PART III

NEW OBSERVATIONAL TECHNIQUES

RADIO OBSERVATIONS OF Be STARS

(Review Paper)

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1. Introduction

During the past few years the search for radio stars has been both intensive and extensive, and Be stars are among the various types of objects which have been examined. A large number of Be stars have *not* been detected, and to date no classical Be star has been found to emit detectable amounts of radio emission. However, following the tradition of radio astronomy to emphasise the abnormal or extreme cases, radio emission has been observed which is associated with a few peculiar Be stars.

The fact that only peculiar Be stars are seen at radio wavelengths is not surprising. If thermal radio emission from ionised gas is considered, then the same argument can be applied as was invoked a long time ago to demonstrate the very poor prospects for detecting radio emission from stars in general. In terms of modern radio telescopes, an angular diameter for the emitting gas in excess of $0\farcs1$ is required if the gas is optically thick in the cm. wavelength range, and larger if it is optically thin. If non-thermal radio emission is considered (synchrotron radiation, or plasma oscillations) then clearly an unusual object is required which involves intense flaring, or mass exchange* as in the radio-emitting binaries, or some other energetic phenomenon.

The two different types of radio stars mentioned above can be distinguished on the basis of their radio characteristics, and represent physical objects which are quite different. Those which have a thermal radio spectrum and whose intensity does not vary with time are associated with very large circumstellar envelopes, whereas those with a non-thermal spectrum and/or fairly rapid time variations are associated with mass-transfer in binary systems. As far as the Be stars are concerned the radio emission is, with one exception, attributed to thermal emission from circumstellar envelopes which have dimensions of many hundreds of astronomical units.

2. Instrumental Considerations

To observe such objects the basic requirements of the radio telescope are sensitivity, because of the low flux levels involved, and resolution, because of the incidence of confusing sources – particularly in the galactic plane. Table I summarises the telescopes which are actively used for radio-star work. The list is a simplification, as all major radio telescopes have been used to observe radio stars, but those shown are

* During this symposium the hypothesis that mass-exchange binaries might be quite common among Be stars was vigorously defended.

A. Slettebak (ed.), Be and Shell Stars, 157–164.

involved in active 'programmes' of such observations. The wavelength range covered is 21 cm to 3 mm (noting that only continuum observations have been attempted for Be stars). It should also be noted that the sensitivities of these instruments, considering the collecting areas and the receiver bandwidths used, are comparable, within an order of magnitude, with the exception of the 11 m dish which in any case is limited by atmospheric effects at 90 GHz.

TABLE I

TELESCOPE (Commonly used name)		FREQUENCY (GHZ)
BONN	100-m DISH (WEST GERMANY)	10.6
WESTERBORK	RADIO SYNTHESIS TELESCOPE (NETHERLANDS)	1.4 and 5.0
CAMBRIDGE	5-Km RADIO TELESCOPE (ENGLAND)	5.0 and 14.5
ALGONQUIN	46-m DISH (CANADA)	10.6 and 22.2
NRAO	3-ELEMENT INTERFEROMETER (USA)	2.7 and 8.1
KITT PEAK	11-m DISH (USA)	90.0
PARKES	64-m DISH (AUSTRALIA)	6.2 and 8.9

MAJOR INSTRUMENTS USED IN DETECTION AND OBSERVATION OF RADIO STARS, AND THE FREQUENCIES AT WHICH THEY ARE MOST COMMONLY USED FOR THIS PURPOSE.

The single-dish instruments listed in Table I operate at high frequencies, with resolutions in the 1′ to 3′ range, and hence are useful for radio star observations. However, confusion effects are appreciable with such resolutions, particularly in the galactic plane or in the Cygnus or Carina regions, and measurements made with single dishes should be approached with considerable caution unless amply confirmed, preferably by one of the interferometer/synthesis arrays. The three arrays currently in operation are listed separately in Table II, with references to published material which provides detailed technical information. The Westerbork and NRAO instruments have also been described and compared by Braes and Miley (1973) at the *IAU Symp.* **55**. It is interesting to note that the resolution which can be obtained with these instruments is comparable to that of conventional optical telescopes.

Some caution is also required in the interpretation of interferometer data, in the cases where only a few Fourier components of the angular structure are measured. If a full synthesis observation is taken, then a reasonably unambiguous radio map is obtained. However, it is often the case that only a selection of spacings is used, in the interests of economy: if then the radio source is resolved, or partly resolved, the angular structure is often derived by what is essentially a model-fitting process. In these cases it is not common practice to publish the complete visibility curve, but only

TABLE II

TELESCOPE	FREQUENCY (GHZ)	MAXIMUM RESOLUTION (ARC secs)	REFERENCE
WESTERBORK	1.4 5.0	22 6	BAARS & HOOGHOUDT, ASTRON. & ASTROPHYS. 31, 323, 1974 CASSE & MULLER, ASTRON. & ASTROPHYS. 31, 333, 1974
CAMBRIDGE	5.0 15.4	2 0.7	RYLE, NATURE 239, 435, 1972
N R A O	2.7 8.1	8 2	HOGG et al, ASTRON. J, 74, 1206, 1969

SYNTHESIS INSTRUMENTS USED IN STUDY OF RADIO STARS.

the final result based on the assumed model. To interpret such information, one should be aware of the spacings that are used, and of the assumptions inherent in the model.

3. Observations

3.1. Negative results

The long lists of non-detections for Be stars are, for the most part, unpublished. I will mention only the four 'Symposium 70' stars (ζ Tau, γ Cas, ϕ Per and Pleione) for which we have established upper limits of ~20 mJy.

3.2. Radio objects with a continuum spectrum having the approximate form of flux density proportional to frequency

The prime example of this type of radio source is MWC 349, classified optically as Bep. In 1942 Swings and Struve (1942) noted the similarity of its spectrum to that of RY Scuti, which is also a radio object. More recent spectra have been obtained by Ackermann (1970), Herbig (1972), Kuhi (1973), Greenstein (1973), and by Ciatti and Mammano (1975). Absorption bands were found by Ciatti and Mammano and by Ackermann in the near infrared, but none have been reported at shorter wavelengths. Greenstein, however, suggested a spectral class in the B0–B5 range, based on the dereddened optical continuum. Extinction is large, giving ~9 magnitudes of absorption in the V band, the Hα line is very strong, and variable, and many other species of lines are observed, including the nebular lines. The object is sometimes referred to as a small H II region, but the radio data indicates that the emitting gas is intimately associated with the star, and I prefer to call it an extended circumstellar envelope. The infrared excess is large (Geisel (1970), Allen (1973)) and has been attributed to reradiation by dust in this envelope.

The radio observations do not indicate variability. The data defining the continuum spectrum is shown in Figure 1, where it is obvious that the spectrum is not the standard form for Bremsstrahlung radiation from a homogeneous slab of gas (i.e.

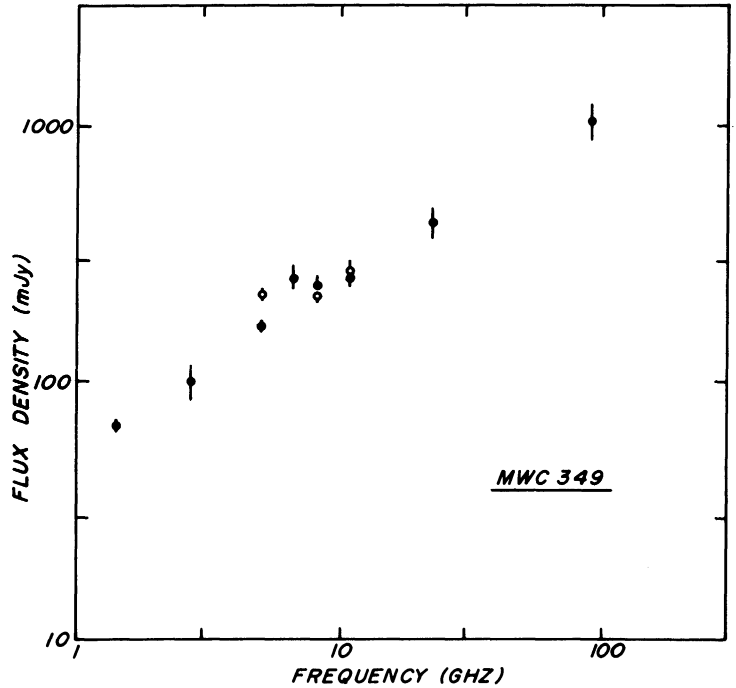

Fig. 1. Flux density measurements of MWC 349. The data have been taken from Olnon (1975) at 1.4, 5.0 (solid circle) and 10.6 (open circle) GHz; from Hjellming *et al.* (1973) at 2.7 and 8.1 (solid circle) GHz; from Baldwin *et al.* (1973) at 5.0 (open circle) GHz; from Gregory and Seaquist at 6.6 and 10.6 (solid circle) GHz; from Greenstein (1973) at 8.1 (open circle) GHz; and from Marsh, Purton and Feldman (unpublished) at 22.2 and 90 GHz.

slope ~0 if optically thin, ~2 if optically thick). In the usual notation of $S \propto \nu^{\alpha}$, the value obtained for the spectral index (α) for MWC 349 is 0.7. This type of radio spectrum is produced by a spherically-symmetric shell of gas with an inverse-square density distribution, such as would result from a steady and continuous mass outflow from the central star. Such a density distribution for radio-emitting gas was first considered by Weymann and Chapman (1965) for α Orionis, and the associated theory has been applied more recently to observations of V1016 Cygni by Seaquist and Gregory (1973). Since then the theory has been refined by three groups: Wright and Barlow (1975), Panagia and Felli (1975), who applied their results to P Cygni, and by Olnon (1975) who considered MWC 349 itself.

The physical size of such a circumstellar shell would be appreciable, and in fact the MWC 349 radio object has been resolved by the Cambridge interferometer. Olnon (1975) has analysed both the Cambridge and Westerbork data in detail, taking into consideration the complete visibility curve (although assuming circular symmetry), and has shown that the data is compatible with an inverse-square density distribution. The exact value of the radio spectral index implies a distribution of the form $n_e = kr^{-2.1}$, and the value of k was found, from a knowledge of the distance to

MWC 349 (2.1 kpc. as suggested by Reddish (1967) on the basis of its membership in the Cyg OB II Association) and an assumed temperature of the emitting gas (the results are rather insensitive to temperature), to be $\sim 6 \times 10^{38}$ in cgs units.

A number of similar objects have been considered by Marsh (1975a), who shows that in each case the spectrum is steeper than expected from an unbounded inverse-square density distribution, but that the data for each agrees well with the spectrum that is produced by an exact r^{-2} distribution truncated at some outer radius. If the same model is taken for MWC 349, then the observed spectrum indicates a value for the outer radius of $r_{\text{out}} \sim 10^{17}$ cm. Constraints can also be placed on the inner radius of the envelope. As the continuum spectrum is still optically thick at 90 GHz, then $r_{\text{in}} \lesssim 10^{15}$ cm. However, the density at the inner edge cannot exceed $\sim 3 \times 10^{8}\ \text{cm}^{-3}$, otherwise the short recombination times prohibit the ionising photons from penetrating to the remainder of the envelope; hence $r_{\text{in}} \gtrsim 10^{14}$ cm. This lower limit to r_{in} applies at all times, and the fact that emission lines have been observed for the past 40 years implies that $r_{\text{in}} \gtrsim 10^{14}$ cm for at least that long. Presumably, if the envelope is expanding, as indicated by the r^{-2} density and the P Cygni profiles, then r_{in} was less than that value in the not-too-distant past, and the entire envelope bcame ionised in a relatively short time as the inner radius passed through the critical value.

If you prefer to regard envelopes of this size as planetary nebulae, then note that the total mass of the gas is only $\sim 0.03\ M_\odot$ (Marsh (1975b)), which is a bit low. However, MWC 349 may well represent the low-mass equivalent of a planetary nebula.

Other objects are known which have the same type of radio spectrum as MWC 349. Of these, good data is available for V1016 Cygni, Vy2-2 and Hb12, two of which have been observed with the Cambridge interferometer (Ryle, 1975). These latter observations show that the intensity distribution of V1016 Cygni is roughly as expected for an inverse-square density distribution, but indicate a somewhat more complex structure for Vy2-2. Reasonable data is also available for Hen 1044 (Wright *et al.*, 1974) and HD 167362. Finally, the data available for P Cygni and RY Scuti suggest that these objects may also be of this radio type. All these objects form a homogeneous class of radio objects, but appear with the various optical classifications of planetary nebulae, Wolf-Rayet stars, symbiotic stars, and Bep stars. In the above list only the last two have been classified as Bep, and only these will be discussed further.

P Cygni: this well-known star is a weak-radio source (Wendker *et al.*, 1973), and flux-density information is available at only two frequencies. However, the optical spectrum indicates mass outflow, and the radio spectral index of ~ 0.7 is compatible with the inverse-square model. The densities in the circumstellar envelope would be considerably lower than for MWC 349, by a factor ~ 300 at the same radius, but the velocity of the outflowing gas is relatively high. Both Panagia and Felli (1975) and Wright and Barlow (1975) obtained mass-loss rates of $\sim 10^{-5}\ M_\odot\ \text{yr}^{-1}$.

RY Scuti: this object was described in the HD catalogue as having faint dark absorption lines, but in 1922 (Merrill) was classed as Pec, with some P Cygni features, and it still exhibited emission lines in 1928 (Merrill). If the same model is adopted as has been suggested for MWC 349, then the epoch at which emission lines appeared

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would correspond to the inner radius of the envelope expanding beyond the critical value at which the central star is able to ionise the envelope.

In 1937 Gaposhkin deduced, on the basis of the light curve, that RY Scuti was an eclipsing binary system similar to β Lyrae. In 1943 Popper found that some emission lines varied as for a spectroscopic binary, and interpreted his results as a binary system of large mass ($>100\,M_\odot$) but accompanied by a shell surrounding both components which was responsible for most of the emission lines. A detailed spectrum by Swings and Struve (1940) contained absorption lines which suggested that the brighter component was of spectral class O or B0. The infrared measurements of Geisel (1970) again indicate the presense of circumstellar dust.

The radio data is sparse. RY Scuti was initially detected at Algonquin by Hughes and Woodsworth (1973), but the region is confused, and the measured flux density unreliable. Measurements at two frequencies with the NRAO interferometer (Hjellming *et al.*, 1973) indicate that the radio emission is not variable, and suggest a spectral index of ~ 1.0. Both the radio and the optical measurements indicate the presence of a significant circumstellar shell, and the radio object is probably similar to MWC 349 rather than to β Lyrae, i.e. the binary nature of the object is not directly related to its radio emission.

3.3. Radio objects with a continuum spectrum of optically thin gas

An example of this type of object is MWC 957, classified as Be by Vyssotsky *et al.* in 1945, and independently in the Mount Wilson Catalogue (Merrill and Burwell,

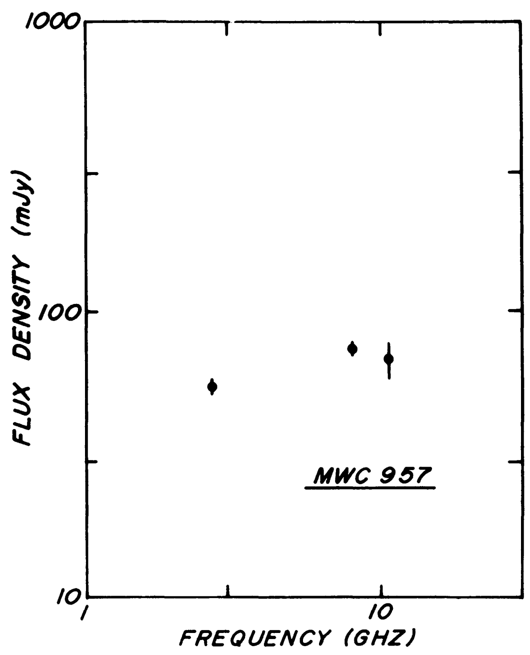

Fig. 2. Flux density measurements of MWC 957. The data have been taken from Marsh, Purton and Feldman (unpublished) at 2.7 and 8.1 GHz, and from Feldman *et al.* (1973) at 10.6 GHz.

1949). However, both Perek and Kohoutek (1967) and Henize (1967) take it to be a planetary nebula. Measurements by Allen (1973) in the H and K bands show an infrared excess, but do not indicate the presence of circumstellar dust.

The radio data is again sparse (see Figure 2), partly because it is a weak radio source – particularly for the higher frequencies – and partly because less interest is taken in an object of this type. Measurements with the NRAO interferometer show the region to be free of confusing sources, hence the single-dish measurement of Feldman *et al.* (1973) is probably reliable. The data suggest a standard Bremsstrahlung spectrum from gas which is optically thick at frequencies below 3 GHz. The radio spectrum in the optically thick region is not known, and could be of the $\alpha = +2$ or the $\alpha = +1$ type: if the latter is found to be true then the cirumstellar shell could be of the type associated with MWC 349, although of lower density and/or with a larger value of r_{in}. The radio object was unresolved with the NRAO interferometer, hence the angular size is $\lesssim 1''$, suggesting, independently of the rather dubious spectrum shown in Figure 2, a turnover frequency as high as 3 GHz. The emission measure is then $\sim 3 \times 10^7$ cm^{-6} pc, and for any reasonable distance at all (say a few kpc. within a factor of 3) the mass of the cirumstellar shell is even less than that of MWC 349.

There are many objects which have a similar radio spectrum, but most of them are classified as planetary nebulae, although the radio spectra indicate a shell mass which is relatively small. One of these objects which has been classified as Bep is MWC 247, for which only single-dish measurements are available (Wright, 1975), but these suggest that it is optically thin in the 5–10 GHz range.

3.4. β Lyrae

This is a special case. It is classified as Bep, but is also an eclipsing binary of large mass. The radio emission is weak and variable (Wade and Hjellming, 1972), hence the radio spectrum is difficult to determine. However, the radio luminosity is several orders of magnitude lower than that of the objects discussed above (Woodsworth, 1975), and it is most likely that the radio emission is associated with mass transfer in the system, as has been suggested for Algol (Hjellming, 1973; Jones and Woolf, 1973), and for the radio-emitting X-ray stars (see, for example, Gursky and Schreier, 1975), i.e. the Be classification of β Lyrae is not directly related to its radio emission.

4. Conclusions

Although normal Be stars do not produce detectable amounts of radio emission, a few peculiar Be stars are associated with radio objects by virtue of their very extensive circumstellar shells. The masses of the shells discussed in this review are probably $\lesssim 10^{-2}\ M_\odot$, and some appear to be the result of a prolonged mass outflow at a steady rate of $10^{-5}\ M_\odot\ \mathrm{yr}^{-1}$ or less (Marsh, 1975b). The connection between these objects and Be stars as a class is not clear. However, the connection with any other class of emission-line objects, such as planetary nebulae or Wolf-Rayet stars, is not clear either. It should be noted that the mass of the shell is quite small compared to the mass of a main-sequence early-type star, leaving open the possibility that these objects could represent a transient phase in the life of an early-type star.

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DISCUSSION

Hutchings: The limits you quoted for the four *Symp.* **70** stars seem rather high. I thought it was possible to do better than that.

Purton: Yes, the limiting flux is determined by the integration time and the estimated confusion. The synthesis arrays can work to ~5 mJy. The limits of 20 mJy come from observations with the Algonquin dish and represent a modest amount of integration time.

Because of the pressure for observing time on the synthesis arrays the practice is growing of taking preliminary observations with dishes, then checking out the possible detections with an interferometer.