Scientific context: We propose e-MERLIN observations in order to map critical, otherwise unseen, structures within strongly lensed radio quiet quasars (RQQ). Since strong gravitational lensing results in the dramatic magnification of a background object, we can use strong lenses as cosmic telescopes, typically increasing the effective sensitivity of the observing instrument to that of one 25-100 times larger. We can study quasars and their host galaxies in more detail, resolving beam-limited structure into individual components.

Although originally discovered in a radio survey, most quasars produce relatively low levels of radio emission. Evidence for the physics behind this emission is not yet conclusive, with most authors making strong arguments for either starburst activity or for AGN engines as the main mechanism responsible. It is important to distinguish between these two processes, both statistically and in individual cases, so that the wider problem of galaxy evolution, in particular the role of AGN feedback in star formation, can be addressed. The possible causes of RQQ emission have been debated extensively in the literature over several decades. Kellermann et al. [1989] used the VLA to study an optically-selected sample of the Palomar Bright Quasar survey, and found an apparent bimodality within the radio-optical emission ratios. More recent work by Condon et al. [2013] used a sample from the NVSS to find an upturn in source counts at the faint end of the quasar luminosity function, hinting at a large population of star-forming sources residing at the Jy level. On the other hand, source count studies undertaken by Blundell and Beasley [1998] and Leipski et al. [2006] showed a less firm distinction between the two regimes, finding sources of intermediate flux density. Together with evidence of source variability by Barvainis et al. [2005], these findings point to a unified model, where the same AGN engine is operating in each case. Alternative approaches to the problem have made use of the tight radio-FIR flux density correlation observed in star-forming regions (e.g. Stacey et al. [2018]. White et al. [2017] showed, in a sample of QSOs from the Spitzer-Herschel Active Galaxy Survey, an excess of radio emission compared to that expected from the radio-FIR correlation, which cannot be explained by star-formation alone. This result contradicted the findings of Bonzini et al [2015]. Exotic mechanisms such as optically-thin bremsstrahlung emission in the core of the sources [Blundell and Kuncic, 2007] or emission from magnetically-heated coronae [Laor and Behar, 2008] are also suggested.

The various investigations described have been statistical in nature and are subject to potential biases arising from sample selection. Additionally, some investigations have relied on the use of assumed spectral indices when converting catalogues of observed flux densities from between wavebands. Lensing allows us access to the very faintest radio sources, probing a unique population in order to build a more detailed picture of quasar behaviour over cosmic time. The magnifying power of lensing also stretches source structure to scales significantly larger than closer, unlensed quasars. Combined with the resolution and sensitivity of e-MERLIN, we have a powerful tool for determining the nature of the radio structure by directly imaging it.

Results from the programme to date: VLA, e-MERLIN and EVN results have been published in three papers so far (Jackson 2011, Jackson et al. 2015, Hartley et al. 2019, the latter two including e-MERLIN data) with two more (VLA/ALMA) in preparation or about to be submitted (Badole et al. 2019, Hartley et al. 2019b). Our results are as follows:

- The RQQ HS 0810+2554 is clearly a lensed AGN with intrinsic flux density about 1μJy. (Fig. 1)
- The RQQ SDSS J1004+4112 is a lensed AGN, because its flux density in some components with VLA in A-configuration is considerably brighter than an earlier observation with C-configuration. This means that the flux density is variable over timescales of years, and cannot therefore originate in an extended star-forming disk. (Fig. 1)
- The RQQ SDSS 0924+0219 has radio emission at a very low level (detected in 12 hours at the VLA), which is coincident with the ALMA line emission and appears to be about the same size.

This is intriguing as it suggests an origin in a star-forming molecular disk in this case, although unfortunately the radio emission is too faint for e-MERLIN (or EVN).

- The RQQ PG 1115+080 has brighter emission with the VLA. e-MERLIN observations at C-band are awaited for this object, and an EVN proposal has been accepted and just correlated.
- The RQQ 0435−1223 is an interesting case with a possible extended source (Jackson et al. 2015, Fadely & Keeton 2011) but we do not have higher-resolution observations than the VLA.

This proposal: We intend to focus on two interesting objects:

PG1115+080. This is a relatively bright RQQ with a peak 5-GHz flux density of about 670μJy (and hence an unmagnified flux density of a few tens of μJy, assuming the source is approximately pointlike). It is interesting for a number of reasons. There is a “flux anomaly” in this object, the physical manifestation of which is the non-unity flux ratios of the nearby components A and B (Fig. 1) which would be expected to be 1 if the lens model were smooth. This may indicate small-scale substructure in the lensing galaxy, which in turn is a strong prediction of CDM (e.g. Mao & Schneider 1998, Dalal & Kochanek 2003). This is already known in the optical, but we should get further information about the mass model by upcoming e-MERLIN 5-GHz observations (awarded last semester). We would also like, however, to observe this source at L-band. The aim here will be to get a matched-resolution spectral index map with the VLA C-band map; the components are just resolved and we aim to search for spectral index gradients in the lensed images, which will translate (via a lens model) to spectral index gradients in the source. This would be important evidence in favour of an AGN origin if we found bright flat-spectrum core emission surrounded by steeper-spectrum diffuse emission.

HE 0435−1223. This is a more difficult source because it is fainter (each image about 40μJy at 5 GHz, though likely 50-60 at L-band) and at a more awkward declination. We have been awarded 48 hours to look at it with the EVN, however, as it is an intriguing object. The flux density ratios of the four images (Fig. 1) are different from those in the far-IR (Jackson et al. 2015, Fadely & Keeton 2011); modelling predicts that this implies a source size of about 80 mas in the source plane. The VLA does not give the resolution to confirm this directly, even with the stretching of a factor of $\sim$5 due to gravitational lensing, but the e-MERLIN resolution of 200 mas should allow us to do this. e-MERLIN is also an essential bridge between the low resolution of the VLA and the high resolution of the EVN which may resolve out some of the structure, especially if any AGN does not contribute significantly to the radio emission. e-MERLIN with thus allow us to determine the scale and thus the physical origin of the radio structure.

Technical requirements. We propose to observe both sources at L-band. PG1115+080 is straightforward: we want to match the noise level of the VLA image, scaled by a spectral index of about −0.7 between C- and L-band. A noise level of 10μJy will therefore suffice, which can be reached in one track with the Lovell telescope, or three tracks with the Mk2. HE 0445−1223 is quite faint, and will require a noise level of about 7μJy in order to detect the faintest image at 3σ. We assume that the noise at this declination is about 50% worse than at more northerly declinations, and so need 3 tracks with the Lovell for this object (again, 9 tracks with the Mk2 would also suffice). Observations can be obtained in standard continuum mode, with the channelization limited only by adequate RFI removal (both fields of interest are very small).

References

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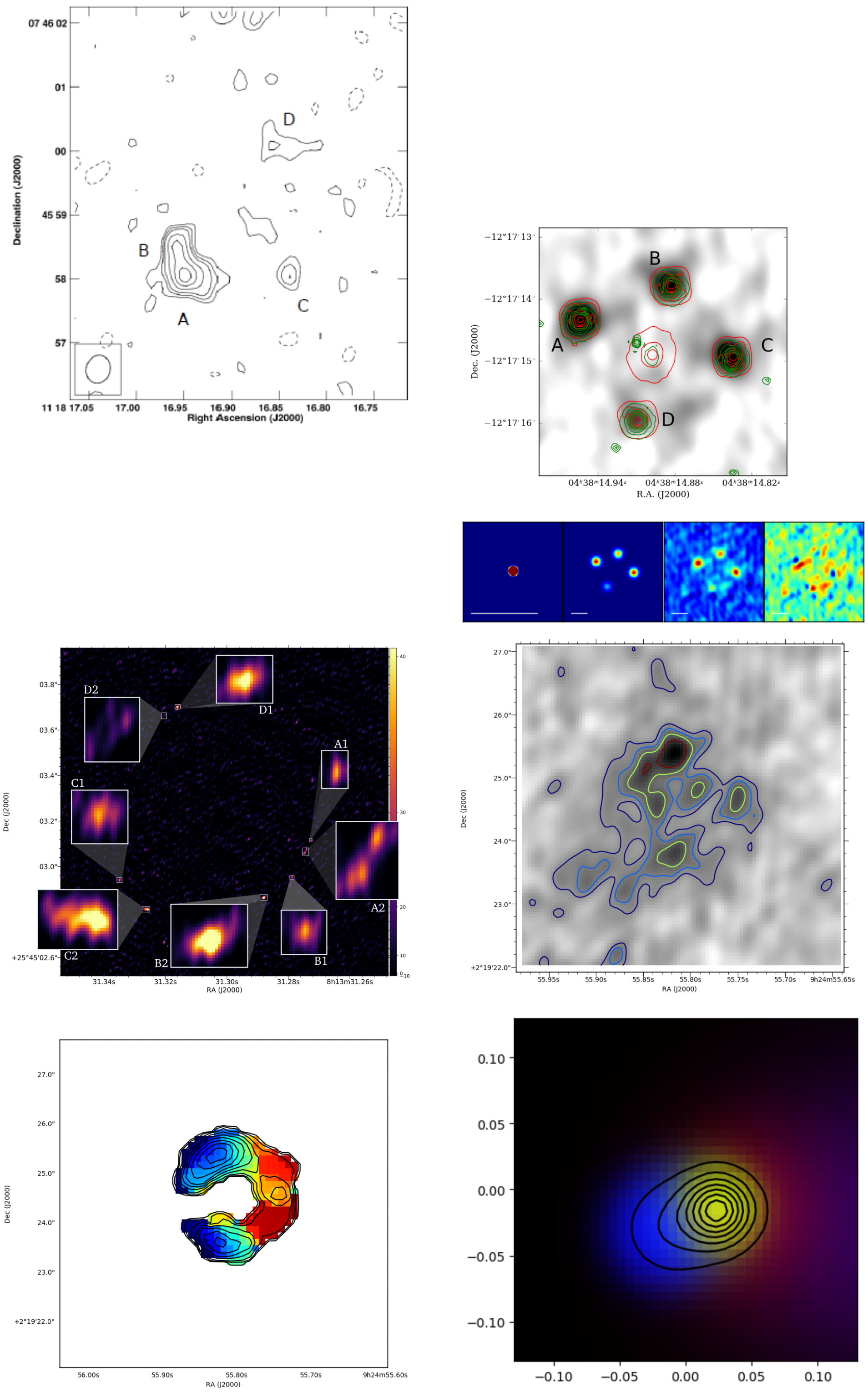

Figure 1: Top: objects in this proposal. Left: PG1115+080 (VLA, C-band) showing the four lensed images, slightly extended. Right: 0435, with VLA greyscale on HST contours, and model of the VLA data which predicts a slightly extended source. Middle: Previous results on HS0810+2554 (Hartley et al. 2019) and SDSS J0924+0219 (VLA, Badole et al. 2019). Bottom: ALMA CO-line results on SDSS J0924+0219 (moment map, and reconstructed source plane image showing the size of the molecular disk).