# Slow Jets in Seyfert Galaxies: NGC 1068

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We have used the Very Long Baseline Array at 5 GHz to image the nucleus of NGC 1068 at two epochs separated by 2.92 yr. No relative motion was detected between the high brightness-temperature knots within components NE and C relative to the nuclear component S1, placing an upper limit of 0.075 $c$ on the relative component speeds at distances of 21 pc and 43 pc from the AGN. The low speed is consistent with the low bulk flow speed previously inferred from indirect arguments based on ram pressure at the bow shock and on line emission from the jet-cloud collision at cloud C. The components are probably shocks in the jet, and the bulk flow speed could conceivably be higher than the limit reported here.

## 1. Introduction

Four years ago we began our VLBA studies of nearby Seyfert galaxies with the aims of imaging the central radio sources, looking for absorbed core spectra that might be due to an obscuring torus (Roy *et al.* 1999), looking for direct thermal emission from ionized gas at the inner edge of the torus (Mundell *et al.* 2000), and measuring jet speeds for comparison to the jets in powerful radio galaxies and quasars (Ulvestad *et al.* 1999). Enough time has now elapsed to detect motions slower than 0.1 $c$ (depending on distance) and we have made relative speed measurements on scales of parsecs to tens of parsec scales in four Seyferts (Mrk 231, Mrk 348, NGC 4151, and NGC 5506). These have turned out to be systematically slow ($< 0.25\ c$) compared to jets in powerful radio galaxies and quasars, which is interesting when one attempts to distinguish between intrinsic and extrinsic effects that cause jets in Seyfert galaxies to be weak. In this paper we report an upper limit on the motion of compact components in NGC 1068.

## 2. NGC 1068 Background

NGC 1068 is a nearby (14.4 Mpc) archetypical Seyfert 2 type with a hidden broad-line region. Within its 13 kpc radio disc emission is a 1 kpc-long central linear structure, which radiates $3.6 \times 10^{22}$ W Hz$^{-1}$ at 4.9 GHz. VLA observations at 15 GHz with 0.4 arcsec resolution (Wilson & Ulvestad 1987) resolve the linear structure into a classic core-jet-lobe structure, and from ram-pressure arguments at the bow shock, they infer that the incident jet is slow (4000 to 15000 km s$^{-1}$) and light ($2.5 \times 10^3$ to $10^5$ m$^{-3}$). MERLIN observations at 5 GHz with 60 mas resolution (Muxlow et al. 1996) resolve considerable detail in the jet, and spectral ageing rates along the jet infer a jet velocity $< 5 \times 10^4$ km s$^{-1}$ (Gallimore et al. 1996b). An $H_2O$-maser disc is present around component S1 (Gallimore et al. 1996a; Greenhill et al. 1997) and its rotation curve infers a mass within the central 0.65 pc of $1.5 \times 10^7 M_\odot$. The accretion rate is 0.04 $M_\odot$

$\mathrm{yr}^{-1}$ from the maser properties (Maloney et al. 1997, private communication to Bicknell et al. 1998) and 0.05 $M_\odot$ $\mathrm{yr}^{-1}$ from the bolometric luminosity, assuming a conversion efficiency of accreted mass into bolometric luminosity of 0.1 (Bicknell et al. 1998).

A detailed analysis of the jet-cloud collision at component C was carried out by Bicknell et al. (1998). Assuming that the optical line emission from the cloud is excited by a radiative shock driven by the jet impact, they found the mass flux incident on the cloud is 0.5 $M_\odot$ $\mathrm{yr}^{-1}$, which is ten times larger than the accretion rate, and that the incident jet speed is 0.04 $c$ (within a factor of three). They found that such a slow, mostly thermal jet is different from the ultra-relativistic plasmas found in powerful radio jets, and suggested that Seyfert jets may be radio-weak because they carry a substantial load of thermal plasma, perhaps due to entrainment or due to the jet formation mechanism. It is therefore of considerable interest to make a direct measurement of the jet speed in NGC 1068.

## 3. Observations

NGC 1068 was observed using the VLBA at 5.0 GHz at two epochs separated by 2.92 yr between 1 June 1996 and 3 May 1999. We recorded LCP with two-bit sampling and 32 MHz bandwidth during the first epoch, and the same but 64 MHz bandwidth during the second epoch. The data were initially phase calibrated by phase referencing to the nearby source J0239-0234, which provided a sufficiently good starting model for phase self-calibration on NGC 1068. Final images were made using uniform weighting. Baselines longer than 40 M$\lambda$ were discarded because those did not detect NGC 1068, yielding beam sizes of 6.2 mas $\times$ 4.3 mas for the first epoch and 5.9 mas $\times$ 4.4 mas for the second epoch. Both epochs were processed in the same manner at the same time by the same person (ALR), using AIPS. On-source integration times were 1.2 hr in the first epoch and 2.4 hr in the second epoch, yielding rms noise of 0.20 mJy $\mathrm{beam}^{-1}$ for the first-epoch image and 0.16 mJy $\mathrm{beam}^{-1}$ for the second-epoch image, which are close to the thermal noise limit. Positions were measured in the image plane by fitting a quadratic surface to each peak. The formal uncertainty of the peak position was estimated as equal to the synthesised beamwidth divided by the signal-to-noise ratio for each component, and the individual uncertainties were combined in quadrature to estimate the uncertainty in component separation. For example, for components S1 and C in the first epoch, this yielded a 1 $\sigma$ uncertainty of 0.32 mas for the component separation.

## 4. Results

We detected at least three compact, bright components (Fig 1) that lie within the extended regions S1, C and NE of the MERLIN image by Muxlow et al. (1996). Most of the extended jet emission seen in the MERLIN image is not visible in the VLBA images because of their much smaller beam and hence poorer brightness sensitivity limit.

The relative component separations (Table 1) did not change significantly between the two epochs. The maximum difference in component separation was 0.3 mas, which is 0.07 of a beamwidth and is too small to be significant. We quote a 3 $\sigma$ upper limit to the separation change of 0.96 mas which corresponds to $v < 0.075\ c$ (assuming a distance to NGC 1068 of 14.4 Mpc for $H_0 = 75$ km $\mathrm{s}^{-1}$ $\mathrm{Mpc}^{-1}$).

## 5. Discussion

The upper limit to the component speeds in NGC 1068, $v < 0.075\ c$, is consistent with the low jet speeds inferred by both Wilson & Ulvestad (1987) ($0.013\ c < v < 0.050\ c$)

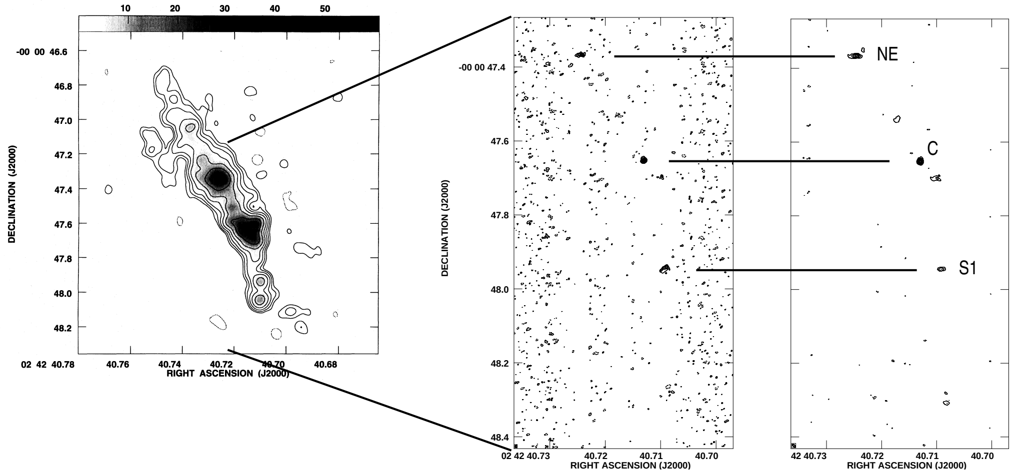


FIGURE 1. Left: MERLIN 5.0 GHz image by Muxlow et al. (1996) for orientation, and the VLBA images of NGC 1068 at 5.0 GHz at epochs 1996.42 (middle) and 1999.34 (right). Contour levels are -1.5, -1.0, -0.5, 0.5, 1.0, 1.5, ... 5.5 mJy beam$^{-1}$ and the restoring beam is 6.2 mas $\times$ 4.3 mas in position angle $-17°$ in 1996.42 and 5.9 mas $\times$ 4.4 mas at 48° in 1999.34

| *Epoch* | *Component* | *dRA* (mas) | *ddec* (mas) | *total* (mas) | *peak flux density* ( mJy beam$^{-1}$) | *total flux density* (mJy) |
|---|---|---|---|---|---|---|
| 1996.42 | NE | 230.7 | 577.3 | 621.7 | 4.2 | $11.4 \pm 2.3$ |
| | C | 59.0 | 289.5 | 295.5 | 12.1 | $24.2 \pm 4.3$ |
| | S1 | 0.0 | 0.0 | 0.0 | 3.3 | $4.5 \pm 1.2$ |
| 1999.34 | NE | 228.3 | 577.9 | 621.4 | 4.3 | $8.2 \pm 1.6$ |
| | C | 59.4 | 289.8 | 295.8 | 9.2 | $17.3 \pm 3.0$ |
| | S1 | 0.0 | 0.0 | 0.0 | 2.4 | $5.5 \pm 1.2$ |

TABLE 1. Preliminary measurements of NGC 1068 component parameters from Fig 1

and by Bicknell *et al.* (1998) (0.04 $c$ with an uncertainty of a factor of three). Note however that we may have measured the speed of shocks within the flow, and the flow itself might be faster. Measurement of the large-scale bulk flow must await a proper-motion measurement of the extended emission visible to MERLIN. However, to detect motion of 0.1$\times$ the MERLIN 60 mas beam at 5 GHz (0.42 pc) with a flow speed of, say, 0.05 $c$, would require 27 years between epochs, or more due to limited image fidelity.

Proper-motion measurements or limits are available now for six Seyfert galaxies, and the distribution of speeds is shown in Fig 2 along with a histogram of speeds in powerful radio sources for comparison. The Seyferts clearly have relatively slow jets on the parsec scale, and thus we conclude that Seyfert galaxy jets must be either launched sub-relativistically, or else are decelerated within the first parsec or ten parsecs.

## 6. Conclusion

We have made VLBI images of the nucleus of NGC 1068 at 5 mas resolution and at two epochs separated by 2.92 yrs, and have detected no motion of the compact components

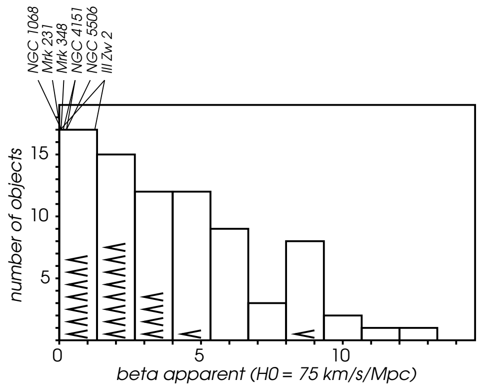


FIGURE 2. The distribution of jet speeds of Seyfert galaxies with proper motion or upper limits measured (III Zw 2 is from Brunthaler *et al.* 2000) and, for comparison, is shown a uniform sample of strong, flat-spectrum objects, comprised of quasars, BL Lac objects, galaxies, and empty fields (Vermeulen 1995). The Seyferts populate the slow end of the distribution.

greater than 0.075 $c$ (3 $\sigma$), consistent with speeds inferred by Wilson & Ulvestad (1987) and Bicknell et al. (1998). The compact components may be standing shocks in the jet and the large-scale flow could conceivably be faster. Sub-relativistic jet speeds have been found now in six Seyfert galaxies. Future measurements can lower the upper limits to the speeds of the compact components. However, measurements with lower resolution to measure motion of the large-scale outflow would require about a 30 yr baseline to provide interesting limits on NGC 1068. Better targets might lie at higher declinations where better image fidelity is achievable.

ALR enjoyed discussions with A. Pedlar, T. Muxlow, and C. Mundell in the charming English countryside, about Seyferts and proper motion measurements with MERLIN.

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