Obscured quasars: radio emission at sub-kiloparsec scales

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ABSTRACT
Radio observations using the European very long baseline interferometry network (EVN) at 18 cm have been carried out on 11 z ≥ 2, radio-intermediate obscured quasars. Radio emission in 8 out of 11 sources is detected at sub-mJy level. The detected radio emission of each source account for ~ 50 − 80% of the entire flux density. The physical extent of this emission is ≤ 257 pc, and the derived properties indicate this emission originates the present of an active galactic nuclei (AGN). The missing flux density resolved out by the interferometer cannot be accounted for by star-formation only, and radio jets of physical size between ≥ 257 pc and ≤ 40 kpc are likely to be present.

Key words: techniques:interferometric - galaxies:active - galaxies:nuclei - quasars:general - radio continuum:galaxies

1 INTRODUCTION
Active galactic nuclei (AGN) show a range of observed properties, some of which have been explained as occurring due to the differences in orientation of an accreting supermassive black hole with respect to our line of sight (e.g. Urry & Padovani 1995). When our line of sight is close to the axis of symmetry, the central region of the accretion disk can be seen and the AGN appears unobscured. If the line of sight is blocked by the dust surrounding the accretion disk (the torus), the AGN appears obscured.

The density evolution of optical selected quasars that host such an accretion disk shows an increase at redshifts around 2.5, indicating enhanced nuclear activity at such epoch (Fan et al. 2006, and references therein). Nevertheless it has been speculated that a large fraction of such sources are invisible by this studies due to heavy obscuration. The Spitzer space telescope has enabled the search for heavily obscured AGN up to high redshifts, using mid-infrared criteria, and numerous examples of obscured quasars have been detected (e.g. Lacy et al. 2004, Houck et al. 2005). And by selecting a sample of radio-intermediate obscured quasars by using a combination of data at 24 µm, 3.6 µm and 1.4 GHz it has been shown that most supermassive black hole growth is obscured by dust (Martínez-Sansigre et al. 2005). And about half of the sampled objects did not show any emission lines in optical spectroscopy and mid-infrared spectroscopy of these sources has confirmed them as obscured quasars (Martínez-Sansigre et al. 2008, MS08). This has led to the suggestion that the torus invoked by unified schemes might not be the only source of obscuration, and that obscuration by dust on a larger scale (~kpc) might be responsible for the lack of observable narrow lines (e.g. MS06a, Rigby et al. 2006, Brand et al. 2007).

The sources in this sample are radio intermediate, and show radio spectral characteristics consistent with low-redshift FR-I sources (Fanaroff & Riley 1974), but surprisingly some show the flat radio spectra characteristic of unobscured quasars with the radio jet close to the observer’s line of sight (Martínez-Sansigre et al., 2006b, MS06b). This is not expected for quasars obscured by the torus, but can be explained, if the obscuring dust is distributed on ~kpc scales and not necessarily related to the torus of the unified schemes.

Observations using very long baseline interferometry (VLBI) are ideal to investigate the radio emission structure of these sources at milli-arcseconds scales (mas). Given that the sources in this sample have radio properties consistent with FR-I sources, a significant fraction of the flux is expected to arise from relatively compact regions, detectable

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as a “core”. The diffuse radio emission either from radio jets or from from extended star-forming regions is, due to the spares telescope spacing, most likely resolved out, and only compact components may be detected. Quantifying the fraction of the radio emission arising in compact and extended regions will help to determine the orientation of the radio outflow in the nuclear region.

This article presents observations of a subsample of 11 out of 21 sources in the MS05 sample, using the European VLBI Network (EVN). All 11 sources have now been spectroscopically confirmed as obscured quasars, from either optical or mid-infrared spectroscopy (MS08). Throughout this paper a LCDM cosmology is assumed with the following parameters: $h = H_0/(100 \text{ km s}^{-1} \text{ Mpc}^{-1}) = 0.7$, $\Omega_m = 0.3$, $\Omega_\Lambda = 0.3$.

## 2 OBSERVATIONS AND DATA REDUCTION

EVN observations were performed on the 29th, 30th October and 1st November 2005, hereafter dates A, B and C. The telescopes used during these observations form an array with baselines ranging of 266 km to 8476 km [Effelsberg, Onsala (85 ft), Jodrell Bank (Lovell), Medicina, Torun, Urumqi, Shanghai and WSRT (phased array)]. The WSRT data on the target sources have been lost due to technical problems. This results in an array having the shortest baseline of ~637 km which corresponds to a spatial sensitivity of ~62 mas.

Due to the faintness of the actual targets, the observations make use of the phase-reference technique, observing a target- and a phase-calibrator source (target source 10 minutes & J1722+5856 3 minutes) within a cycle of 13 minutes. The target sources are between 0.4 and 1.3 degrees apart from the phase-calibrator source. Additional sources have been observed to fringe fit (J2005+7702, 3C345) and to cross check the phase-referencing technique (J1722+6105, J171156.0+590639).

The observations uses the Mark5A recording system (1024 Mbit/s) with 2 bit sampling, in 2 polarizations and 2s integration time. The high data rate capability allows the simultaneous observation of 8 sub-bands. Each of the sub-bands has 32 channels with a bandwidth of 16 MHz. The total frequency coverage is from 1594.99 MHz to 1704.49 MHz which results in a central frequency of 1658.24 MHz. With a fractional bandwidth of about 8% a significant increase of UV coverage is due to the bandwidth range. As an example the UV-coverage of the phase calibrator source is shown in Figure 1. With an on-source integration time of ~1 hour, the expected sensitivity in a naturally weighted image is ~20 $\mu$Jy.

After observations the data has been correlated at the Joint Institute for VLBI in Europe [JIVE]. The positions of the target sources are determined on the basis of VLA-B array observations at 5 arcsec resolution (FWHM). The integration time (2s) and the number of channels assure that the field of view (FoV) of the EVN observation is larger than the synthesised VLA beam. Furthermore, this setup ensures that the expected loss in amplitude of about 10% (assuming a point source response) due to time-smearing would be expected at a distance of 16.7 arcseconds from the pointing center and due to bandwidth-smearing at 9.9 arcseconds (based on the EVN sensitivity calculator\(^1\)). In addition, to instrumental effects that could cause a loss in flux density, are introduced phase variations by the Ionosphere. Plotting the fraction of the detected radio emission versus the angular distance to the phase center does not show any correlation (Fig. 2) and therefore an observational effect for the flux density loss can be neglected.

Data reduction and analysis have been performed using AIPS and ParselTongue [Greisen 1990; Kettenis et al. 2006]. The observational data was a-priori gain calibrated by using the system temperatures measured at each individual telescope. Prior phase delay corrections are applied by using the Ionosphere electron content and the AIPS task TECOR. The phases were then calibrated by initial fringe finding (FRING) followed by

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a full self-calibration procedure on the phase calibrator itself (CALIB). The bandpass of the system has been calibrated by using the phase-calibrator source (BPASS), because no simultaneous measurement of the fringe and bandpass calibrator (3C 345) could be recorded for all telescopes. The final UV-dataset has been produced by applying the calibration correction of J1722+5856 in phase, in amplitude and bandpass excluding 4 channels on each edge of each sub-band. Reducing the total frequency range to 96 MHz and the theoretical image sensitivity to \(~22.5 \mu\text{Jy/beam}.\) Flaging the UV-dataset is based on the individual channels and on the pseudo-continuum emission of the phase-reference source. In addition, minor flagging has been done on the noise-dominated data of the target sources.

The imaging procedure has been performed in three steps (using the task IMAGR). First, a dirty image, with no weighting applied, has been produced covering the FoV of the low resolution VLA-beam. Second, a cleaned image has been produced with a robust weighting of 0.5 to reduce the side-lobe levels. When radio emission has been detected at a 5\sigma \sim 130\mu\text{Jy level}, a Gaussian fit to the emission has been used to determine the coordinates of the emission. The third image has been produced by shifting the tangent-point of the data, using a robust weighting of 3 and cleaning the centre region of the image. The properties of the detected radio emission have been determined by IMFIT.

The estimated radio flux of the calibrator J1722+5856 is $141.4 \pm 0.7$, $129.9 \pm 0.5$ and $129.0 \pm 0.8$; for dates A, B and C respectively. The estimated position of the phase-calibrator is consistent within positions in the VLBI catalogue C-VCS4 (Petrov et al. 2006). The flux discrepancy between observations is consistent within 10\%, as expected. Observation on date A, however, suffers from poor data quality. In order to test the reliability of the phase-calibration technique, two test sources (J1722+6105 and W171156.0+590639) have been observed and calibrated in identical manner to the target sources. The VLBI calibrator J1722+6105 has been scheduled within all three observing runs like an additional target source. The angular separations between the phase-reference source and J1722+6122 is $2.16 \degree$. The radio flux densities of the source J1722+6122 are $181.1 \pm 8.7$ (date A), $131.1 \pm 15.9$ (B), $131.5 \pm 11$ (C) which indicates an additional error of the order of 23\% to 34\% percent for the measurements of observation A. The estimated position of J1722+6122 for each day of the observations match the coordinates within the errors of the astrometric reference frame (Petrov et al. 2006). The percentages of the individual target sources have been displayed in Figure 2 showing no systematic reduction of the missed flux. In addition, the observations on the 1st of November the source J171156.0+590639 has been observed in order to test the observing strategy. This source is 1.38 \degree separated from the phase-reference calibrator and has been observed with the
VLBA at 1.4 GHz. The flux density at 1.4 GHz VLBA of 17.0±1.29 mJy (Wrobel et al. 2004) are within the errors comparable with the EVN measurements at 1658.24 MHz is 15.6±2.0 mJy (27±19 mas) shown in Figure 3. The small difference in flux densities can be explained by the slightly different observed frequencies provided that, at VLBI resolution, J171156.0+590639 has a spectral index $\sim \alpha = 0.5$ (throughout this paper, we follow the convention $S_\nu \propto \nu^{-\alpha}$).

3 RESULTS

Eight out of 11 sources have been detected and their radio continuum emission is shown in Figure 3. All sources are found to be point-like. In the maps of AMS09 and AMS19 hints of extended emission are present. In these two sources, extended emission is also hinted by the difference between the peak and integrated flux densities (see Table 1). Within the field of view around each source, there are no other point-like sources detected at high significance (5$\sigma$). In the fields of AMS01, AMS06, and AMS17 no radio emission has been detected above a 5$\sigma$ level.

Low resolution radio observations (MS06b) at various frequencies are used to determine the spectral indices and the 1658.24 MHz flux density at VLA resolution ($S_{\text{VLAM1.6}}$). The fraction of the flux density which is recovered by the EVN observations is shown in Table 2. For the detections, the percentages cover a range between 31% and 76%, with the missing flux being resolved out. The percentages for the non-detected sources are $\lesssim$34%, thus, for the non-detections, a compact source with a fraction $\sim$30% that is similar to that of some detections (AMS12 and AMS16), cannot be rule-out. For the detections, the mean recovered fraction is 54%. Thus, typically half of the radio flux density is confined to a region of $\lesssim$257 pc, while the other half must be in regions large enough to be resolved out by the interferometer. Given that the shortest baseline is $\sim$700 km, at the observed frequency this corresponds to an angular scales of $\gtrsim$20 mas. Thus, the interferometer is insensitive to emission structures extended on scales larger than $\sim$60 mas. In Section 4 the characteristics of the detected and the missing flux will be discussed.

Figure 4 display the EVN flux densities and the VLA low resolution flux densities (MS06b). Comparing the VLA 1.4 GHz with the EVN measurements all sources show higher flux densities at low resolution and frequency indicating a spectral index $> 0$. Furthermore, sources with flux densities above 500 $\mu$Jy are less grouped than those with less flux. Whereas comparing with the VLA at 4.9 GHz no clear clustering is shown. Comparing the 4.9 GHz data with the 1.6 GHz data 4 sources show more flux indicating an inverted spectral index $< 0$ and 4 sources show less flux. By taking the error bars into account AMS16 and AMS19 are clear candidates to have an inverted spectral index, if the radio fluxes emerges from the same region. Using the same assumption a core spectral index and its error has been determine and are quoted in Table 2. The assumption that the 4.9 GHz-emitting region (rest-frame range 14 to 25 GHz) has a physical projected size equal to the EVN beam at 1.66 GHz (rest-frame range 4.5 to 8.3 GHz). Only in this case is the spectral index between the EVN flux density at 1.66 GHz and the VLA density at 4.9 GHz a meaningful quantity. For core dominated source this assumption is most likely to be true and also for a starburst embedded AGN like Mrk 231 (Ulvestad et al. 1998).

Figure 5 displays the recovered fraction and the spectral indices (spectral indices and errors have been calculated using the flux measurements of MS06b). One might expected that the low resolution flux densities of flat-spectrum and gigahertz-peakes sources will be recover to a larger fraction than for the steep-spectrum sources. There is no clear correlation between $\alpha_{0.410}$ and $\alpha_{1.4}$ and the percentage of the recovered flux. In case of a $\alpha_{1.4}$ a trend might be shown and by determine the fraction at spectral index of 0 using a linear regression one would expect to observe 64±14%.

Since the spectral indices at the mas spatial resolution are not known, the conversion to rest-frame 1.66 GHz is not possible. Therefore, the luminosities quoted in Table 2, $L_{\text{rest}}$, are at $\nu_{\text{rest}} = 1.66 \times (1 + z_{\text{spec}})$ GHz, where the $z_{\text{spec}}$ is the spectroscopic redshift for each source. Given that the median redshift is $z = 2.5$, this corresponds to typically $\nu_{\text{rest}} \sim 5.8$ GHz (and to 8 GHz in the case of AMS16), while the median surface brightness temperature, $T_B$, is $\sim 6 \times 10^6$ K.

Furthermore the missed emission has been converted to a star-formation rate (SFR), following Condon (1992) and is shown in Table 2.

4 DISCUSSION

4.1 The EVN flux

The radio emission observed by the EVN emerges from a region at projected size of $\lesssim$ 30 mas. The flux density limit is above 130$\mu$Jy and the nature of the origin of the emission might be of non-AGN nature. The radio emission of an individual supernovae remnants is too faint to be detected at cosmological distances. In the case of the lowest redshift source in this sample, at $z = 1.8$, a radio supernovae like SN1988 is only expected to generate $\sim 0.6$ $\mu$Jy (Williams et al. 2002). The mean brightness temperature, $T_B \sim 1 \times 10^6$ K (see Table 2), is slightly too high to be accounted for by synchrotron radiation from supernovae (SNe) and SNe remnants only. The regions with radio emission due to star-forming typically have $T_B \lesssim 10^5$ K (?) , however the values of $T_B$ in this sample are close to the limiting value. Therefore, the possibility that the radio emission detected by the EVN are in fact dense star-forming regions needs to be considered. In the following is the flux density detected by the EVN observations refered to as the “core” and treated as a physical entity with projected size $\lesssim$ 260 pc.

The detected cores have a median luminosity, $L_{\text{rest}} = 3 \times 10^{23}$ W Hz$^{-1}$ sr$^{-1}$. If this emission was due to star-formation, then the estimated star-formation rate (SFR), following Condon (1992), would correspond to a SFR$\sim$ 3600 $M_\odot$ yr$^{-1}$ (of massive stars only $\gtrsim 5 M_\odot$), and integrating over a Salpeter initial mass function would result in a total SFR of $\sim 14 \times 1000 M_\odot$ yr$^{-1}$. Such SFRs are comparable or generally greater than the SFR inferred for submillimetre-selected galaxies (Smail et al. 1997), except they are confined to a significantly smaller volume. Given that the beam size is typically 25 x 25 mas$^2$, corresponding to about 315 x 315 pc$^2$ at $z = 2.5$, these are unreasonable SFRs for.
such a small region. Also, the hypothesis of dense star-formation regions can be rejected on the basis of the required molecular gas mass to power such a SFR. An estimate of the typical star-formation density of the cores, assuming a total SFR of 14 000 M$_\odot$ yr$^{-1}$ in an area with diameter a 315 pc, corresponds to $\Sigma_{\text{SFR}} = 1.8 \times 10^5$ M$_\odot$ yr$^{-1}$ kpc$^{-2}$. Thus, if these cores followed the Kennicutt-Schmidt law ($\Sigma_{\text{SFR}} = 2.5 \times 10^{-4} (\frac{\Sigma_{\text{gas}}}{M_\odot \text{ pc}^{-2}})^{1.4}$ M$_\odot$ yr$^{-1}$ kpc$^{-2}$, Kennicutt 1998), they would have extreme gas densities of $\Sigma_{\text{gas}} = 2.1 \times 10^6$ M$_\odot$ yr$^{-1}$ pc$^{-2}$, or an unphysically large gas mass of $1.7 \times 10^{11}$ M$_\odot$ in this small central region region. Thus, the hypothesis that the detected cores are dominated by star-formation only can be safely rejected.

In fact, the luminosities of the observed cores are similar to the core luminosities of local FR-I and FR-II that range between $10^{22}$ – $10^{24}$ W Hz$^{-1}$ sr$^{-1}$ (Zirbel & Baum 1995). And are significantly higher that the core luminosities of the Ultra-luminous Infrared galaxies (ULIRG) MRK 231, where the nuclear emission is powered by an extrem star-forming regions and an embedded AGN.

Figure 3. EVN phased-references images of the radio emission (Stokes I) at 1658.24 MHz of 8 obscured quasars. The boxed ellipses show the Gaussian restoring beam at FWHM. The contours are at 30 $\mu$Jy $\times 2^n$ (n=2, 3, etc.). The image at the bottom right displays the radio emission of the FLSVLA source (Wrobel et al. 2004) with contours of 800 $\mu$Jy $\times 2^n$ (n=2, 3, etc.).
Table 2. Properties of the obscured quasars. Redshifts with 3 decimal are from optical spectroscopy, while with one decimal place are from mid-infrared spectroscopy (see MS06a, MS08). Monochromatic EVN Luminosity and brightness temperatures at Restframe. Radio spectral index is based on the VLA measurements by (Martínez-Sansigre et al. 2006b). Expected VLA flux at the EVN observing frequency. Detection limits and errors. The undetected sources AMS01, AM06, and AMS17 have detection limits of 26%, 33%, and 34% respectively. Monochromatic restframe luminosity of the non-detected radio emission. The starformation rate of the undetected radio emission. Core spectral index assuming that all the VLA emission emerge from the same physical region as the EVN emission. Upper limited of the physical extent of the EVN emission region. Note that the spectral index at small scales is not known and therefore no K-correction has been applied and therefore the luminosity and brightness temperature is calculated in rest frame.

(see e.g. Mrk 231; Ulvestad et al. 1998; Klöckner et al. 2003; Carilli et al. 1998) . Figure 6 displays the total- and core- luminosities of the EVN observations and including samples of the 3C sources (Blundell et al. in prep.), ULIRG (Smith et al. 1998), and a sub-sample of BQS quasars (Miller et al. 1993) (Miller et al. 1992). The FR sources are loosely grouped above their defining luminosities. The ULIRG galaxies are grouped at the lower luminosity end and the luminosities of BQS quasars connects the luminosities of FR and ULIRG. The dashed line indicates a core dominated radio emission. Only a few FR sources have core dominated emission, whereas the majority shows total luminosities a factor of 100 or more stronger. The ULIRG shows more core dominated emission. The strongest ULIRG Mrk 231 have comparable luminosities to AMS06. The BQS sources PG1309+355 show similar luminosities and falls on top of the values of the obscured quasars. The observed sources are distributed closely to the core dominated ratio. The correlation between the total and core luminosities indicates that the radio emission of the source is powered by an AGN. Thus, in the remainder of this article, the core radio activity is considered to be dominated by an AGN.

4.2 The missing flux

In MS06a, the flux densities of this sample at 1.4 GHz obtained by the VLA (5-arcsecond resolution, from Condon et al. 2003) and WSRT (14-arcsecond resolution, from Morganti et al. 2004) were compared and found to be consistent within the errors. There is no evidence for the VLA to resolve out flux at 1.4 GHz on scales > 14 arcseconds, and the the VLA flux densities at 1.4 GHz (and $S_{\text{VLA,1.6}}$) can be safely considered to represent the entire flux densities of the radio sources. There is no intermediate resolution data, and thus no information on scales < 30 mas and > 5 arcseconds, corresponding to < 257 pc and < 100 kpc.

Figure 4 display the EVN flux densities and the VLA low resolution flux densities. Generally a larger fraction of the VLA 1.4 GHz flux density is resolved out compared with the 4.9 GHz. In this subsample, typically 50% of the $S_{\text{VLA,1.6}}$ flux density is resolved out by the EVN. There is no information about the morphology of this extended emission, which could therefore be due to star-formation on a galaxy scale, due to a radio jet, or a combination of both. The two limiting cases are considered here.

1) The entirety of the missing flux is due to star-formation. Following Condon (1992), the estimated SFRs are in the range ~ 500 – 9000 M$_\odot$ yr$^{-1}$ (see Table 2). This is only for massive stars, with $M > 5$ M$_\odot$, so the total star-formation rates would be 4x larger if integrated over a Salpeter IMF. Thus, except in the cases of AMS09 and AMS21 (and maybe AMS15), these are unphysically high SFRs. This is not surprising, since this sample was selected using a radio criterion to avoid contamination for luminous starbursts. Thus, in the sample as a whole, it is extremely unlikely that the missing flux is all due to star-formation.

2) If the missing flux is instead all due to AGN jets, then the median jet luminosity is $L_{\text{jet}} = 6 \times 10^{25}$ W Hz$^{-1}$ sr$^{-1}$, comparable to those of FR-I radio galaxies. Therefore, it is most likely that the missing flux is dominated by jet emission, so the sources in this sample are expected to have radio jets of physical size $< 257$ pc and $< 40$ kpc. Heywood, Blundell & Rawlings (2007) have shown that unobscured quasars are often associated with FR-I-like jets, so it should not be a surprise to find such jets associated with obscured quasars. If the flux density at 610 MHz is all jet dominated, and only ~50% of the flux density at 1.66 GHz is due to jets, then the intrinsic spectral indices for many of these sources of the jets must be even steeper than the $\alpha \sim 1$ value inferred by MS06b.

While the extended emission is likely to be completely dominated by an AGN-jet, it is not possible to rule out the additional presence and thus contribution of a powerful starburst.

4.3 Further radio properties

The low resolution radio emission compared with the EVN observations shown in Figure4 indicates that the 1.4 GHz flux densities are resolved out by the EVN. Whereas 4 sources (AMS05, AMS12, AMS15, AMS19) have comparable flux densities at 1.66 GHz (EVN) and 4.9 GHz (VLA). In some cases the 1.66 GHz flux is even higher than at
4.9 GHz. The core spectral indices, $\alpha_{4.9}$, are shown in Table 2 and the assumption used are discussed in the Section 3. Three sources have negative core spectral indices (AMS12, AMS15, and AMS19), suggesting that the core spectrum is brighter at $\sim 17$ GHz than at $\sim 5.8$ GHz (both rest-frame). Taking the error into account a flat spectral index is possible and more likely. The rest of the sources have values of $\alpha_{4.9}$ much flatter than their overall $\alpha_{1.6}$ value at VLA resolution. This is consistent with the picture of the core being a more compact and dense region of relativistic electrons. Due to the higher density of energetic electrons, the effect of synchrotron self-absorption is important up to relatively high frequencies. However, none of the spectral indices are close to the expected value of $\alpha = -2.5$ for the entirely self-absorbed regime (at frequencies lower than the peak frequency). The likely explanation is that the peak in flux density probably occurs at an intermediate frequency somewhere between 5 and 17 GHz (rest-frame), so that the measurements are being taken on each side of the peak, and the observed values of $\alpha_{4.9}$ are relatively flat ($\sim 0$).

Such gigahertz-peaked (GP) cores are not expected to contribute significantly to the lower frequency flux density (at 610 MHz from GMRT). However, at low spatial resolution (VLA and GMRT) AMS15 and AMS19 both appear to be flat-spectrum between 610 MHz and 4.9 GHz, so there is also a significant flux density at 610 MHz that is not expected to originate from the core. In addition,
at 1.66 GHz, both sources have a significant (50-60%) resolved out component. These observations are consistent with a two-component radio emission: a GP-core and a steep-spectrum jet that, when combined together, appear flat.

The flux density at high frequencies, presumably originating in the cores, is modest for most of the sources in this sample. For the cores of AMS15 and AMS19 to contribute so much to the total flux density at low spatial resolution, then in these two sources the core must be intrinsically more powerful compared to the extended jets. Alternatively, in these two sources the cores could be Doppler-boosted, if at the base, the jet is closely aligned to the observer’s line-of-sight. This the traditional explanation for flat-spectrum unobscured quasars, so the properties of AMS15 and AMS19 are consistent with a close-to-face-on jet.

Indeed, the orientation of the large scale jets can be estimated by using the fractional core flux (EVN) to the total flux density ($S_{V, LA, g}$). Assuming the following model of a core emission, the unresolved bases is produced from two oppositely directed jets showing a quasi-continuous stream of material (Lorentz factor $\gamma = \frac{1}{\sqrt{1-\beta^2}}$ for which $\beta = v/c$ Orr & Browne 1982; Kapahi & Saikia 1982). Furthermore the oppositely directed jets and the outer lobes are thought to be at rest and radiating isotropically. The fraction can be determined via

$$\text{fraction}(\theta) = [1 + \frac{2}{B(\theta)}(\frac{1}{\text{fraction,core}} - 1)]^{-1},$$

where $B(\theta) = (1 - \beta \cos(\theta))^2 + (1 + \beta \cos(\theta))^2$.

The angle $\theta$ is between the jet-axis and the line of sight (projected extend = intrinsic linear size $\times \sin(\theta)$). The fraction,core is the fraction of the flux densities in the core if the jet axis were perpendicular to the line of sight ($\theta = 90^\circ$). In the literature the R-value has been used more frequently that the fraction, which translates like R-value = $\frac{1}{\text{fraction,}}$. The log(R) values of the observed sample is shown in Table 3 and cover a range between -0.33 and 0.5. The range of values is compared to log(R)-values of the FRI and FRII sources (-2.0 -- -2.0; ?) quite narrow. Using mean values of log(R) from samples of FRI, FRII, ULIRG, and flat-spectrum sources as fraction,core limits of the Lorentz-factor and the orientation can be made. The orientation angle of the possible radio jets and the resulting R-values are displayed in Figure 7 and shown in Table 3. Comparing the R-values with the values of flat-spectrum sources ($<\log(R)> = -0.055$ Barthel et al. 2000) there is no gamma and no orientation which could resemble the observed R-values. Whereas using the core fraction of FR-I $<\log(R)> = -1.40$, FR-II $<\log(R)> = -1.91$ and ULIRG $<\log(R)> = -0.87$ the observed R-values do show an overlap with the estimates. In spirit of this interpretation the range of $\gamma$ between 1.2 to 7 suggests in some sources a Doppler-boosted core scenarios and that the orientation of the jet axis ranges between $0^\circ$ to $54^\circ$.

From the unified schemes, obscured quasars are not expected to have face-on jets, since the radio jets are expected to emerge along the axis of symmetry of the dusty torus, and hence cannot be obscured by it. However, by assuming that these sources have similar core properties than
ULIRG a halve obscuration angles of about 52° would be needed to obscured some of these sources by a nuclear torus. Such obscuration angles have been observed in Seyfert 1.5 source (Schmitt et al. 2001) and therefore nuclear obscuration would be possible for jet-angles ≥ 39°. In this scenario AMS09, AMS12 and possibly AMS15 cannot be obscured by a nuclear torus.

In addition, neither AMS15 or AMS19 show the expected narrow emission lines from “torus-obscured” obscured quasars, despite being at redshifts where the Ly α line is potentially visible in the optical. Recent work on obscured AGN suggests that dust on scales larger than the torus is probably contributing significantly to the obscuration (MS06b, Rigby et al. 2006, Brand et al. 2007, MS08). Thus, taking the spectral index, optical measurements and the simple jet-core model into account is more likely that AMS09, AMS15, AMS19, AMS21 are examples of “host-obscured” quasars.

5 CONCLUSIONS AND SUMMARY

A subsample of 11 high-redshift obscured quasars has been observed at 1.66 GHz with the EVN, reaching rms~ 25 μJy/beam and a spatial resolution of ~25 mas. Eight out of 11 sources are detected, and show compact radio emission.

At these sensitivity such a detection rate is higher than the detection rate of a few percent of recent VLBI surveys of faint radio population that have been successfully carried out in the NOAO BOOTES Field and the Spitzer FIRST-LOOK survey (Garrett et al. 2005, Wrobel et al. 2004).

Amongst the detections, ~31 – 76% of the entire flux density is recovered. Comparing the core- with total- flux densities of several galaxy samples and using SFR and SFR-density diagnostics, the observed radio flux density is interpreted as being dominated by an AGN radio core, and not a nuclear starburst. In the 3 non-detections, the limits inferred for the radio emission are ≤ 30%, so that an AGN core cannot be ruled out either.

At the redshifts of the sources, in most cases the missing flux density corresponds to too high radio luminosities to be consistent with star-formation only. It is therefore also interpreted as being dominated by radio jets, comparable in luminosity to those of FR-I radio sources. However, a hybrid scenario with on-going star formation cannot be ruled out. Under the assumption that the radio flux is dominated by emission from jets, the orientation angle of the jets, span a range of values between 0 and 54 degrees with respect to the line of sight. In addition, under the assumption that the emission at 4.9 GHz detected by the VLA, originates in the same spatial scale as the emission recovered at 1.66 GHz by the EVN, the cores are found to have relatively flat or even inverted spectra. This is interpreted as a GHz-peaked core. Such sources would also have the radio-jet oriented close to the line of sight, this would not be expected with obscuration by the torus of the unified schemes.

By assuming that the core emission fraction is similar to ULIRG and torus obscuration angles like Seyfert-1.5 sources AMS09, AMS15, AMS19, AMS21 are examples of “host-obscured” quasars whereas by assuming a FR-I or FR-II core fraction AMS12 or AMS16 examples of “torus-obscured”.

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