Radio properties of $0.4 < z < 0.8$ BAL QSOs

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Abstract. We present MERLIN 18 cm radio continuum observations of three $0.4 < z < 0.8$ broad-absorption-line (BAL) quasi-stellar objects (QSOs). The question, whether BAL QSOs can be interpreted in a pure orientation scheme, or whether evolutionary aspects have to be taken into account, is still a matter of debate. Radio-interferometric observations can provide additional information about both aspects. The presence of jets, their orientation, and beaming can provide clues on the orientation of the nuclear components. On the other hand, the compactness of the nuclear radio emission and its spectral index can provide information about the evolutionary state of the AGN, and of starbursts, if present.

1. Introduction
There appears to be an intimate link between the growth of supermassive black holes (SMBHs) and the galaxy bulges they reside in (e.g., [1, 2] and references therein). This suggests the existence of physical feedback mechanisms to regulate their co-evolution. In the quasi-stellar object (QSO) phase, i.e. during which the bulk of the accretion of matter onto the SMBH occurs, winds/outflows from the innermost region of the quasar can be an important source of feedback [2]. An extreme manifestation of strong outflows is the broad absorption line (BAL) phenomenon in QSOs. BAL QSOs are a rare subclass, comprising about 15% of the QSO population at high redshifts [3]. The outflows in the BAL QSOs are revealed by metal absorption systems with large blueshifted velocities (several thousand km/s). In recent years, two interpretations of this phenomenon emerged:

1) Unified scheme: Under the assumption of the unified scheme for active galaxies [4], the absorbing clouds have a small covering factor as seen from the QSO nucleus [5]. Thus, the frequency of detection just translates to the rate at which our line of site intercepts the outflow.
(2) Evolution scheme: The evolution model for BAL QSOs represents one aspect of the merger-driven ultraluminous-infrared galaxy (ULIRG)-to-QSO-evolution scenario proposed by [6], which describes the process of accumulation of large amounts of molecular gas and dust in the center of the merger remnant, subsequently triggering massive star formation (ULIRG phase) and nuclear activity. In the next phase, which marks the BAL QSOs stage, these young objects are ejecting their gaseous envelopes at very high velocities following the initial turn-on of the active galactic nucleus [7, 8, 9]. This turn-on can also be connected with circumnuclear starbursts which contribute to such outflows [10]. In the final stage the AGN feedback has removed all the gas and dust from the nuclear region and appears as a classical QSO with a red elliptical host [11]. There is quite some controversy about the nature of the BAL phenomenon, since several investigations support one or the other model (cf. discussion in [12]).

Quite recently, studies in the radio domain have been able to shed light on these issues [13, 14, 15, 16]. The radio properties can be used to study orientation and compactness of BAL QSOs. The former revealed that BAL QSOs apparently occur in two varieties, namely in equatorial and polar configurations [17]. The latter, combined with radio-spectral indices, shows that BAL QSOs are similar to young radio sources [15, 16]. It, therefore, appears that the BAL phenomenon is more complex and probably a combination of the two "basic" scenarios.

The origin of the BAL phenomenon is still under debate and maybe linked with the host galaxy in an evolution scenario. BAL QSOs are typically found at high redshifts (z > 1) [18] coinciding with the peak of the cosmic QSO space density. Because of the small angular extent of the host galaxy and brightness of the QSO, it is very costly to address this issue. However, when inspecting observations of the handful of low-redshift BAL QSOs, one finds that virtually all of them are associated with galaxy mergers and enhanced star formation [9, 10]. Therefore, it might be instructive to have a closer look at the extended radio emission in BAL QSOs.

2. Observations and results

Here, we focus on the z < 1 part of the redshift distribution of BAL QSOs, which will allow us to carry out more detailed structural investigations (Zuther et al. in prep.). In a pilot study, we chose three low-ionization BAL QSOs in the 0.4 < z < 0.8 range from the sample of SDSS low-ionization BAL QSOs [19]. These three objects were detected as unresolved sources with the Very Large Array FIRST survey at a few milli-Jansky (0758+553, 1017+125, 0908+407). Based on the 20 cm and SDSS i-band flux densities, their radio-loudness is of intermediate character, log R ≡ log(S20cm/Si) ≈ 1. They have SMBH masses of about 10^7.5 M⊙ and accrete at the Eddington limit (based on their g-band luminosities and a bolometric correction according to [20]). We observed these three BAL QSOs at 18 cm with the Multi-Element-Radio-Linked Interferometer Network (MERLIN). The reconstructed images have an angular resolution of about 300 milli-arcseconds (mas). This corresponds to linear scales of 1.6-2 kpc at the object’s redshifts. Maps are presented in Fig. 1.

The objects in the MERLIN maps are unresolved and recover about 60% of the FIRST 20 cm flux density. Most of the flux, therefore, is constrained to the central two kilo-parsecs. These objects show no jet-like large-scale structures, neither in the FIRST images on scales of several 10 kpc, nor our MERLIN images. Taking variability and interstellar scintillation into account, which typically can be of the order of 10-30%, it seems plausible that low-surface-brightness emission due to extended emission by star formation does not play a dominant role - at least at radio wavelengths. We, furthermore, estimated the star-formation rate assuming that all radio emission is due to star formation. This would then predict about 1000 M⊙yr⁻¹. The corresponding far-infrared luminosity would be of the order of 10^{13} L⊙, in conflict with the fact that none of the objects has been observed to be a ULIRG. The brightness temperatures of about 10⁵ K, estimated from the MERLIN beam size, are on the lower end of brightness temperatures found for typical accretion scenarios (~ 10^{5-7} K, [21]). Nevertheless, assuming
that the emission is originating from an even more compact region (e.g., [13, 22]), one can expect the MERLIN-based brightness temperatures to be a lower limit. We therefore conclude that the radio emission is not dominated by starbursts.

This conclusion is supported by the fact that the SDSS spectra are dominated by the QSO, even though one might expect to recognize the host galaxy in the spectrum because of the strong suppression of the AGN emission by the BAL outflow (lower right panel in Fig. 1). However, the [OII] emission is relatively strong and might be related to star formation [23]. Therefore, higher angular resolution observations, preferentially at several wavelengths are needed.

3. Summary
We presented preliminary results from a radio-interferometric study of intermediate-redshift BAL QSOs. Our MERLIN 18 cm data show compact emission on the sub-2 kpc scale. The compactness together with the brightness temperatures and the AGN dominated SDSS spectra indicate that star formation does not play a dominant role in these objects - at least as traced
by the radio emission.

Although we did not find jet structures on large scales, we cannot conclude on the orientation properties, because the scales probed with MERLIN at 18 cm are still too large. We showed the feasibility to study intermediate-redshift BAL QSOs at milli-Jy flux-density levels with interferometric techniques. Future follow-up observations at shorter wavelengths, especially with eMERLIN, will provide higher angular resolution and additional spectral information, necessary to study the origin of the compact radio emission in these objects.

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