hydrogen Column Density

The inferred P^{+4} column is log(N)=15.3. Assuming a peak ion fraction for P^{+4} of 0.5 (Hamann 1997), and an abundance ratio of [P/H]=-6.5, we infer an equivalent hydrogen column of log(N_H)=22.4. The estimate would be lower if metals abundances are elevated and higher if the ionization state is not such that P^{+4} fraction is optimal.

Launch radius

If we assume that the BAL outflow is accelerated by radiation and decelerated by the gravitational field of the central black hole, we can estimate the radius of the launch point of the outflow using Eq. 3 of Hamann 1998. We esimate the luminosity at 5100A to be 8x10^{42} erg s^{-1}, and a bolometric correction factor of 9 gives L_{BOL}=7.3x10^{43} erg s^{-1}. Using the Hbeta FWHM=1200 km s^{-1} (Grupe 1996) yields a black hole mass of 1.2x10^6 solar masses from the Kaspi relationship. For an optical-depth weighted velocity of 2600 km s^{-1}, and assuming that 10% of the bolometric luminosity accelerates the outflow, we estimate a distance of 0.0029 parsecs. This is a larger radius than the broad-line region, estimated to lie at 0.00064 parsecs.

We note that this limit is uncertain. The column density estimate assumes maximal P^{+4} ions. Since we see OVI absorption, the typical ionization state of the absorbing gas may be larger, in which case the column density would be larger and the radius smaller. The dynamical upper limit (at which the launch radius is at the central engine) on the column density is 7.6x10^{22} cm^{-2}, only three times larger than our esimate. On the other hand, if the gas is metals-enriched, the equivalent hydrogen column will be smaller and launch radius correspondingly larger.

The Origin of the X-ray Weakness

The discovery of the BAL in WPVS 007 may solve the problem of the X-ray weakness. BALQSOs are notoriously soft X-ray weak (e.g., Brandt, Laor & Wills 2000). Often, their X-ray spectra are found to be absorbed (e.g., Gallagher et al. 2002). It should be noted, however, that the inferred maximum column of 7.6x10^{22} cm^{-2} is not sufficient to explain the X-ray weakness if WPVS 007 has intrinsically typical X-ray flux. Specifically, we would have expected to detect 1500 photons in the Chandra observations, a factor of 150 times higher than observed. It is possible that the total column density is higher but that not all of it is outflowing.

BAL flows in Low Luminosity AGN

Broad, high-velocity absorption lines are found in the rest-frame UV spectra of about 10% of quasars, but not generally in lower-luminosity Seyfert galaxies. In Seyfert galaxies, absorption lines tend to have relatively low velocity and to be narrow.

Laor & Brandt (2002) investigated the dependence of UV absorption line velocities on luminosity. They find that more luminous objects have higher v_{max}, and there appears to be an upper limit on the velocity for a particular luminosity. The plot below shows that WPVS 007 deviates significantly from their relationship, having a much higher v_{max} for its relatively low M_V (=-20.4 using H_0=50 km s^{-1} Mpc^{-1}). Note that Laor & Brandt plot v_{max} of CIV while we plot v_{max} of PV. However, Hamann 1997 show that PV and CIV are both expected to be strong in gas with similar ionization state, so v_{max} of PV should be a valid surrogate for v_{max} of CIV.

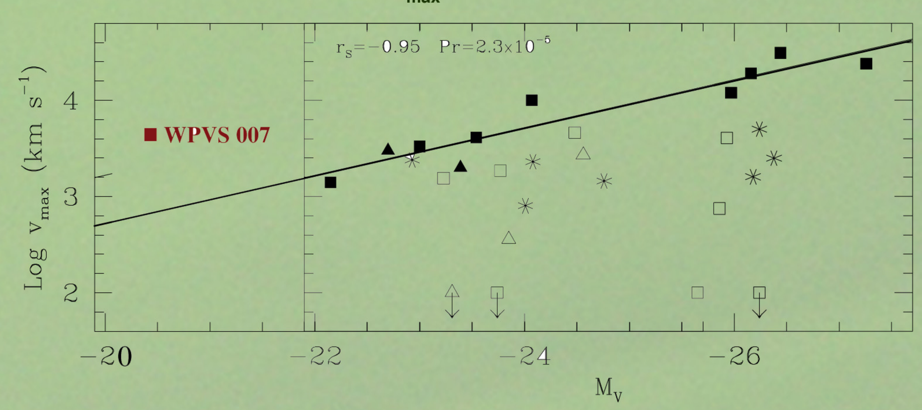


Figure 6 from Laor & Brandt 2002 shows v_{max} for CIV absorption as a function of M_V in quasars, extrapolated to lower luminosities. Filled squares mark soft X-ray weak quasars, possibly similar to WPVS 007. The broad absorption line in WPVS 007 has a much higher velocity than expected for an object of its luminosity.

The Development of a BAL in WPVS 007

In the interval between 1996 and 2003, a BAL outflow apparently developed in the low-luminosity Narrow-line Seyfert 1 galax WPVS 007. Generally, absorption-line variability is confined to changes in opacity; variability in the velocity has been seen in only a couple of objects.

The development of the BAL in WPVS 007 may be associated with its low luminosity. WPVS 007 has a small black hole mass and therefore central engine and emission regions are small. LBQS 1212+1445 has an outflow with similar velocity, but with M_V=-27.6, it is 100 times more luminous, and we expect its emission regions to be 100 times larger. Thus, while it may be feasible for an emerging outflow to traverse and cover the central emission region over period of 7 years in WPVS 007, it might require 700 years to observe a similar change in a more typical BAL quasar such as LBQS 1212+1445.

Future Work

WPVS 007 is an important object for understanding outflows in AGN. Time variability of the UV absorption profiles will set limits on the acceleration mechanisms for the outflow.

It is very possible that the outflow in WVPS 007 will continue to develop. Our approved *FUSE* Cycle 7 observation will permit us to see if there has been any further change over a period of 3 more years.

An exciting possibility is that the outflow will vanish. We are currently making short observations of WPVS 007 with *Swift* every 6 to 10 weeks, with the expectation that if the X-ray flux increases, it will mean that the BAL outflow has disappeared.