THE EXTRAORDINARY ABUNDANCES OF QUASAR BROAD ABSORPTION LINE REGIONS: A MATTER OF NOVAE?

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ABSTRACT

The broad absorption lines (BALs) of QSOs indicate abundances of heavy elements, relative to hydrogen, that are 1–2 orders of magnitude higher than the solar values. In at least one QSO, an especially large enhancement of phosphorus is observed. These abundances resemble those in Galactic novae, and this suggests that novae may produce the BAL gas. The needed rate of nova outbursts may come from single white dwarfs that accrete gas as they pass through a supermassive accretion disk around a central black hole.

Subject headings: accretion, accretion disks — galaxies: abundances — novae, cataclysmic variables — quasars: absorption lines

1. INTRODUCTION

BAL QSOs show broad absorption troughs attributed to rapidly outflowing gas (of unknown origin) located outside the continuum source and the broad emission line region. BALs typically occur in Lyα, C IV λ1549, Si IV λ1400, N v λ1240, O VI λ1034, and, sometimes, Mg II λ2798 and Al III λ1857 (see reviews by Weymann, Turnshek, & Christiansen 1985, hereafter WTC; and Turnshek 1988, 1995). BALs often set in at the systemic velocity of the QSO, but in some objects “detached” BALs begin at velocities up to ~10^4 km s^{-1}. The absorption often extends to velocities ~3 × 10^4 km s^{-1}, with varying degrees of structure and residual intensity through the line profile. The derived column densities for the absorbing ions (e.g., C^{+2}) are ~10^{19} cm^{-2}. BALs occur in about 10% of radio-quiet QSOs (Weymann et al. 1991) and rarely in radio-loud QSOs. Either most radio-quiet QSOs have BAL material covering about 10% of the sky, as seen from the continuum source, or a subset of QSOs have BAL regions with a larger covering factor. The BAL region may have a disklke geometry (Turnshek 1995; Goodrich & Miller 1995). The absorbing material must have a transverse dimension ~10^16 cm, sufficient to cover the continuum source. The N v BAL often strongly absorbs the Lyα emission line, implying a column density ~10^{18} cm^{-2} (Turnshek et al. 1996). The absorbing clouds, which occupy only a tiny fraction of the volume, may be accelerated by radiation pressure involving the resonance lines or by ram pressure of a fast-moving wind (WTC). Proposed sources for the BAL gas include winds from red giant stars (Scoville & Norman 1995) or from a supermassive accretion disk (Murray et al. 1995).

2. CHEMICAL ABUNDANCES

The BAL gas has remarkably high abundances of heavy elements, relative to hydrogen. The abundances are derived from column densities of ions (in turn, derived from observed BAL optical depths), together with photoionization models of the ionization equilibrium. Junkkarinen et al. (1987) argued for a minimum (Si/H) ~ 10(Si/H)⊙ for their sample of BAL QSOs, and their discussion suggests a likely value (Si/H) ~ 25(Si/H)⊙. Turnshek et al. (1987) reported a C/H ratio 10–100 times the solar value in Q0932+501 (see also WTC), and for Q1413+113, they found that S/C and either P/C or Fe/C are at least 100 times solar. For Q0226–1024, Korista et al. (1992, 1996) found a heavy-element abundance Z/Z⊙ ~ 5–10, in the context of an assumed chemical evolution scenario. Analyzing the same observations of Q0226–1024, Turnshek et al. (1996) developed a two-component photoionization model that gave ratios ~4, 9, and 120 times solar for N/O, N/Si, N/C, and N/H, respectively (best-fit model). Enhancements of other elements, including S and Ar, are observed in some cases (Turnshek 1995). Remarkably, P/C is ~65 times the solar value in PG 0846+301 (Junkkarinen et al. 1995; Junkkarinen 1995). The heavy-element enhancements can be reduced, but not eliminated, by using complicated shapes for the ionizing continuum (WTC).

Novae show very large enhancements of C, N, O, and, sometimes, Ne, Mg, Al, Si, Ar, Ca, and Fe (André et al. 1994, and references therein). Novae are produced by thermonuclear explosions on the surface of white dwarf stars accreting hydrogen-rich gas from a close companion star (see review by Starrfield 1989). The ejected gas is enriched with heavy elements mixed in from the white dwarf. Enhancements of Ne and heavier elements, observed in “neon novae,” are attributed to events on O-Ne-Mg white dwarfs (Politano et al. 1995, and references therein). Hydrogen burning leads to especially large enhancements of nitrogen, and in the case of O-Ne-Mg white dwarfs, heavier odd-numbered elements. Figure 1 illustrates the abundances in a set of novae, determined in a uniform manner by André et al. (1994). Abundances of C, O, and Si are typically enhanced by 1–2 orders of magnitude, compared with solar values, and N/H is enhanced by 2–3 orders of magnitude.

I have estimated abundances for several BAL QSOs by assuming that their elemental abundance ratios scale, from those given by Turnshek et al. (1996) for Q0226–1024, in proportion to the corresponding ionizing column densities. (This assumes that the ionization corrections are similar in all these objects. Column density ratios for ions of a single element are generally unavailable to constrain models for individual objects.) Column densities were taken from Junkkarinen et al. (1987) for five BAL QSOs and from Junkkarinen (1995) and coworkers for Q0946+301. Figure 1 shows the resulting abundance ratios along with a value (C/H) = 30(C/H)⊙ for Q0932+501 (Turnshek et al. 1987). The abundance distribu-
tions for C, N, O, and Si for novae and BAL QSOs are similar. Politano et al. (1995) predict P/C ratios of ~50 and 300 times solar for nova explosions on O-Ne-Mg white dwarfs with masses of 1.25 and 1.35 $M_{\odot}$, respectively, bracketing the value for PG 0946+301. These results suggest that the BAL gas may come from novae in a massive star cluster in the active galactic nucleus.

High Si/C and P/C in BAL QSOs suggest that neon novae are typically involved. If O-Ne-Mg white dwarfs come only from progenitors of mass 8–10 $M_{\odot}$ (Nomoto 1984), they should be only a few percent of Galactic white dwarfs. Truran & Livio (1986) attempted to explain the high observed incidence of neon novae in the Galaxy in terms of a small accreted mass per outburst. However, observed masses of neon novae shells are $\sim 10^{-4} M_{\odot}$ (e.g., Shore et al. 1993), so another explanation may be needed. If O-Ne-Mg white dwarfs come from progenitors down to $\sim 5 M_{\odot}$ (Chiosi et al. 1989), these would be a large fraction of all white dwarfs for a cluster age $\sim 10^9$ yr, the likely duration of a QSO episode (Norman & Scoville 1988). Alternatively, perhaps nuclear burning to high atomic numbers, which Politano et al. (1995) find only for the most massive white dwarfs, actually occurs for lower masses as well. Finally, if the BAL geometry is such that debris of different novae are commingled, as might occur in the disk geometry of § 4, neon novae could contribute heavier elements to the mix.

The heavy-element abundances in the broad emission line gas of QSOs may be up to 1 order of magnitude higher than solar, relative to hydrogen (Hamann & Ferland 1993), but apparently are not as high as in the BAL gas. The emission-line abundances have been attributed to rapid chemical evolution involving the usual stellar sources of heavy elements (Hamann & Ferland 1993), and this would not explain high P/C. This suggests that the two regions likely have different origins.

3. ORDINARY NOVAE

Novae are minor sources of interstellar gas in the Galaxy. Can they, nevertheless, be the dominant source of BAL gas? We first consider ordinary novae in a massive nuclear star cluster and then the possibility of accretion onto single white dwarfs passing through a supermassive accretion disk.

The mass of a nova shell typically is $M_{sh} \approx 10^{-4.3} M_{\odot}$ (Warner 1989). As the shell expands and accelerates radially outward, it presumably fragments into a collection of clouds or filaments. We assume that the lateral expansion continues at the original ejection velocity, $v_{nova} \approx 2000$ km s$^{-1}$, appropriate for neon novae (e.g., Ferland, Lambert, & Woodman 1977; Shore et al. 1993; Gehrz et al. 1985). The column density of carbon atoms through the debris is $N_C \approx M_{sh}/(\pi R_{sh}^2)$, where $R_{sh}$ is the shell radius, $M_{sh}$ is the mass of carbon in the nova shell, and $m_C$ is the mass of a carbon atom. Therefore, we may write

$$r_{sh} \approx \left(10^{17.3} \text{ cm}\right) M_{sh}^{1/2} N_C^{-1/2} C/10^{16} \text{ cm}$$

where $N_C = M_{sh}/10^{-5} M_{\odot}$ and $N_C/10^{16} \text{ cm}^{-2}$. For a carbon abundance $C/H = 10^{-3}(C/H)_S$, we expect $M_{sh} \approx 10^{-5} M_{\odot}$. Assuming that roughly half of the carbon is $C_{16}$, we find $N_{C_{16}} \approx 1$ for $r_{sh} \approx 10^{17.0}$ cm. This radius is large enough to cover the continuum source and, within the uncertainties, the Ly$\alpha$ emitting region. As the debris expand, the continuum radiation pressure presumably ablates off material in the form of small clouds, which move radially outward as they are accelerated to the observed outflow velocities (cf. WTC). For $D_{\alpha} \approx w_{nova}/v_{nova}$, $N_{C_{16}}$ drops to unity for distances $\Delta R \approx (w_{nova}/v_{nova})^2 \approx 10^{15}$ cm from an initial location at radius $R_{init}$ where $w \approx 10,000$ km s$^{-1}$ is the outflow velocity.

The expected covering factor for nova shells depends on the nova rate in the star cluster in the galactic nucleus. The covering factor for one shell is $\Omega_{sh}/4\pi \approx \pi r_{sh}^2/(4\pi R^2) \approx 0.25 (v_{nova}/w)^2$, where the second equality assumes $R_{init} < \Delta R$. The number of shells in play at a given moment is $N_{sh0} \approx NR/w$, where $N$ is the rate of nova explosions and $R/w \approx r_{sh}/v_{nova}$ is the crossing time. We evaluate $\Omega/4\pi$ for the value of $r_{sh}$ that gives $N_{C_{16}} \approx 1$. This leads to

$$\frac{\Omega}{4\pi} \approx 0.25 N_{\alpha} v_{nova} w^{-2} \approx 10^{0.15} N_0 (v_{nova}/w) w_0 M_{sh}^{1/2} C/10^{16} N_{C_{16}}^{-1/2}$$

where $N_{\alpha}$ is the nova rate per year and $w_0 = w/10^0 \text{ cm s}^{-1}$. If $R_{sh} \approx \Delta R$, this result should be adjusted accordingly. Note that $\Omega/4\pi$ varies as $(N_{M_{sh}})^{1/2}$, so that events involving a small mass, such as novae, are highly effective for a given average mass-loss rate, $\dot{N}_{M_{sh}}$. The nova rate in the Galaxy (mass $\sim 10^{11} M_{\odot}$) is $\sim 40$ yr$^{-1}$ (Warner 1989; Ciardullo et al.)
and, therefore, we take \( \dot{N}_0 \approx 10^{-11} M_{\odot} \), where \( M_{\odot} \) is the mass of the nuclear star cluster in \( 10^8 M_\odot \). Then we find

\[
\Omega/4\pi \approx 10^{-11} M_\odot (v_{\text{nov}}/c_m) w_1 \approx 10^{-15} M_\odot .
\]

A 10% covering factor requires \( M_\odot \approx 10 \). Analogous estimates of the covering factor for BAL absorption due to planetary nebulae, supernova remnants, and “stellar contrails” (Sovick & Norman 1995) indicate that novae are competitive or dominant by up to 1 order of magnitude. However, none of these sources match the BAL abundances as naturally as do novae.

The mass-loss rate in carbon alone can be estimated as

\[
\dot{M}_c \approx N_c m_c 4\pi R^3 (R/w)^{-1/2} (\Omega/4\pi) \approx 10^{-44} M_\odot \text{ yr}^{-1} \text{ } N_c R_{16} w_5 (\Omega/4\pi).\]

For \( N_c R_{16} \approx 10^4, \Omega/4\pi \approx 0.1 \), this gives \( \dot{M}_c \approx 10^{-54} M_\odot \text{ yr}^{-1} \). This is comparable to the total mass-loss rate, and, therefore, is \( \approx 10^{-12} M_\odot \text{ yr}^{-1} \), a rather modest value.

Norman & Scoville (1988) discussed a coeval star cluster of mass \( \approx 10^8 M_\odot \), the evolutionary debris of which fuels the central black hole. The age of the nuclear star cluster is at most \( 10^8 \) yr at redshift \( z = 2 \) for \( q = 1/2 \) and \( H_0 = 15 \) Gyr, and it could be as young as the estimated QSO lifetime of \( \approx 10^9 \) yr. The “evolutionary flux” of stars leaving the main sequence is an order of magnitude as a coeval cluster evolves from a massive primary. The central collision time would be shorter than the star’s lifetime. The estimated mass-loss rate into the QSO lifetime is \( \approx 10^7 \) yr.

The required star cluster, confined to a radius not much larger than \( 10^3 \) cm, would have a stellar velocity dispersion of several thousand km s\(^{-1}\). The stellar collision time would be shorter than the Hubble time and possibly even the estimated \( \approx 10^9 \) yr lifetime of a QSO episode. Observations of nearby galactic nuclei offer little support for such massive nuclear star clusters (e.g., Lauer et al., 1992, and references therein). Thus, we are motivated to consider ways to enhance the novae rate in QSOs.

### 4. SINGLE WHITE DWARFS

An intriguing possibility is suggested by the work of Artymowicz, Lin, & Wampler (1993, hereafter ALW). They consider stars on orbits passing through an accretion disk around a central black hole of mass \( M_\bullet \), accreting disk gas during each passage. White dwarfs orbiting through the disk will also accrete disk material, and this raises the possibility of nova explosions on single white dwarfs that have accreted the requisite amount of hydrogen-rich gas (cf. Truran et al. 1977). The circular velocity in units of \( 10^8 \) \( \text{km s}^{-1} \) is \( v_{\text{c,8}} \approx 10^{10} M_{\odot}^{2/3} R_{18}^{-1/2} \), where \( M_{\text{tot}} = M_\bullet + M_d \). The average stellar velocity, \( v_\text{a} \), will be roughly \( v_{\text{c,8}} \). Let \( v_{\text{rel}} \) be the velocity of a star relative to the orbiting material in the disk. If the cluster is corotating with the disk, most stars will have \( v_{\text{rel}} \) substantially less than \( v_{\text{c,8}} \). For parameters of interest, \( v_{\text{rel}} \) is less than the escape velocity from the surface of a white dwarf and large compared with the sound speed in the disk. The accretion rate onto the white dwarf while in the disk is

\[
\dot{m} \approx 2.5 \pi G^2 m^2 \rho v_{\text{esc}}^3 \]

(Bondi & Hoyle 1944), where \( m \approx M_\odot \) is the mass of the white dwarf and \( \rho \) is the gas density in the disk. Following ALW, we assume that the disk thickness \( H \) is such that the Toomre (1964) stability parameter, \( Q \), is near unity. Consequently, \( \pi \Sigma R^2 / M_d \approx H/R \approx 10^{-2} \), where \( \Sigma = 2 \rho H \) is the disk surface mass density and a value \( H/R \approx 10^{-2} \) corresponds to the disk’s expected vertical equilibrium. Then, \( \Sigma \approx (10^{15} \text{ g cm}^{-2}) M_{\odot} R_{18}^{-5} \), \( \dot{m}_\text{n} \approx 10^{-10} M_{\odot} R_{18}^{-5} v_{\text{esc}}^3 \), where \( \dot{m}_\text{n} = \dot{m}/(10^{-1} M_\odot \text{ yr}^{-1}) \). If the star’s vertical velocity \( v_z \approx \sqrt{G M_\bullet / r} \), then the duration of passage through the disk is \( \Delta t \approx (10^{-2}) R/\Omega_{\odot} \), and the mass accreted is \( \Delta m \approx (10^{-2}) M_\odot R_{18}^5 v_{\text{esc}}^4 \). If this much mass is accreted twice per orbital period, \( P \approx 2 \pi R/v_\text{rel} = (10^{33}) \text{yr} R_{18}^5 v_{\text{esc}}^4 \), then the average accretion rate is \( (\dot{m}_\text{n}) \approx (10^{-12}) M_\odot R_{18}^5 v_{\text{esc}}^4 \). A typical white dwarf will undergo an explosion at intervals \( t_{\text{nov}} \approx (10^{11}) \text{yr} M_{\odot} R_{18}^5 v_{\text{esc}}^4 \).

Suppose there are \( N_{\text{WD}} \approx 10^7 M_\odot \text{ white dwarfs in the nuclear star cluster (Allen 1973, p. 251). (For a Salpeter 1955 initial mass function ranging from 0.2 to 20 \( M_\odot \), and a mass-selected sample from 1.4 \( M_\odot \), corresponding to an age of \( 10^{9} \) yr, one has \( N_{\text{WD}} \approx 10^8 M_\odot \text{ white dwarfs in the cluster.} \) Let the stars have a typical velocity \( v_{\text{rel}} \), then the average accretion rate is \( \approx (10^{-8}) M_\odot R_{18}^5 v_{\text{esc}}^4 \). For \( M_{\odot} R_{18}^5 v_{\text{esc}}^4 \approx 10^{-4} \), then the duration of passage through the disk is \( \Delta t \approx 10^{-4} \text{yr} \). If this much mass is accreted twice per orbital period, \( P \approx 2 \pi R/v_{\text{rel}} = (10^{33}) \text{yr} R_{18}^5 v_{\text{esc}}^4 \text{.} \) This gives \( N_{\text{WD}} \approx 10^{-8} M_{\odot} R_{18}^5 v_{\text{esc}}^4 \). For \( R_{18} \approx M_{\odot} \approx 1 \) and \( \sigma v_{\text{rel}} \approx 0.5 \), we then have

\[
\Omega/4\pi \approx 10^{-0.8} (v_{\text{nov}}/c_m) w_5 \approx 10^{-15}.
\]

However, accretion is most rapid onto stars with small \( v_{\text{rel}} \), and these can dominate the novae rate in spite of their relatively small numbers, \( N(v_{\text{rel}})/N \approx (v_{\text{rel}}/v_\text{rel})^3 \). If relative velocities down to some minimum, \( v_{\text{min}} \), contribute to the novae rate, then a simple integration over \( v_{\text{rel}} \) shows that the preceeding expressions for \( N_{\text{WD}} \) and \( \Omega/4\pi \) should be increased by a factor \( \approx (v_{\text{rel}}/v_{\text{min}}) \). If violent nova explosions occur for \( m < 10^{-7} M_\odot \text{ yr}^{-1} \) (van den Heuvel et al. 1992), then we may take \( v_{\text{min}} \approx 10^{10} \text{cm s}^{-1} \approx 10^{-1} \text{yr} \). This increases \( N_{\text{WD}} \) and \( \Omega/4\pi \) by 1 order of magnitude, so that \( \Omega/4\pi \approx 10^{-0.8} \). Within the uncertainties, this is consistent with the observed \( 10^{-0.8} \) incidence of BALs. For the assumed parameters, novae involving single white dwarfs outnumber ordinary novae by a factor \( \approx 40 \).

Indications of a flattened BAL region are consistent with novae from white dwarfs with small \( v_{\text{rel}} \), which would orbit close to the disk \( (z/R \approx v_{\text{rel}}/c_m) \). The actual nova event would occur at a random place in the white dwarf’s orbit. The association of BALs with radio-quiet QSOs might involve the absence of a suitable accretion disk in radio-loud objects, perhaps because the latter typically occur in elliptical galaxies.

### 5. DISCUSSION

In summary, the high chemical abundances derived for the BAL region of QSOs resemble the abundances of Galactic novae. The mass of heavy elements in a nova shell is consistent with constraints on the dimensions and location of the BAL absorbing material. A very massive nuclear star cluster must be postulated in order for ordinary nova outbursts to explain the observed incidence of BALs in QSO spectra. Accretion of gas by white dwarfs passing through a supermassive accretion disk can provide sufficient nova outbursts with a more modest star cluster.

Observational consequences include a small BAL region that could show changes over a few years. Different velocity components in the BALs of a given object could result from...
different novae and show different abundances. Odd-numbered elements such as Al and P should be especially enhanced in abundance.

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