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Compact Structure in Continuum Radio Sources*

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Abstract

Present-day VLBI networks make observations of compact structure in a wide variety of radio sources. Examples are shown of milli-arcsecond scale structures in radio galaxies, quasars, stars and supernova remnants.

1. Introduction

The general theme of this Symposium is Astronomy in the Southern Hemisphere, with papers being presented on current research carried out here. However, I will be reviewing areas of high angular resolution work that will be investigated in the south once the plans for expanding very long baseline interferometry (VLBI), outlined by Ron Ekers and Dave Jauncey, come to fruition, and using as examples, sources observed by northern hemisphere VLBI networks. It turns out that quite a number of the objects I will show can be observed from the middle latitudes in Australia, so in that sense my contribution fits the theme of astronomy *from* the southern hemisphere rather than *in* the southern hemisphere.

First a brief note on the northern VLBI networks. There are two major ones: the US VLBI Network which started operation in 1976 and which is in the process of being subsumed by the dedicated VLBI array, the very long baseline array (VLBA), due to start operation in 1992, and the European VLBI Network (EVN) which formally began operation in 1980. The majority of observations carried out in the north combine telescopes in Europe and the USA, this being called, rather grandly, the Global Network. Typical observations involve 12–16 stations using narrow bandwidth recording equipment, and 6–8 using broad bandwidth recorders. Limitations are set by the size of the correlators.

In fact, the global distribution of telescopes is in the process of becoming far greater than these two networks, as is shown in Fig. 1. The more than forty telescopes expected to be equipped for VLBI in the mid-nineties can be grouped into five regional arrays: USA/VLBA, Europe/EVN, USSR, Asia, and Australia. One can also imagine that an even higher order grouping will occur, e.g. VLBA+EVN, EVN+USSR+Asia, Australia+Asia+Hawaii (Pacific Rim). Correlation of

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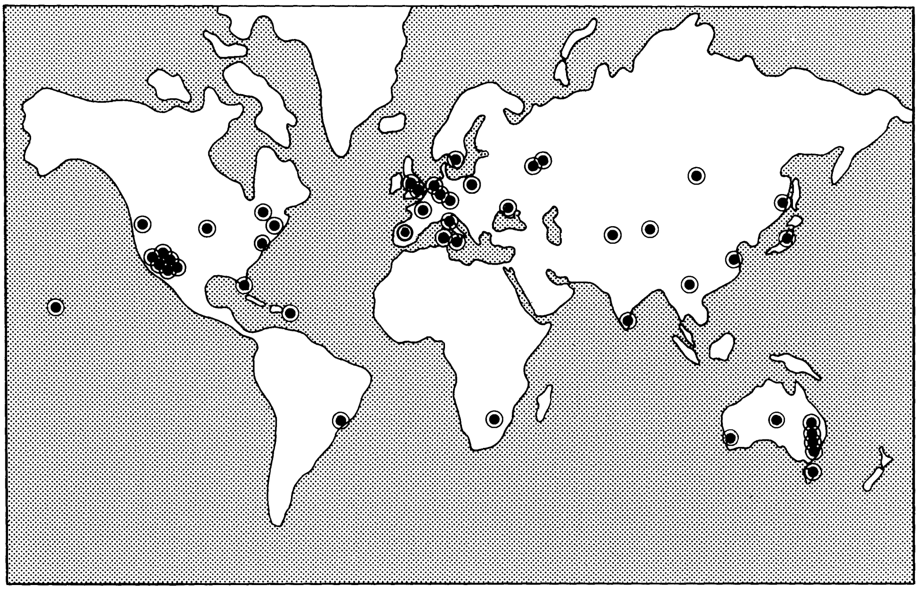

Fig. 1. Telescopes expected to be available for centimetre wavelength VLBI by the mid-1990s.

the signals to produce visibility data will occur at a number of processing centres around the world of which the largest is the VLBA 20-station correlator now under construction. The EVN is seeking funding for a similar sized machine, while Japan proposes building a 10-station correlator as part of its space VLBI project, VSOP.

VLBI is used for a wide variety of observations ranging from studies of the evolution and scale of the universe to the star formation process. I will touch on a number of these areas in this contribution, making use of examples from the literature and work in progress.

2. Surveys

Surveys of relatively large samples of objects are essential for a deeper understanding of the astrophysics of compact structures in radio sources. Obtaining sufficient observing time on part-time VLBI networks has not been easy, but nevertheless some six surveys of extragalactic sources have been, or are being, carried out (Pearson 1990):

(i) Pearson, Readhead and co-workers (Pearson and Readhead 1988) have imaged 45 sources from a complete flux density limited sample of 65 sources selected at 5 GHz, in many cases at more than one epoch. Five major classes of source were identified:
   - (a) core-dominated and core-jet sources ($N = 25$). The bulk of superluminal sources are found in this class;
   - (b) irregular flat spectrum objects ($N = 6$);
   - (c) compact double sources ($N = 7$);
   - (d) compact steep spectrum (CSS) objects ($N = 7$);
   - (e) extended double sources ($N = 20$) which have little detectable compact structure at their sensitivity limit ($S_{\min} \geq 0 \cdot 1$ Jy).

(ii) Witzel *et al.* (1988) have carried out a multi-wavelength study of a sample of 13 flat spectrum sources selected at 5 GHz. All fall into category (a) of Pearson and Readhead.

(iii) Three groups are carrying out studies of compact cores in samples of lobe-dominated quasars (e.g. Hough and Readhead 1989; Zensus and Porcas 1987; Barthel *et al.* 1989; Hooimeyer 1991). A number of relatively slow superluminal sources have been discovered in these samples.

(iv) Fanti *et al.* (1990) and Spencer *et al.* (1989) have been studying the CSS sources in the 3CR sample selected at 178 MHz. A clear sub-classification based on radio morphology can be made: galaxies have a simple double structure, sometimes with weak radio jets and weak radio cores. Quasars are triple with a strong central component, or jet-like, or complex. The cores and jets are much stronger in quasars than in radio galaxies.

(v) Roberts *et al.* (1990) are carrying out a polarisation survey of a sample of core dominated objects. They find that quasars have strongly polarised jets, but weakly polarised cores. The orientation of the magnetic field is perpendicular to the jet direction. In contrast, BL Lac objects have strongly polarised cores and jets, and magnetic field orientations parallel to the jet.

(vi) Wehrle *et al.* (1990) are surveying a sample of 37 objects selected by their flux density at 10·7 GHz. A particular aim is to study the distribution of proper motion as a function of redshift in the sample and thereby place constraints on cosmological models, e.g. Cohen *et al.* (1988).

3. Distant AGNs

Systematic VLBI studies of high redshift quasars ($z \geq 3$) are being made by Gurvits *et al.* (1992) and by Wehrle and Unwin (unpublished) in

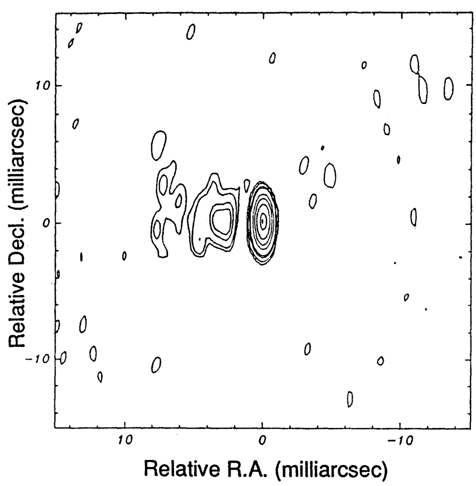

Fig. 2. A 5 GHz image of the $z = 3{\cdot}402$ quasar, OH471 (Gurvits *et al.* 1992).

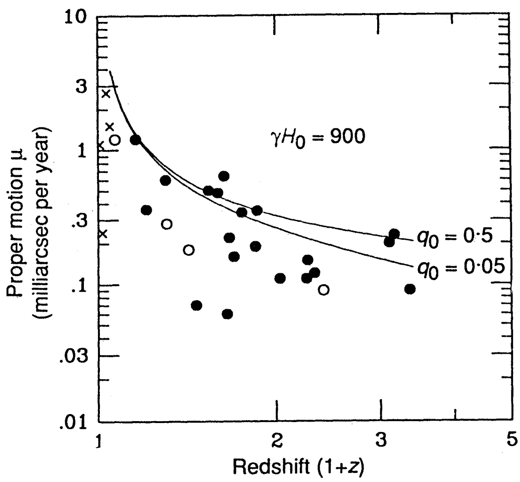

Fig. 3. Proper motion–redshift diagram for 28 objects with measured proper motion. Quasars are solid circles, BL Lacs are open circles, and galaxies are crosses (Wehrle *et al.* 1990).

order to compare the structures found with those in samples of lower redshift quasars ($z \leq 1$) and to search for signs of evolution. Quasars in these two redshift ranges are at widely separated epochs in terms of age ($t_{z=3\cdot5} = 0\cdot1 t_0$, $t_{z=0\cdot5} = 0\cdot5 t_0$, where t_0 is the present age of the universe) and average density [$\rho_{z=3\cdot5}/\rho_{z=0\cdot5} \sim 30$, $\rho = \rho_0(1+z)^3$].

Of the eight objects observed by Gurvits *et al.* so far at 5 GHz, images are available for four and these all show structures dominated by an unresolved point source (Fig. 2) even at an angular resolution of 1 milliarcsec. Further elucidation of the structures of these sources at 5 GHz will have to wait for the longer baselines provided by space VLBI. The control sample contains the most luminous radio quasars with $z \leq 1$ observed with VLBI at 2·8 and 1·35 cm in order to compare properties near the same emitted wavelength.

On arcsec scales, Barthel and Miley (1988) found that high redshift quasars were smaller and more bent than a control sample at lower redshift, presumably due to the effects of a denser intergalactic medium at the earlier epochs restricting the outward motion of the radio emission. Something similar may occur on the smaller scales.

As mentioned in the previous section, Cohen and collaborators (e.g. Cohen *et al.* 1988; Wehrle *et al.* 1990) are also studying sources at high redshift to measure their internal proper motions and thereby populate the proper motion–redshift diagram at the high redshift end (Fig. 3). The upper envelope of the points in Fig. 3 has been modelled in the context of a Friedmann universe assuming a relativistic-beam model for the superluminal sources with $\gamma H_0 = 900$, where γ is the maximum Lorentz factor of moving components in the jet. Clearly, interesting limits on the geometry of the universe may come from this approach but more points are required at high redshift to constrain the value of q_0, and the possible effects of cosmological evolution on compact source structure will also need to be taken into account.

There is as yet little high resolution information on the high redshift galaxies recently discovered by Miley, van Breugel and their collaborators.

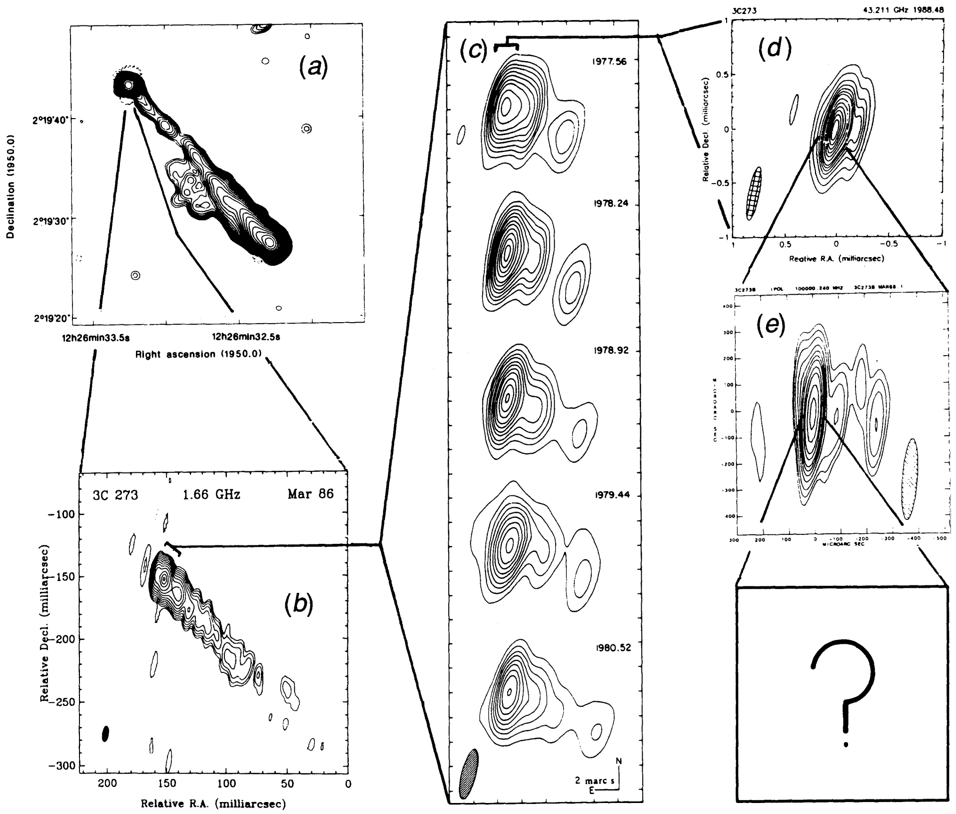

Fig. 4. Quasar 3C273 imaged at different angular resolutions from 408 MHz to 100 GHz: (*a*) MERLIN at 408 MHz showing the core (to the NE) and the 21 arcsec long jet which coincides with the optical jet (Davis *et al.* 1985); (*b*) VLBI at 1·66 GHz on a scale 250 times smaller than panel (*a*) (Unwin and Davis 1988); (*c*) a series of VLBI images at 5 GHz on a scale a further factor of four smaller than panel (*b*) (Pearson *et al.* 1981). The changes in angular position of some of the features over the course of several years imply linear velocities in the plane of the sky well in excess of the speed of light. This superluminal motion is usually interpreted in terms of relativistic bulk motion close to the line of sight towards the observer; (*d*) the first image obtained of 3C273 at 43 GHz on a scale ten times smaller than panel (*c*) (Krichbaum *et al.* 1990); (*e*) the first ever image at 100 GHz showing the 'core' at 43 GHz is in fact composed of a number of features (Baath *et al.* 1991).

Low frequency VLBI observations at 327 MHz by Schilizzi *et al.* have detected structure in a number of objects but no details are yet to hand.

4. Not So Distant AGNs

High quality VLBI imaging of nearer objects shows that jets are a ubiquitous feature of compact morphology. These jets appear to be continuous fluid flows rather than blobs in ballistic motion [e.g. panel (*b*) in Fig. 4 and Fig. 6]. Fig. 4 is a collage of radio images of 3C273 on many different angular scales from 20 arcsec to 50 microarcsec. Panel (*e*) is an image at 100 GHz, the highest frequency for which a VLBI image has been made.

Panel (*c*) shows a sequence of images over a period of three years depicting superluminal motion of a blob moving westwards. Close to the self-absorbed core in superluminal sources, components do not move in straight lines but have different apparent velocities (Fig. 5) and orientations. Some hints of quasi-sinusoidal or helical motion are claimed by various workers, but have yet to be substantiated.

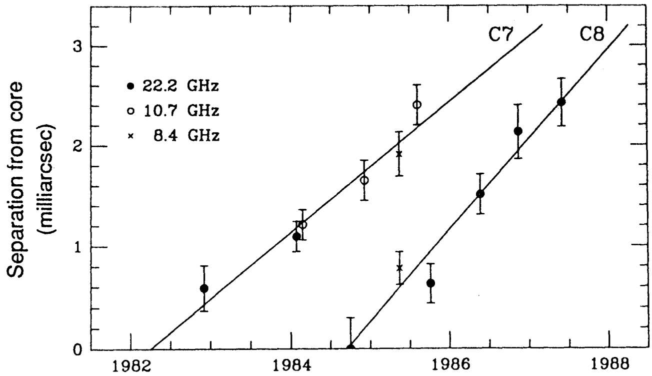

Fig. 5. Distance of two discrete features in the 3C273 jet from the core component, as a function of epoch. The slopes of the lines are 0·65±0·09 milliarcsec/yr (C7) and 0·90±0·11 milliarcsec/yr (C8) (Unwin 1990).

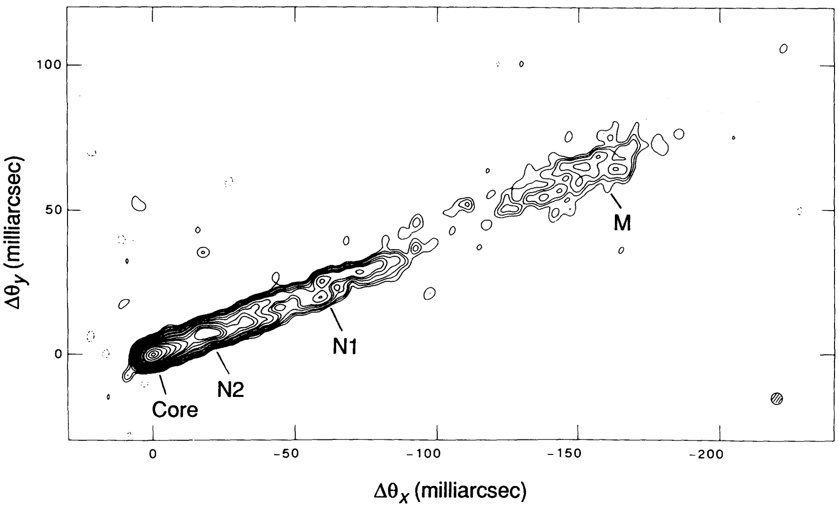

Fig. 6. A 1·66 GHz image of the nucleus of M87 at epoch 1984·26. The beam size is 4 milliarcsec (Reid *et al.* 1989).

Not all jets on compact scales are superluminal. M87 is an example of a subluminal jet on 25 milliarcsec scales ($v = 0 \cdot 2c$) which, however, reaches higher velocities on arcsec scales (Biretta *et al.* 1990). The superb image of M87 shown in Fig. 6 demonstrates that in this galaxy the jet is already well-collimated on linear scales of 0·5 pc, although not with a constant opening angle, and it has an edge-brightened jet whose brightness centroid oscillates

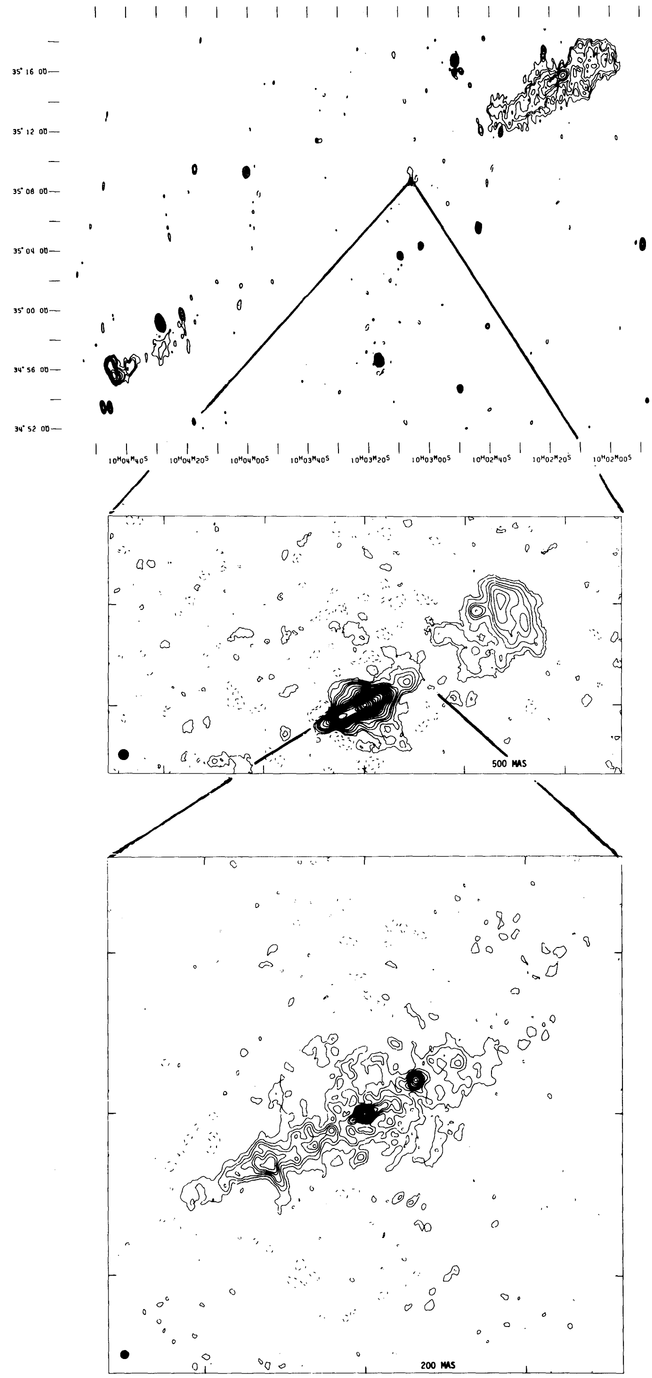

Fig. 7. The structure of the radio galaxy 3C236. The top panel shows a 1·4 GHz image obtained with the WSRT. The overall angular scale is 39 arcmin (4 Mpc) (Barthel *et al.* 1985). The middle and bottom panels show images of the nuclear component at 1·66 GHz made with a combined VLBI+MERLIN array with angular resolutions of 50 and 10 milliarcsec respectively (Schilizzi *et al.* 1988).

from side to side with a characteristic wavelength of 10 to 30 milliarcsec. This latter effect may be the result of precession of the jet nozzle, hydrodynamic instabilities, or magnetic fields.

The M87 jet, in common with many others, appears only one side of the nucleus and plausibly links up with the large scale jet. In superluminal sources this is usually ascribed to the effects of Doppler boosting of the approaching jet causing it to outshine the receding counterjet, but in M87 and in other non-superluminal sources the explanation may have to be found in intrinsic differences from one side of the nucleus to the other.

As far as I am aware, there are only three examples known of two-sided jets on compact scales, in the quasars 3C138 (Fanti *et al.* 1989) and 3C286 Spencer (*et al.*, in preparation) and in the galaxy 3C236, the largest extragalactic object known. Fig. 7 shows a collage of images on different scales of 3C236, and in the bottom panel the two-sided jet on 10 milliarcsec scales can be seen. Superluminal motion in the nucleus of 3C236 is not expected since it is most probably oriented in the plane of the sky. The overall size of the extended structure of 3C236 is ~4 Mpc ($H_0 = 75$ km s^{-1} Mpc^{-1}), and of the nuclear component alone 2·2 kpc. 3C236 is also interesting because it bridges two of the Pearson and Readhead classes—it is an extended classical double with a CSS nucleus.

CSS sources are one of the three major types of extragalactic radio source found in complete samples, with fractions ranging between 15% and 30% (e.g. Fanti *et al.* 1990). Their linear dimensions put them well within the confines of their parent optical objects. It is not clear whether they are small in dimension because they are (i) young; or (ii) they are 'frustrated' in the sense that the interstellar medium is too dense for the radio emission to make its way further out; or (iii) the source is in the process of being recycled (perhaps like 3C236) and the CSS component is therefore a young version of an old

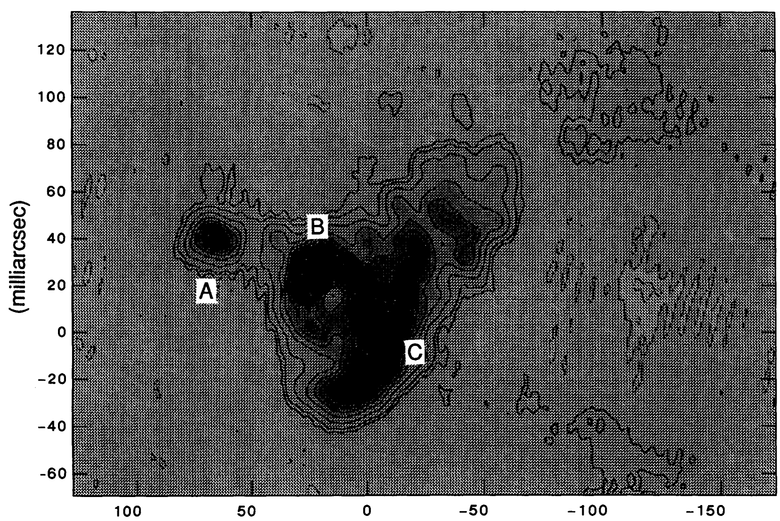

Fig. 8. A greyscale and contour representation of the structure of the CSS quasar 3C343 at 1·66 GHz. The angular resolution is 8 milliarcsec (Schilizzi *et al.*, in preparation).

source; or (iv) the source is in the process of being recycled but is currently smothered, a combination of (ii) and (iii).

In the case of 3C236, the fact that we see radio emission in the central component only on scales of the narrow optical line emitting region suggests that the radio emission is due to interaction of the relativistic electrons with the gas in the interstellar medium.

There is evidence of violent interaction in a number of the CSS sources. The 18 cm VLBI+MERLIN image of the quasar 3C343 (Fig. 8, Schilizzi *et al.*, in preparation) is a good example of an extremely distorted morphology extending over 200 milliarcsec, for which there is no known larger scale structure. Fragmentary evidence from incomplete observations at 6 cm indicate that the detached component to the north–east (A) has the flattest spectrum and is most likely to be the nucleus. The remainder of the structure can

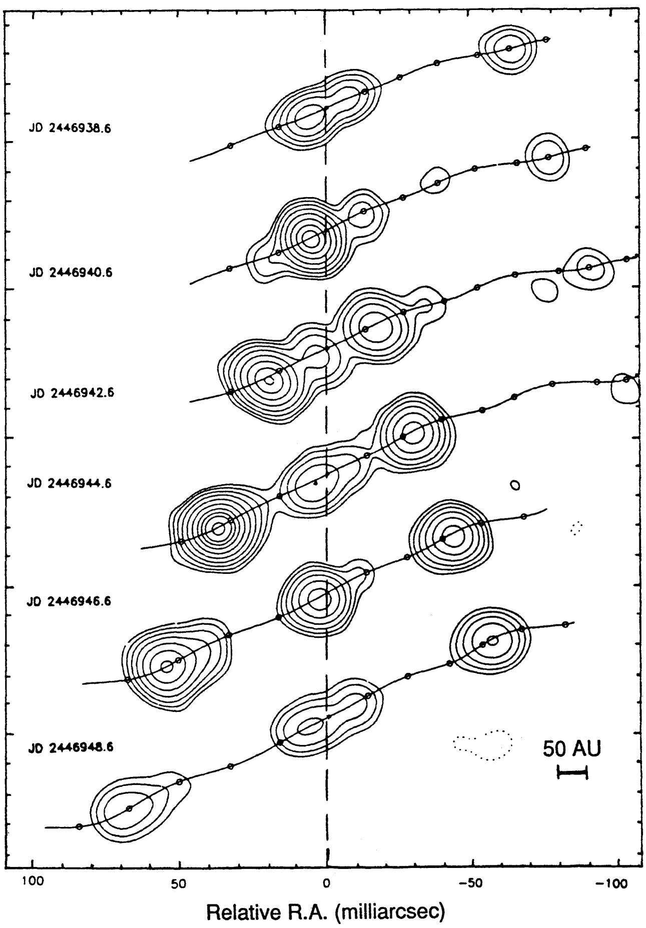

Fig. 9. EVN images of SS433 observed at two-day intervals in May/June 1987. The same absolute contour levels are displayed for all six images. The locus of emission predicted by the kinematic model is shown with markers drawn at ejection age intervals of two days along the locus. The beam size was 10 milliarcsec (~50 AU at the distance of SS433, 5 kpc) (Vermeulen *et al.* 1992*a*, 1992*b*).

be interpreted as the result of a major disruption of the (unseen) jet at the location of the bright component B. The curved structure to the south–west (C) might then be a shock front caused by the impact of the jet on the interstellar medium. A similar disruption appears to occur in 3C48 (Wilkinson *et al.* 1991).

5. Stars

Radio emission has been detected from several different types of star. With the exception of Bremsstrahlung radiation from the outer regions of stellar winds, the emission is very compact requiring high angular resolution in order to study the morphology.

Quiescent emission from nearby M-dwarfs has only very recently been detected using highly sensitive VLBI networks (e.g. Benz *et al.* in preparation). The most common radio stars investigated with VLBI have been the RS CVns and X-ray binaries in flaring mode (e.g. Lestrade 1988). One of the most famous of these is the eclipsing radio X-ray binary star, SS433. SS433 first came to the attention of the astronomical community by virtue of its unique set of red and blue Doppler-shifted Balmer lines which move in observed wavelength from night to night. This behaviour has been interpreted (Abell and Margon 1979; Margon 1984) as being due to the ejection of gas in a jet and counterjet with a speed of $0 \cdot 26c$, the axis of ejection precessing with a $162 \cdot 5$ day period. The binary system is generally thought to include a massive early-type star at a distance of 5 kpc, losing mass to a thick accretion disc surrounding a compact object possibly a black hole. Evidence for the jets can be observed over at least eight orders of magnitude in extent from 10^{12} cm (X-ray spectroscopy) to 10^{20} cm (radio observations of the W50 remnant surrounding SS433, e.g. Elston and Baum 1987).

The most detailed view of the jets is available on scales of 10^{14} to 10^{17} cm from VLBI and VLA measurements over the last decade (e.g. Schilizzi *et al.* 1984; Romney *et al.* 1987; Vermeulen *et al.* 1987; Spencer 1984; Hjellming and Johnston 1986). The evidence points to ballistic motion of the gas following the locus predicted from the kinematic model of Abell and Margon. Fig. 9 shows the latest in a series of measurements made using the European VLBI Network (Vermeulen *et al.* 1992*a*). The series of images graphically demonstrates the outward motion of discrete blobs of radio emission at ~9 milliarcsec per day. The observations took place at an epoch when the jets were oriented as close to the line of sight as occurs in the precession cycle (~60°). Since astrometric information is lost in VLBI measurements, the registration of the images on the locus of emission expected on the kinematic model has been performed assuming that blobs in the jet and counterjet were ejected simultaneously. On this assumption, the expected differential light travel time effects between the approaching eastern beam and the receding western beam can be seen clearly in the last three images of the series.

SS433 underwent a transition from a quiescent to a flaring phase during this series of measurements (Vermeulen *et al.* 1992*b*). The first flare appears to take place in the central component in image 2, but thereafter the flares occur in the moving blobs themselves. The reasons for this flaring well away from the central region are not well understood (see also Vermeulen *et al.* 1987). Fejes (1986) pointed out that, since matter in the SS433 beams moves

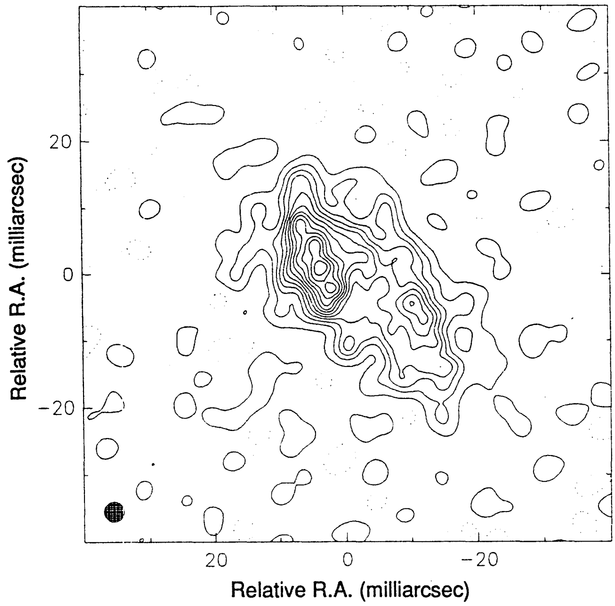

Fig. 10. A 1·66 GHz image of the radio supernova remnant 41·9+58 in M82 (Wilkinson and de Bruyn, in preparation). The angular resolution is 3 milliarcsec and the overall extent of the emission is 0·56×0·32 pc.

at 0·26*c*, Doppler boosting effects should be seen at the time of closest approach to the line of sight. The asymmetry in flux density observed between east and west of a factor of ~2 is in good agreement with the value expected.

6. Extragalactic Supernova Remnants

Recent VLBI images of powerful extragalactic supernova remnants in M82 (41·9+58, Wilkinson and de Bruyn, in preparation) and NGC 891 (SN1986J, Bartel *et al.* 1991) show shell-like structures with substantial deviations from circular symmetry. Fig. 10 reproduces the 41·9+58 image by Wilkinson and de Bruyn. These authors suggest it is ~50 years old and that its average expansion velocity is ~6000 km s^{-1}. The lack of symmetry could be caused by intrinsic asymmetry in the gas flow or by a non-isotropic circumstellar medium into which the gas expands.

7. Conclusions

The VLBI technique provides the only means of obtaining morphological information on small physical scales in a wide variety of radio sources, information that is often crucial to the astrophysical interpretation of the objects. The examples shown here from northern hemisphere observations serve to demonstrate the current capability of VLBI and highlight possible future directions for the southern hemisphere VLBI network.

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