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Compact radio-loud Broad Absorption Line Quasars

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Abstract. For a long time, radio-loud Broad Absorption Line Quasars (BAL QSOs) were thought to be extremely rare objects. The absorbing troughs seen in their optical spectra are due to strong winds which probably have their origin within the inner region of the AGN, as a result of the accretion processes. Their radio emission constitutes an additional diagnostic tool which is successfully contributing new perspectives and raise new questions, with the aim to enrich our understanding of the BAL phenomenon.
In this contribution, we introduce a first characterisation of the radio-loud BAL QSO population. Radio continuum spectra have been collected for a sample of 15 objects, which we present together with their radio polarisation properties. VLA maps in A configuration confirm the compactness of these objects at different frequencies up to 43 GHz, yielding projected linear sizes below 1 kpc. We note that many of their radio properties are common to the population of young radio-sources, like Compact Steep Spectrum (CSS) or Gigahertz-Peaked Spectrum (GPS) sources.

Key words. quasars: absorption lines – galaxies: evolution – Radio continuum: galaxies – Polarization

1. Introduction

The presence of Broad Absorption Lines (BALs) in the optical spectra of a significant

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fraction of quasars is interpreted as a footprint of powerful quasar winds. The importance of constraining and understanding the properties of these winds is multiple because they impact on several astrophysical problems, from the quasar evolution itself to the interaction with the environment at different spatial scales.

The fraction of optically-selected Broad Absorption Line Quasars (BAL QSOs) depends on the exact definition of a BAL trough, which is necessary in order to classify a quasar as a BAL QSO or not. Refined classifications have permitted to have good estimates on the true (intrinsic) fraction of BAL QSOs after correcting for several observational biases. This fraction has been found to be about 15 per cent of the quasar population (Reichard et al. 2003; Knigge et al. 2008)

On those BAL QSO samples selected in the near-IR, where the obscuration effects are smaller, this fraction has been found to be higher than in the optical (Dai et al. 2008; Maddox & Hewett 2008). In the radio domain, radio-loud BAL QSOs were thought to be extremely rare just two decades ago (Stocke et al. 1992). With the advent of the FIRST survey (Becker et al. 1995) a considerable population of these objects have been found. However, it has been shown that radio powerful quasars are less likely to show BALs (Becker et al. 2001; Shankar et al. 2008).

Two types of model have been proposed in order to explain the nature of BAL QSOs. On the one hand, all quasars might host an outflow and BALs are only seen on those for which our line of sight to them intersects that outflow (e.g. Elvis 2000). On the other hand, the BAL phenomenon might occur in one or more specific periods along the evolution of the quasar (e.g., Gregg et al. 2006). The intriguing anti-correlation between radio power and strength of the BAL troughs seems to suggest such an evolutionary scenario. There are, in addition, some observational facts not consistent with simple orientation models, like the coexistence of populations of polar and FR II-type BAL QSOs (Zhou et al. 2006; Gregg et al. 2006) suggesting opposite orientations, or the presence of steep and flat spectral indices among BAL QSOs (Becker et al. 2000; Montenegro-Montes et al. 2008).

Thus, radio observations have become an important diagnostic tool to explore the nature of BAL QSOs. Their radio emission allows us to have information about the orientation and evolutionary status of these objects.

2. Radio BAL QSOs

The first sample of radio BAL QSOs was extracted by Becker et al. (2000) from the FIRST Bright Quasar Survey (FBQS) and included 29 objects with a radio cut in flux density of $S_{1.4\,GHz}$ >1 mJy. They found compact radio morphologies for these objects in contrast with the mixture of compact/extended morphologies found within the population of FBQS quasars. Their observations at 1.4 and 8.4 GHz showed a variety of spectral indices with two thirds of the sample having steep spectra.

Some properties of the radio sources associated to BAL QSOs recall those of Compact Steep Spectrum (CSS) or Gigahertz-Peaked Spectrum (GPS) sources. These sources are defined by a convex radio continuum spectrum peaking at a few hundred MHz (CSS) or about 1 GHz (GPS). They present compact radio morphologies with projected linear sizes of a few kpc (CSS) or below 1 kpc (GPS). The most accepted scenario explaining the nature of these objects is the *youth* scenario (e.g., Fanti et al. 1995) in which GPS sources would be young radio sources evolving into larger CSS sources, and later possibly into larger radio galaxies.

It has been proposed that these groups of CSS and GPS sources, which are defined on the basis on their spectral shape and their radio morphology, can include different kind of objects with different physical conditions. For instance, Snellen et al. (1999) have shown that some GPS sources associated to optical QSOs can be just normal flat-spectrum quasars for which a jet/knot/hot-spot dominates the spectrum, which then adopts the characteristic convex shape of a GPS source. Stanghellini et al. (2005) have studied VLBI samples of GPS sources confirming this scenario. In fact, these “contaminant” quasars seem to be present, even in high percentages, in many well-defined samples of GPS sources (Torniainen et al. 2005). Two characteristics of "genuine" young GPS radio sources are low polarisation and low variability (O'Dea 1998), while flat-spectrum quasars show higher polarisation and variability.

In order to characterise the radio properties of BAL QSOs and locate them in the framework of the orientation versus evolution scenario, we have collected multi-frequency observations in full polarisation of a sample of 15 radio BAL QSOs (Montenegro-Montes et al. 2008). These observations complemented by literature data cover the spectral range from 74 MHz up to 43 GHz. The selection was based on the available samples of radio-loud BAL QSOs in the literature when the project was started. The main selection criterion was a cut in flux density of $S_{1.4\ \mathrm{GHz}} > 15$ mJy in order to facilitate total power detections at high frequencies and also the detection of polarised emission from those sources with a higher degree of linear polarisation.

2.1. Spectral shapes

Many of the sources in the sample have a relatively steep spectrum at high frequency. About 75 per cent of the sample show flattening of the spectrum at low frequencies (typically below 1-5 GHz) which could indicate synchrotron self-absorption. However, in some cases some variability cannot be excluded, since the 1.4-GHz measurements were taken some years before the others. About 1/3 of the sample show, in addition, enhanced emission at MHz frequencies which might indicate a second component emitting mostly in this range. Again, variability cannot be ruled out, but any possible time variability is expected to be less pronounced at lower frequencies.

In Figure 1 we show all the spectra after transformation to a common normalisation rest-frame frequency of 25 GHz. We see a variety of spectral slopes around this frequency. Assuming that variability effects are not very important, Figure 1 reflects the rest-frame spectrum of a typical BAL QSO in our sample. It is in general convex, quite flat below

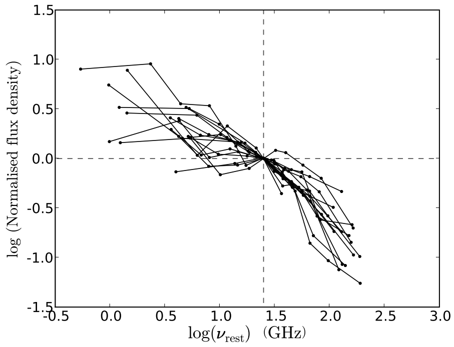

Fig. 1. Rest-frame spectra of 15 BAL QSOs in the sample. They have been normalised to ν_{rest}=25.0 GHz (log(ν_{rest})=1.398)

10 GHz, and steepening around 25 GHz. For about half of the sources the spectra steepen even further at frequencies higher than 50 GHz.

A preliminary variability study with only two observing epochs is shown in Montenegro-Montes et al. (2008). A high percentage of the sample does not show significant variability when comparing the flux densities at 1.4 GHz at 2 different epochs. Some BAL QSOs show significant variability at 8.4 GHz but not strong enough to exclude them from the candidates to young radio sources.

2.2. Polarisation

Compact GPS sources are supposed to be completely embedded in their narrow line region. On this basis, Cotton et al. (2003) proposed the existence of a typical frequency-dependent scale, below which the GPS source becomes completely depolarised, the so-called "Cotton effect".

At 8.4 GHz, one third of the sample (i.e, 5 out of 15) show at least a 3-σ detection in Stokes Q, Stokes U or both. From these 5 BAL QSOs only 1624+3758 is strongly polarised showing 6.5 per cent of linearly polarised flux density (Benn et al. 2005). The fractional polarised intensity in the other four objects is below 3 per cent. The upper limits for most of

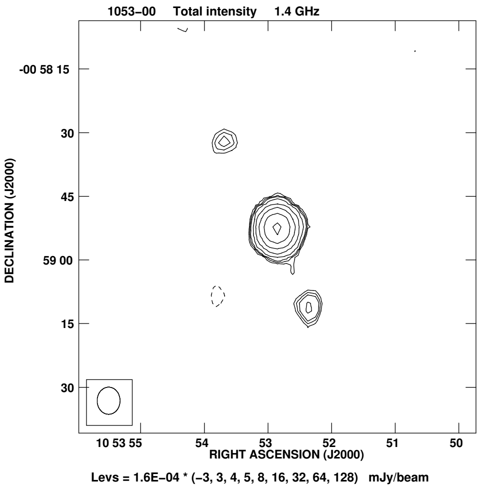

Fig. 2. Map of BAL QSO 1053−00 from FIRST at 1.4 GHz. The synthesized beam-size is shown in the lower-left corner.

the 10 undetected sources are below 1 per cent indicating strong depolarisation.

The median fractional polarisation at 8.4 GHz ($m_{8.4}$) of the 5 polarised BAL QSOs is ~1.3 per cent, but the remaining 10 BAL QSOs show $m_{8.4} \lesssim 1$ per cent. As a comparison Saikia et al. (1987) found a median polarisation degree at 6 GHz of about 2 per cent in a subsample of quasars from the sample of ~400 compact sources of Perley (1982). Saikia et al. (1987) found no significant differences between the median value of flat-spectrum cores and CSS quasars whereas radio sources associated to galaxies or to empty fields (no optical identifications) were found to be less polarised at 6 GHz, with a median value of ~0.5 per cent. More recently, Stanghellini (2003) found a mean fractional polarisation of 1.2 and 1.8 per cent for GPS and flat-spectrum quasars, respectively, and $m < 0.3$ per cent for galaxies.

2.3. Morphology

The FIRST maps at 1.4 GHz show a compact morphology for all 15 BAL QSOs, at a resolution of ~5″. To quantify this we have computed the morphological parameter Θ, based on the FIRST integrated and peak flux densities, $\Theta = \log(S_{int}/S_{peak})$, and for all 15 sources $\Theta < 0.03$. Our VLA maps show very compact morphologies for all 15 sources at all frequencies, at a maximum resolution of 80 mas. The exceptions are 1312+23 which shows some elongation at 22 and 43 GHz, and 1053−00 which is extended at 1.4 GHz showing two faint lobes not detected at higher frequency (Figure 2)

3. Conclusions

Our analysis of a sample of 15 radio BAL QSOs show that they share several properties similar to young CSS/GPS radio sources, like convex radio spectra or moderate variability and polarisation. This supports the scenario in which BAL QSOs can be quasars at the early stages of their evolution, as opposed to simple orientation models.

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