VLBI OBSERVATIONS OF THE M81-M82 PAIR OF GALAXIES

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ABSTRACT. VLBI observations show that the center of the nearby (∿ 3.3 Mpc distant) spiral galaxy, M81, consists of a single elongated radio core, of dimensions 1000 x 4000 AU, with the major axis aligned, in projection, within 3° ($<1\sigma$) of the galaxy's rotation axis. This morphology can be interpreted in terms of an active galactic nucleus (AGN) with either a core-jet structure residing in M81's center or an accretion disk filling out the broadline region of this center. In contrast, the radio structure in the companion galaxy, M82, is very complex. VLBI observations of M82 yield the diameters and spectral index distribution of the hot spots, and the morphology and expansion velocity of the brightest hot spot, 41.9+58. Our results argue against the hot spots being core and jet condensations, or young supernovae (SNe), or typical supernova remnants (SNRs). We suggest that the hot spots in M82 are the remnants of stellar events that yielded some combination of SNRs and "exotic" objects.

1. M81

The galaxy M81 (NGC3031, 0951+693) is a spiral of type Sb which in many ways resembles both the Andromeda nebula and our own Galaxy. However, its nuclear region is apparently more active. Broad Hα and MgII emission lines (FWHM ∿ 2500 km s^{-1}) lead to a classification of the galaxy as a Seyfert 1.5, although a low-luminosity one (Peimbert and Torres-Peimbert 1981). Ionized gas is leaving the central region at a rate of ∿ $10^{-2} M_{\odot}$ yr^{-1} (Goad 1974); moreover, this region's X-ray luminosity is ∿ 1.7 10^{40} ergs s^{-1} (Elvis and van Speybroeck 1982) and therefore about 30 times higher than that of the brightest known binary X-ray source, SMC X-1. The most intriguing results come from VLBI observations. A compact core was detected in the nuclear region of M81 (Kellermann et al. 1976), with the major axis of this core being in fairly close alignment ($\lesssim 10°$, $\lesssim 2\sigma$) with the projection on the sky of the rotation axis (PA = 62°±3°; Rots, Shane 1975) of M81 (Bartel et al. 1982). The major axis is also directed approximately towards linearly-polarized extended radio components located a few kiloparsecs away (Beck et al. 1985). Based on the addition-

E. Ye. Khachikian et al. (eds.), Observational Evidence of Activity in Galaxies, 521–527.

al observations of a frequency dependence of the core's flux density and size, we interpreted our results in terms of a wind of relativistic electrons directed along the rotation axis of the galaxy and pulling out the magnetic field lines from an originally dipolar field configuration (Bartel *et al.* 1982).

We made more extended observations of the core of M81 with the Mark III VLBI system (Rogers *et al.* 1983) at 1.7 GHz in October 1982. We used a five-antenna array consisting of the 100-m-diameter antenna near Bonn, F.R.G., the 43-m antenna in Green Bank, WV, the 25-m antenna in Ft. Davis, TX, the phased array of 27 25-m antennas of the VLA near Socorro, NM, and the 40-m antenna near Big Pine, CA. The data were recorded on magnetic tapes, correlated with the Mark III VLBI processor at Haystack, calibrated in the usual manner for Mark III observations (see, e.g., Bartel *et al.* 1982), and then used to make a hybrid map of the core of M81.

The map reveals that the core is very compact, almost unresolved. In such a case a model fit it more enlightening. We estimated the parameters of an elliptical Gaussian model and obtained for the total flux density $\sim$58 mJy, for the lengths of the major and minor axes $\sim$1.3 mas ($\sim$ 4000 AU) and $\sim$0.23 mas ($\sim$ 1000 AU), and for the position angle of the major axis 65°. The combined statistical and systematic uncertainties of the first two parameters are $\sim$10 percent. The uncertainty of the third parameter is $\sim$100 percent since the core is essentially unresolved along its minor axis. The uncertainty of the position angle of the major axis is $\sim 3^\circ$. A more detailed error analysis will be given in a forthcoming paper (Bartel *et al.* 1987a).

The major axis of the elongated core of M81 (at 1.7 GHz) is aligned within 3° ($<1\sigma$) with the rotation axis of the galaxy and provides further evidence for an energetic engine residing in the central region of M81 with a jet being ejected along the aligned rotation axes of the engine and M81. The 50 percent contour of the modelled brightness distribution of M81's core is shown in the inset (c) of Fig. 1. However, this evidence is far from being conclusive. Other interpretations are certainly possible. If, for example, the broadening of the Hα and MgII lines is caused by circular orbital motion, then a compact object of mass $10^6 \lesssim (M/M_\odot) \lesssim 2\ 10^7$ must reside in the center and the broadline region must have linear dimensions of 100 to 3000 AU (Peimbert and Torres-Peimbert 1981), about equal to the dimensions of our VLBI core. The elongated compact core could therefore also be interpreted as being radio emission from the accretion disk of a black hole in the center of M81 with the alignment between the core's major axis and the galaxy's rotation axis being purely accidental. Monitoring of the core's brightness distribution may provide further clues as to its nature.

2. M82

The galaxy M82 (NGC3034, 3C231, 0951+699) is only 35 kpc from M81 in projection on the sky. Given the anomalous HI velocities for those parts of M81 adjacent to M82 (Roberts 1972), it may well be tidally interacting with M81. Perhaps because of this interaction and the difference in the galaxies' masses, M82 appears to be very different from M81. M82 used to be considered the prototype of a galaxy with an AGN but is now more often considered the prototype of a starburst galaxy. The central region of M82 is characterized by a complex, very elongated brightness distribution, first mapped by Hargrave (1974) and Kronberg and Wilkinson (1975). Later, observations with the VLA (Kronberg *et al.* 1981, 1985) and MERLIN (Unger *et al.* 1984) distinguished $\gtrsim 20$ unresolved radio "hot spots" with diameters $\lesssim 2.7$ pc and luminosities a few to 150 times higher than that of Cas A, the most luminous SNR in our own Galaxy, but comparable to those found for radio supernovae in other galaxies (Weiler *et al.* 1986). The flux density decreases (Kronberg and Sramek 1985) and spectra (Kronberg *et al.* 1985) of many of the hot spots, and the compactness of the brightest hot spot, 41.9+58, as observed with VLBI by Geldzahler *et al.*(1977), Shaffer and Marscher (1979), Jones *et al.* (1981) and Wilkinson and de Bruyn (1984), also represent similarities with SNe or young SNRs. However, this brightest hot spot could also be the active nucleus of the galaxy, and the other hot spots jet cendensations. Perhaps, instead, we are observing as yet unclassified "exotic" objects.

On 9 May 1983, we observed M82 with the Mark III VLBI system at 2.3 and 8.4 GHz simultaneously with eight antennas located in the U.S. and Europe (see Bartel *et al.* 1985b). Preliminary results were reported by Bartel *et al.* (1986a). We mapped 41.9+58 at 2.3 GHz and determined at 8.4 GHz its expansion velocity by comparison with visibility data taken nine years earlier by Geldzahler *et al.* (1977). For 20 other hot spots, we determined the sizes, or lower bounds on them, at 2.3 GHz and upper bounds on the spectral indices of three of them. The map of 41.9+58 is shown as inset (b) in Fig. 1. The expansion velocity (time derivative of the FWHM of a Gaussian) along the northeast-southwest axis is, with statistical and estimates of systematic errors included, $(0.12\pm0.01)c$ for the period between 1974 and 1983. The sparsity of Geldzahler *et al.*'s 7.9 GHz and our 8.4 GHz data and the lack of astrometric information for either data set did not allow us to distinguish between an expansion in both directions along the above mentioned axis and a directed ejection (see Bartel *et al.* 1986b for such a distinction between the motions of components of a superluminal quasar). However, the asymmetric morphology of 41.9+58 may suggest that the material is not moving with equal velocities in both directions but rather predominantly into the southwest direction. The distributions of the diameters and spectral indices of the hot spots are given in Figs. 2 and 3.

What then is the nature of the hot spots: young SNe, SNRs, an AGN and jet condensations, or, by default, exotic objects? In contrast to the above-mentioned VLA and MERLIN observations, our VLBI observations do not support the interpretation of the hot spots as being SNe or typical SNRs. The morphology of at least one of them, 41.9+58, is too complex and its expansion velocity, if predominantly directed towards the southwest, more than 1.5-fold larger than the largest yet observed for SNe and more than 3-fold larger than that of a typical SN. Further, the hot spots' diameters and equivalent ages, when available, and the lower bounds on them, when not (Fig. 2), argue against most hot spots being young SNe similar to those found in other galaxies. The fourth argument against these hot spots being SNe or SNRs is based on the broad

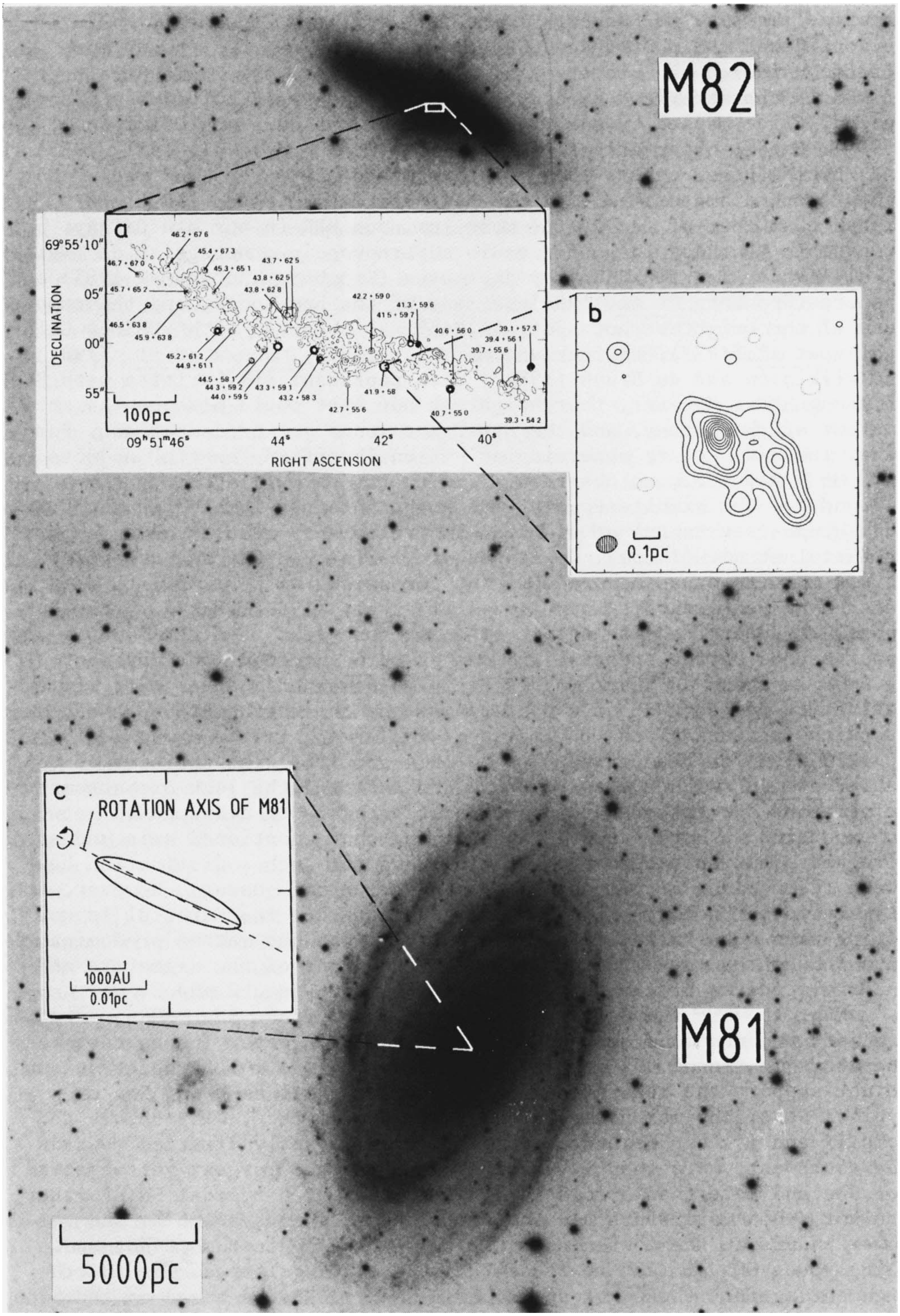
M82
a
69°55′10″
05″
00″
55″
DECLINATION
RIGHT ASCENSION
09h51m46s
44s
42s
40s
100pc
46.2 + 67.6
45.4 + 67.3
46.7 + 67.0
45.3 + 65.1
43.7 + 62.5
43.8 + 62.5
43.8 + 62.8
45.7 + 65.2
46.5 + 63.8
45.9 + 63.8
45.2 + 61.2
44.9 + 61.1
44.5 + 58.1
44.3 + 59.2
44.0 + 59.5
43.3 + 59.1
43.2 + 58.3
42.2 + 59.0
42.7 + 55.6
41.3 + 59.6
41.5 + 59.7
41.9 + 58
40.6 + 56.0
40.7 + 55.0
39.1 + 57.3
39.4 + 56.1
39.7 + 55.6
39.3 + 54.2
b
0.1pc
c
ROTATION AXIS OF M81
1000AU
0.01pc
M81
5000pc

Figure 1. (previous page). The pair of galaxies M81 and M82. Part a displays at 4.9 GHz the inner radio region of M82 with its hot spots, taken from Kronberg et al. (1985). Part b shows at 2.3 GHz a preliminary hybrid map of the indicated brightest hot spot. 41.9+58 taken from Bartel et al. (1986a). Tick marks are separated by 6.4 mas. The contours are at 90, 80, ..., 10, 5, -5% of the peak flux density per beam area. The FWHM of the restoring beam is shown as the striped ellipse in the lower left corner. Part c shows the 50% contour of the radio core of M81, and M81's rotation axis. Tick marks are separated by 1 mas. North is always up, east always to the left.

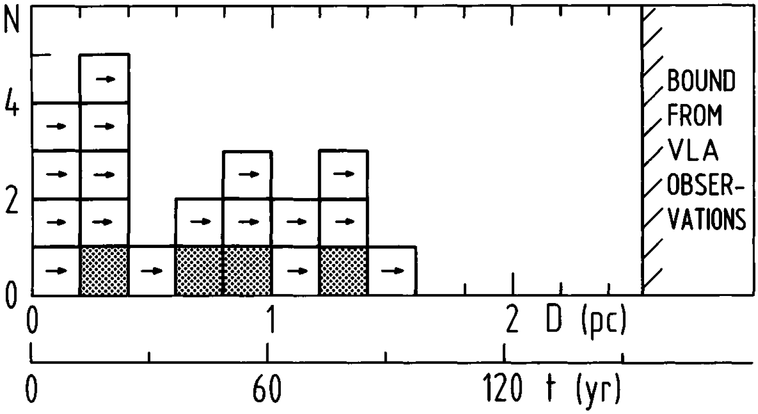

Figure 2: A histogram of the FWHM-Gaussian diameters (grey squares) or lower bounds on them (light squares with arrows) of 21 hot spots in M82. The second ordinate gives the hot spots' ages, assuming that their FWHM points are expanding from a common center with a velocity of 8000 km s^{-1}, equivalent to a maximum expansion velocity of $\sim$ 13000 km s^{-1} (for the full-width at 15% of the maximum). The bound on the diameters from VLA observations is between $\sim$ 2.7 and $\sim$ 5.4 pc depending on the observing frequency and the VLA configuration.

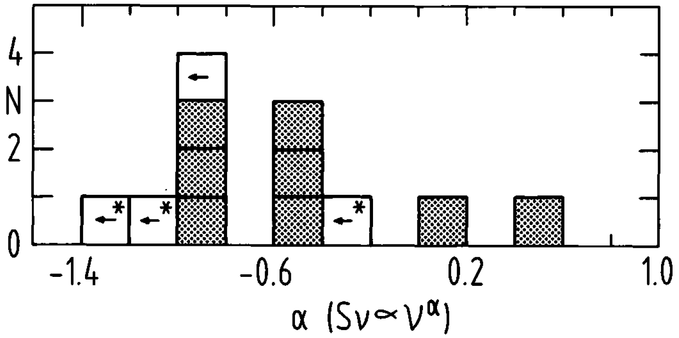

Figure 3. A histogram of the spectral indices (grey squares) or upper bounds on them (light squares with arrows) of 12 hot spots. Nine values here were determined between 4.9 and 15 GHz with the VLA by Kronberg et al. (1985). Three values (marked with a star) were determined between 2.3 and 4.9 GHz by combining our VLBI results with the above mentioned VLA observations.

range of the hot spots' spectral indices (Fig. 3). While the high values of spectral index could result from free-free absorption between 4.9 and 15 GHz, the low values are quite unusual for SNe and SNRs. None of the known SNe and none of the 127 galactic SNRs with measured spectral indices has $\alpha < 1.2$ (Weiler et al. 1986, Green 1984).

Could 41.9+58 then perhaps be an AGN and the other hot spots jet condensations? We do not think so. First, the position of 41.9+58 is about 10 arcsec or 160 pc offset in projection from M82's kinematic center (Beck et al. 1978, Weliachev et al. 1984); second, the radio properties of 41.9+58 are not qualitatively different from those of the other hot spots,and the brightest spot does not appear to be in any special location or relation with respect to the others; and third, although not conclusive, the VLBI structure of 41.9+58 is not oriented towards the other hot spots, and does not resemble the core-jet morphology seen in many AGNs.

Are then 41.9+58 and the other hot spots perhaps exotic objects, such as Cyg X-3 and SS433? Both latter objects eject material with velocities of order 0.1c. However, both objects also display very erratic radio light curves in contrast to the smoothly and slowly decaying radio light curves of many, if not all, of the hot spots in M82.

We conclude that the hot spots may be related to stellar events that yielded some combination of SNRs and exotic objects. A more detailed description and discussion of our results will be given elsewhere (Bartel et al. 1987b).

Finally, we note that the small angular separation (37 arcmin) between M81 and M82 suggests that, in the future, interleaved observations of the two galaxies using VLBI be used to determine differential proper motion, as well as to monitor the sources individually. By analogy with our astrometry of pulsar-quasar pairs at 2.3 GHz (Bartel et al.1985a) sensitivities to velocities of $< 0.05c$ could be obtained in just a few years.

ACKNOWLEDGEMENT

N.B., M.I.R. and I.I.S. were supported in part by the NSF under grant no. AST-8300796.

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DISCUSSION

TERLEVICH: Can you please comment on the surface brightness vs diameter relation for these sources and how it compares with known SNRs including young radio supernovae.

BARTEL: Young radio supernovae (SNe), the hot spots in M82 and galactic supernova remnants (SNRs) are all located on a straight and steep band in the surface brightness (Σ) - diameter (D) diagram, with the hot spots in M82 midway between the young SNe and the galactic SNRs. However, the band is rather broad; three orders of magnitude in the Σ direction and one order of magnitude in the D direction. In other words if the hot spots had, e.g. Σ values up to 1000 times smaller than those observed, they would still be located within the band.