PG 0946+301: the Rosetta Stone of BALQSOs?

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ABSTRACT

We describe the motivation and features of a multiwavelength spectroscopic campaign on broad absorption line (BAL) QSO PG 0946+301. The main goal of this project is to determine the ionization equilibrium and abundances (IEA) in BAL outflows. Previous studies of IEA in BALQSOs were based on the assumption that the BALs are not saturated so that the column densities inferred from the apparent optical depths are realistic. This critical assumption is at odds with several recent observations and with analysis of existing data which indicate that the absorption troughs are heavily saturated even when they are not black. In addition, X-ray observations, which are important for constraining the ionizing continuum, were not available for those objects that had UV spectral data.

Quantifying the level of saturation in the BALs necessitates UV spectroscopy with much higher S/N and broader spectral coverage than currently exist. After taking into account the capabilities of available observatories, our best hope for a substantial improvement in understanding the IEA in BALQSOs is to concentrate considerable observational resources on the most promising object. Our studies of available HST and ground-based spectra show that PG 0946+301 is by far the best candidate for such a program. This BALQSO is at least five times brighter, shortward of 1000 Å rest frame, than any other object, and due to its low redshift it has an especially sparse Lyα forest. At the same time PG 0946+301 is a typical BALQSO and therefore its IEA should be representative. To this effect we are developing a multiwavelength spectroscopic campaign (UV, FUV, X-ray and optical) on BALQSO PG 0946+301. We discuss the goals and feasibility of each observational component: HST, FUSE, ASCA and ground-based.

Subject headings: quasars, absorption lines, abundances

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1. Introduction

Broad Absorption Line (BAL) QSOs are the main manifestation of AGN outflows. BALs are associated with prominent resonance lines such as C IV $\lambda 1549$, Si IV $\lambda 1397$, N V $\lambda 1240$, and Ly$\alpha$ $\lambda 1215$. They appear in about 10% of all quasars (Foltz et al. 1990) with typical velocity widths of $\sim 10,000$ km s$^{-1}$ (Weymann, Turnshek, & Christiansen 1985; Turnshek 1988) and terminal velocities of up to 50,000 km s$^{-1}$. The small percentage of BALQSOs among quasars is generally interpreted as an orientation effect, and it is probable that the majority of quasars and other types of AGN harbor intrinsic outflows (Weymann et al. 1991). In figure 1 we show the spectrum of PG 0946+301 which is a typical high ionization BALQSO.

![Fig. 1.— HST and ground-based data for PG 0946+301 ($z = 1.22$), where the BALs (some of which are identified at the bottom) arise from an outflow with $\Delta v \approx 10,000$ km s$^{-1}$.](image)

Establishing the physical properties of the flow by determining the ionization equilibrium and abundances (IEA) of the BAL material is a fundamental issue in BALQSOs studies. Furthermore, such determinations are powerful probes of abundances in the entire AGN environment. Inferences about the IEA in the BAL region are derived by trying to simulate BAL ionic-column-densities ($N_{\text{ion}}$) using photoionization codes. Several groups (Korista et al. 1996; Turnshek et al. 1996; Hamann 1996) have used extracted $N_{\text{ion}}$ from
HST observations of BALQSO 0226–1024 (Korista et al. 1992) in their IEA studies while introducing innovative theoretical approaches to the problem. However, these works used the BAL apparent optical depths (defined as $\tau = -\ln(I_r)$, where $I_r$ is the residual intensity seen in the trough) to determine their $N_{ion}$. The problem with this approach is that the apparent optical depths in the BALs cannot be directly translated to realistic $N_{ion}$ unless the covering factor and level of saturation are known. Arav (1997) demonstrated that in BALQSO 0226–1024 the optical depths in the major BALs are identical within measurement errors. The probability of such occurrence by coincidence is less than 1%, which strongly suggests that although these BALs are not black, they are all saturated. If the BALs are saturated, the inferred $N_{ion}$ are only lower limits, and thus the conclusions regarding the IEA in this object (i.e., very high metalicity in the flows; Turnshek et al. 1996), and by extension in all BALQSOs, are very uncertain. Evidence for saturation and partial covering factor in the outflows are also seen in the spectra of Q0449–13 (Barlow 1997) and PG 1254+047 (Hamann 1998), and in spectropolarimetry data (Cohen, M. H., et al. 1995; Hines & Wills 1995). This, along with the lack of even a single case where we can say with confidence that saturation is negligible, makes it likely that saturation affects most (if not all) observed BALQSOs.

Thus it has become evident that an IEA analysis based on apparent $N_{ion}$ is unreliable and that it is necessary to account for saturation and partial covering. Since these effects are velocity dependent, a detailed study of the optical depth as a function of velocity $[\tau(v)]$ is essential. Such an analysis requires much higher S/N data than the apparent $N_{ion}$ approach. This is currently feasible only for exceptionally UV-bright BALQSOs by using long integration times. Observing many objects with a S/N level similar to that of available data is of limited use for these studies. In addition to much higher S/N data, a wide UV spectral coverage is needed to cover lines that arise from the same ion, which yield the best saturation diagnostics. A broad UV coverage also yields many lines from different ions of the same element, which are crucial for separating effects of ionization and abundances. These requirements demand the widest possible spectral coverage and can be achieved by combining FUSE, HST/STIS and ground based observations. Such broad-wavelength observations yield more than one BAL for the ions N III, O III, O IV, Si IV and S IV, and BALs from multiple ions for seven elements (C, N, O, Ne, Mg, Si, S).

2. Measuring BAL Saturation

The best way to measure saturation is by a careful study of different BALs from the same ion. By doing so we obtain two or more diagnostics about precisely the same component of the outflowing gas. In the case of PG 0946+301, we have the following
BALs from the same ion in the combined HST-FUSE spectral coverage: Three N III BALs associated with transitions at 991 Å, 685 Å, and 452 Å. Based on their atomic parameters (Verner, Verner, & Ferland 1996), the expected optical depth ratio between these lines should be 9:20:1, respectively. These optical depth ratios give us great dynamical range in trying to quantify the level of saturation in the lines. Other ions also have more than one BAL: O IV 789 Å, 609 Å and 554 Å, with \( \tau \) ratios of 2:1:5; Si IV 1397 Å and 458 Å, with \( \tau_{ratio} = 46:1 \); S IV 1070 Å, 814 Å, 750 Å and 660 Å, with \( \tau_{ratio} = 1:1.6:11:15 \). The case of O III is somewhat unique since its lines (835 Å, 703 Å and 508 Å) have similar intrinsic optical depths \( \tau_{ratio} = 1.08:1.05 \). Therefore, these BALs cannot be used as saturation diagnostics. Instead they are useful in fixing the true level of the continuum and for checking the self-consistency of the \( \tau(v) \) solution algorithm.

### 3. Analysis of Existing Data

Three years ago we began a program to study the IEA in BALQSOs using HST archival spectra. We have analyzed the available HST (and ground-based) spectra of PG 0946+301 (Arav et al. 1998). Our main effort was devoted to a detailed study of \( \tau(v) \) in the BALs. For this analysis we developed a new algorithm to solve for the optical depth as a function of velocity for doublets and multiplets. \( \tau(v) \) for a few lines are shown in figure 2. We found convincing evidence for saturation in segments of the troughs, especially in component B which is seen in all BALs. This supports our previous assertion that saturation is common in BALs and therefore cast doubts on claims for very high metalicity in BAL flows. We found differing covering factors for high vs. low ionization BALs and large differences in ionization as a function of velocity between different BALs. By comparing the available data of PG 0946+301 to those of all other BALQSOs in the HST archive, it became obvious that this object is by far a better candidate for IEA studies than any other known BALQSO.

#### Advantages of PG 0946+301

- PG 0946+301 is the brightest BALQSO in the UV with 5–10 times higher flux between 1250–2500 Å (observed frame) than the second best candidate (Q0226–1024).
- It is a fairly typical BALQSO in terms of luminosity and optical/UV spectrum and therefore conclusions about its IEA should be representative of the whole class.
- The BALs of PG 0946+301 are somewhat narrower than those of other possible candidate, and therefore blend less with each other across the spectrum.
- We can obtain very high-quality data for an unprecedented rest frame spectral region (400 – 1700 Å), with very small contamination by Ly\( \alpha \) forest lines due to the low redshift of the object.
Fig. 2.— Optical depths as a function of velocity are the important physical quantities for analyzing the flow. Shown here, on the same velocity scale, are the $\tau(v)$ for O VI, S VI and Si IV, where the main components of the flow are marked. It is clear that these three $\tau(v)$ are not proportional to each other and therefore using integrated $N_{\text{ion}}$ to study the flow can be very misleading. For example by comparing the optical depth ratio between the high-ionization lines (O VI and S VI) and the low-ionization line Si IV it is apparent that component A is more highly ionized than component B.

4. Campaign Description

Roughly 30 QSO researchers have teamed up in an international-collaboration dedicated to this multiwavelength campaign. Our aim is to obtain: HST UV spectroscopy, FUSE UV spectroscopy, ASCA X-ray data, high-resolution optical spectroscopy and optical spectropolarimetry. Each of these observations will yield important information by itself, but it is the combined constraints that will give the most powerful IEA diagnostics. A 100 ksec ASCA observation has already been approved, a 100 ksec FUSE proposal has recently been submitted and an HST/STIS proposal of roughly 40 orbits will be submitted in cycle 8.
4.1. Observational Components

**HST**: We expect the highest quality data to come from HST observations totaling \( \sim 40 \) orbits. In the far UV (550–800\,Å rest-frame) a thirty orbit observation with the STIS G140L grating should give 6-8 times better S/N combined with roughly three times higher resolution than the available data (shown in Fig. 1). This superb data will allow us to extract \( \tau(v) \) for 8 important BALs in that region, which is not possible with the data in hand. Ten orbits with the G230L grating will give same epoch data with three times the S/N of the available data between 800–1450 \,Å. This division of observing time should yield data with S/N > 70 across more than 80% of whole HST UV band (1150–3200\,Å observed-frame). The instrument-related details of the observations and the data reduction will be handled by Mike Crenshaw (GSFC) who is a member of the STIS team.

**FUSE** (Far Ultraviolet Spectroscopic Explorer): Within the spectral coverage of FUSE (400–530\,Å in the object’s rest-frame) we expect to find BALs that can serve as unique saturation diagnostics (Si IV \( \lambda 458 \) and N III \( \lambda 452 \)), which combined with HST data will enable us to determine saturation levels up to fifty times the apparent optical depth. BALs from very high ionization states (Si XII and S XIV) will give information about material in similar ionization states to the “warm absorbers” seen in Seyfert galaxies and quasars. And BALs from five ions of neon. The instrument-related details of the observations and the data reduction will be handled by Mark Giroux (University of Colorado) who is a part of the FUSE team.

**ASCA**: X-ray data give us the only direct information about the shape of the ionizing continuum beyond \( \sim 30 \) eV, which is vital for constraining the ionization equilibrium. Unlike optical/UV data, the absorption seen in the X-ray data is mainly due to bound-free opacity, whereas the optical/UV absorption data is due to bound-bound opacity (i.e., lines). Therefore, additional diagnostics which are much less sensitive to saturation effects will be obtained by analysis of the X-ray data. We have an approved program for a 100 ksec ASCA observation of PG 0946+301 (PI Paul Green).

**Optical**: In the optical regime it is important to obtain a very high S/N data of the C IV \( \lambda 1549 \) BAL (which is the only one observable from the ground) with a high spectral resolution. From these data an accurate optical depth template can be extracted and compared with all the UV BALs in order to find ionization differences across the troughs. It is also beneficial to obtain spectropolarimetry from the ground. Polarized light gives us information about an indirect photon trajectory through the BAL region which provides valuable information about the geometry of the absorbing gas.
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