Novae and BAL QSOs: The Aluminum Test

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Abstract. Novae have been proposed as the explanation of high reported abundances of heavy elements in the gas producing the broad absorption lines (BALs) of QSOs. High abundances of odd numbered elements, including aluminum, are predicted. Available data contains hints that the Al/Si ratio may be high both in the BAL gas and in the broad emission line (BEL) gas.

1. Abundances in BAL QSOs

Broad absorption lines caused by rapidly (<30,000 km s⁻¹) outflowing gas are seen in the spectra of ≈10% of radio quiet QSOs (Weymann et al. 1991). Analysis of the derived column densities of H0 and various ions of the heavy elements have led to reported abundances of C, N, O, Si, and sometimes other elements, that are 1 to 2 orders of magnitude greater than solar (Turnshek et al. 1996, and references therein). A startlingly high abundance of phosphorus, P/C ≈ 65 (P/C)⊙, was reported by Junkkarinen et al. (1995; see also Junkkarinen et al. in these Proceedings). The problems of scattered light and incomplete geometrical coverage of the continuum source by the BAL gas introduce serious uncertainties (Arav in these Proceedings). Nevertheless, the extraordinary abundances reported for the BAL gas seem likely to survive, at least qualitatively, and the phosphorus anomaly in particular points to an exotic origin.

2. Novae in AGN

Shields (1996) has proposed that the BAL gas largely consists of debris of nova explosions occurring in the inner few light years of the QSO nucleus. This is motivated by high phosphorus abundances in the ejecta of model novae (Politano et al. 1995) and by the resemblance of C, N, O, and Si abundances in observed nova shells to those in BAL QSOs. Approximately one nova per year is required to produce the BAL gas if the BALs occur at a radius of ≈ 10^{18} cm, the minimum allowed by the fact that BALs sometimes absorb the broad line emission. This rate of novae could occur in a nuclear star cluster of mass ≈ 10^8 M⊙ in which single white dwarfs accrete the necessary layer of hydrogen by means of repeated orbital passages through an accretion disk around a supermassive black hole.
3. Aluminum in QSOs

A prediction of nova models is that the odd numbered elements will have enhanced abundances, relative to neighboring even elements, in comparison with normal cosmic abundances. For example, Politano et al. (1995) predict P/C values of 50 and 300 times solar for explosions on white dwarfs of 1.25 and 1.35 $M_{\odot}$, respectively. High Al is observed in nova debris (André et al. 1994). Al III $\lambda$1857 is seen both in BAL and BEL spectra. This offers a potential test of novae as a source of BAL gas and as a contribution to the BEL gas.

3.1. Broad Absorption Lines

BALs typically involve fairly high stages of ionization, e.g., C IV, Si IV, N V, and O VI. Photoionization models (e.g., Turnshek et al. 1996) typically involve gas that is optically thin in the Lyman continuum of H I, $\tau_H << 1$, consistent with the measured column densities of H I. On the other hand, the low ionization BAL QSOs (“Lo-BALs” or “Mg II BAL QSOs”) show a variety of low ionization lines, often including Al III $\lambda$1857 (Wermann et al. 1991; Voit et al. 1993). From the spectra of Wermann et al. (1991), I estimate $\tau_{Al\ III}/\tau_{Si\ IV} \approx 0.30$, 0.30, and 0.36 for QSOs 1011+091, 1231+1325, and 1331–0108 respectively. These values correspond to column density ratios $Al^{+2}/Si^{+3} = 0.22$, 0.22, and 0.27. Figures 2a,b of Voit et al. (1993) give BAL optical depths for models of photoionized clouds with the Mathews and Ferland (1987, “MF”) ionizing continuum and ionization parameters log $U = -1.5$ and -1.0, where $U \equiv \phi_{UV}/Nc$, $\phi_{UV}$ is the incident flux of ionizing photons (cm$^{-2}$ s$^{-1}$), and N is the number density of atoms. For both values of $U$, these models give $\tau_{Al\ III}/\tau_{Si\ IV} \approx 0.05$ for solar Al/Si and an ionization structure extending well into the He$^+$ zone (consistent with the presence of low ionization lines). This suggests that the 3 QSOs may have Al/Si $\approx 6(Al/Si)_{\odot}$.

Unfortunately, this simple approach suffers the uncertainty noted above concerning scattered light affecting the minimum trough intensity. In order to minimize this concern, one may look for cases in which the strongest BALs reach quite low minimum intensities relative to the continuum, $I_{min}/I_{cont}$, but both the Si IV and Al III lines have substantially shallower BALs. The scattered light would then give only a modest contribution to $I_{min}$ in the Si IV and Al III lines, and the derived optical depths would be meaningful in the context of the gross abundance anomalies of interest here. An interesting candidate is UM 232 (Q0019+011), a $z_e \approx 2.12$ BAL QSO for which Barlow et al. (1989) observed Si IV and Al III absorption considerably shallower than C IV. Moreover, the equivalent widths of the BALs decreased with increasing continuum luminosity, L, in a way suggestive of a changing photoionization equilibrium. Adopting this interpretation, I have computed a simple set of photoionization models using the CLOUDY program (Ferland 1996). The models had $\tau_H << 1$, solar abundances, a broken power-law continuum, and a range of ionization parameters. (The abundances have relatively little effect on the ionization for small $\tau_H$.) From the observed fact that the C IV equivalent width decreased with increasing L, but less so than Al III and Si IV, one may estimate $U \approx 10^{-1.9}$ from the fractional abundances $X(A^{+i}) \equiv N(A^{+i})/N(A)$ in the models. This in turn implies an ionization correction, $X(Si^{+3})/X(Al^{+2}) \approx 5$. From the column density ratios...
\[ \frac{\text{Al}^{+2}/\text{Si}^{+3}}{\text{N}(\text{Al}^{+2})/\text{N}(\text{Si}^{+3})} = 0.18 \]
given by Barlow et al. (1989), we find \( \text{Al}/\text{Si} \approx 0.9 \), ten times the solar value \( \text{Al}/\text{Si} = 0.09 \) (Anders and Grevesse 1989).

This result has various uncertainties. Subsequent observations of UM232, and observations of other variable BAL QSOs, do not in general show a clean correlation of BAL depth with luminosity (Barlow et al. 1992; Barlow 1997). Low ionization material has a lower value of \( X(\text{Si}^{+3})/X(\text{Al}^{+2}) \), and a model with a mix of high U and low U material might give a lower derived Al/Si. Nevertheless, the order-of-magnitude Al/Si excess found here by a straightforward analysis provides an intriguing hint that Al as well as P may be enhanced in some BAL QSOs.

### 3.2. Broad Emission Lines

A recently popular view of the abundances in the broad emission-line region (BLR) holds that rapid star formation quickly produces a metallicity \( Z \approx 5 \) to 10 \( Z_\odot \), following a fairly normal chemical evolution scenario (Hamann and Ferland 1993). This view largely rests on the strong observed nitrogen lines together with the expected increase in N/C and N/O with increasing Z because of secondary production of N. (Note that high value of N/C and N/O are also found in nova debris.) However, the inferred dimensions of the BLR are only slightly less than those assumed here \((\sim 10^{18} \text{ cm})\) for the BAL region, and the BLR involves quite modest amounts of gas \((\sim 10 \text{ to } 100 \text{ M}_\odot)\). If only a fraction of the BLR gas comes from the same source as the BAL gas, elevated abundances of P, Al, and other odd numbered elements could result.

The QSO literature contains scattered remarks to the effect that the Al III \( \lambda 1857 \) emission feature is much stronger than expected for solar abundances (Uomoto 1984; Boyd and Ferland 1987). Weymann et al. (1991) find that Al III is especially strong in BAL QSOs, although confusion with Fe emission is an issue. Could these observations find a straightforward explanation in terms of enhanced abundances of Al?

With Fred Hamann of UCSD, I have begun to look at the possibility that gas with abundances resembling those reported for the BAL gas could contribute substantially to the BLR. Here I focus on the specific question of whether Al is enhanced compared with its even numbered neighbor, Si. We have computed a simple grid of BLR photoionization models using CLOUDY. The models have a slab geometry with a gas density \( N_H = 10^{10.5} \text{ cm}^{-3} \) and log \( U = -3.0, -2.0, -1.0, \) and 0.0. The ionizing continuum is that of Mathews and Ferland (1987). Only the model with log \( U = 0.0 \) remained ionized to the stopping column density of \( 10^{23.5} \text{ cm}^{-3} \). Laor et al. (1995) quote Al III intensities for a number of QSOs. For these objects, average values are \( \text{Al III}/(\text{Si III} + \text{Si IV}) \approx 0.30 \) and \( \text{Si III}/\text{Si IV} \approx 0.5 \). The solar abundance models reproduce the Si III/Si IV ratio for log \( U \) slightly greater than -1.0. The models show a substantial increase in Al III/Si III and decrease in Al III/Si IV with increasing U, but Al III/(Si III] + Si IV) is more stable, having values 0.08, 0.07, 0.06, and 0.03 for log \( U = -3, -2, -1, \) and 0, respectively. From the model value for log \( U = -1 \) and the above value of Al III/(Si III] + Si IV), we find \( [\text{Al}/\text{Si}] \equiv \log_{10}[(\text{Al}/\text{Si})/(\text{Al}/\text{Si})_\odot] \approx +0.7 \), assuming the the line ratio scales linearly with the abundance ratio.

In order to test the robustness of this result, we constructed a composite model with equal amounts of ionizing continuum intercepted by solar abundance
clouds with log U = -2, -1, and 0. This is motivated by the “locally optimally emitting clouds” (LOC) picture proposed by Baldwin et al. (1995). This model gave Si III]/Si IV = 1.0, higher than observed; but it had Al III]/(Si III] + Si IV) identical to the log U = -1 model, implying the same Al/Si.

Analysis of a set of BLR models with abundances based on measured BAL abundances is in progress, with the goal of assessing the overall compatibility with observed broad emission-line intensities and the dependence of the derived Al/Si ratio on overall metallicity. Another issue is the possibility of very high densities in QSO emission-line regions. Baldwin et al. (1996) developed a 3 component model to explain the broad emission-line intensities and profiles of 7 QSOs. Their component “A” has $N_H \sim 10^{12.5}$ cm$^{-3}$ and emits strong Al III. This component’s parameters have largely been set to explain the observed Al III intensity. A high aluminum abundance may offer an explanation of the strong observed Al III emission without recourse to such complex geometries. However, the recent observations of the Al III and Mg II doublet ratios in I Zw 1 by Laor et al. (1997) show substantial thermalization (see also Baldwin et al. 1996). This may indicate a high density in the Al III emitting region; and in any case, thermalization will affect the line ratios.

In summary, there are indications that Al/Si may be several times the solar value in the BLR of some QSOs. However, quantitative results are difficult to obtain because of the possible effect of overall high metallicities on the ionization structure and the possibility of high densities and thermalization.

4. Conclusions

The original impetus to consider novae as a source of enriched gas in QSOs was the high P/C ratio reported by Junkkarinen et al. (1995). The high reported abundances of the more common heavy elements in the BAL gas, while still uncertain, resemble those of novae, and accretion onto single white dwarfs in the inner light year of the QSO nucleus provides a possible mechanism for frequent nova eruptions. The high predicted abundances of odd numbered elements in nova debris can be tested by observations of Al III $\lambda 1857$ absorption and emission. The favorable case of UM 232 gives $[\text{Al}/\text{Si}] \approx +1.0$. The strong emission observed in Al III in many QSOs suggests $[\text{Al}/\text{Si}] \approx +0.7$ by a straightforward analysis, but various complications could reduce this value. Nonetheless, these results hint at the possibility of high aluminum abundances both in the absorbing and emitting gas of QSOs. Further observational and theoretical work is needed to confirm the Al/Si results as well as to explore the prevalence of high phosphorus and to test for enhancements of other odd numbered elements. Such confirmation would lend support to the idea that nova explosions (or some other high temperature, nonequilibrium hydrogen burning process) are an important source of gas in QSOs.

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Discussion

*Dr. Burbidge*: In the original nucleosynthesis work, it was slow neutron capture (the s-process for elements in the Ne–Si range) that contributed most to the odd-even element differences. We always had a problem with phosphorus, that is, accounting for its abundance in the solar system abundances.

*Dr. Shields*: The solar system phosphorus abundance can be explained by production in massive stars, mainly neon burning before the star explodes (Woosley and Weaver 1995; Timmes et al. 1995). There are still odd-even abundance differences in the theoretical nova nucleosynthesis results (e.g., Politano et al. 1995). However, nucleosynthesis in nova explosions occurs under nonequilibrium conditions, and the abundances depend largely on cross sections. This gives less of an odd-even effect than for equilibrium nucleosynthesis, in which the odd-even effect reflects differences in binding energy that have an exponential effect on abundances.

*Dr. Foltz*: Do you have enough cosmic time to produce the white dwarfs?

*Dr. Shields*: The Universe was several billion years old when the typical BAL QSO emitted the light we see, so there was plenty of time for white dwarfs if the galaxy formed at a redshift of $z = 5$ or 10. Even if the nuclear star cluster formed at the beginning of the observed QSO outburst, and this lasts only $\sim 10^8$ yr, there could be a substantial population of white dwarfs.

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