PART 4

STELLAR AND CIRCUMSTELLAR SOURCES

"I asked for the physics, not the empirical model."
G. Westerhout, in the discussion following the paper
by Yervant Terzian

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RADIO CONTINUUM OBSERVATIONS OF STELLAR SOURCES

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Abstract. Thirty optically visible stellar sources have been observed in the radio continuum: four red dwarf flare stars, three novae, two red supergiants, eight binary systems, and 13 related peculiar objects. The observations of red dwarfs, novae, and supergiants are briefly reviewed. Their emission seems reasonably well understood. Binary systems such as Algol show erratic flaring; consistent explanations have not yet been given. The related peculiar objects, such as V1016 Cyg and MWC 349, are even less well understood. Some of them may have just arrived on the main sequence; others may be planetary nebulae in an early stage of formation.

(The following summary was prepared from the tapes by the Editors.)

I. Introduction

In this review on stellar radio sources, I shall confine myself to radio continuum observations of optically visible stellar sources. Apart from the Sun, 30 such objects have been detected (see Table I): four red dwarf flare stars, three novae, two red supergiants, eight binary systems, and 13 that I call related peculiar objects.

For only 22 objects, however, can the detection be regarded as definite. For these objects there is either a close positional coincidence, say to within a few arcseconds with the radio source, or there is a correlation between the radio and optical variability. For the eight remaining sources there is strong evidence that they are radio emitters, but definite detection must await accurate measurements of the radio position. These eight objects have so far only been observed with single dish instruments, and their positional accuracy is not high enough to conclude that there is definite radio detection.

The radio emission from all these objects is almost always very faint and highly variable. Their detection has not only been a matter of using high sensitivity instruments with high resolving power, but it has also been a matter of luck and patience. Many more objects have been looked at, of course, at radio wavelengths, but with negative results. In particular, people have looked at early-type stars, Of stars, Wolf-Rayet stars, magnetic variables, but all with negative results. I know of 50 published negative results, but I estimate the total number of negative results to be at least 150. That indicates radio stars might be quite rare, at least down to current sensitivity levels, say 5 mJy. You will see that all the radio stars detected up to now are real pathological cases. You will find most of them discussed in Section IV of the *Eighth Liège Astrophysical Colloquium on Emission-Line Stars*, entitled, 'Étoiles particulières et anormales'.

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II. Flare Stars, Novae, and Supergiants

The red dwarf flare stars detected so far are located in the solar neighborhood, say within 10 pc from the Sun. Observations of the radio emission of these stars have been made from Jodrell Bank and in Australia since 1958. Several cases of simultaneous optical and radio flares have been observed, but spectral information is still limited. In order to find out what the mechanism responsible for the radio emission is, many more measurements of flares at different frequencies are required. We may be dealing here with nonthermal phenomena like radio bursts on the Sun. For a review paper on radio observations of these objects I refer to Wilson (1971).

The novae have been studied extensively by the NRAO group. The spectra they obtained are entirely consistent with thermal bremsstrahlung from the expanding ionized nova envelopes. These novae are easily detectable because the envelopes quickly attain angular sizes of the order of a few tenths of an arcsecond while remaining opaque to radio waves (see, e.g., Herrero *et al.*, 1971).

The red supergiant Betelgeuse, α Orionis, was first detected by Kellermann and Pauliny-Toth (1966) at 15.8 GHz. They found this result only on one night; on the 11 following nights it was not detected. Low also discovered intense and variable infrared emission from that star. Later, Seaquist (1967), using the Algonquin Radio Observatory telescope concluded that he may have detected radio emission from α Ori

TABLE I

Stellar sources detected at radio frequencies

Red dwarf flare stars		
UV Cet (dM5.5e)	YZ CMi (dM4.5e)	
V371 Ori (dM3e)	EV Lac (dM4.5e)	
Novae		
FH Ser (N Ser 70)	HR Del (N Del 67)	
V368 Sct (N Sct 70)		
Red supergiants		
α Ori (M2 Iab)		
π Aur (M3 II)		
Peculiar binary systems		
β Per (B8 V + G8 III)	β Lyr (Bpe + B7 V)	
b Per (A2 III + ?)	Cyg X-1 (B0 Ib + ?)	
α Sco (M1 Ib + Be)	AR Lac (K2 III + F8)	
RY Sct (B0ep + late)	R Aqr (M7e + Pec)	
Related peculiar objects		
HD 37806 (A0e, Dn)	V1016 Cyg (e [ ], D)	MWC 137 (Be [ ], Dn)
M1–11 (e [ ], D)	P Cyg (B1e, F)	
Sco X-1 (Pec)	MWC 349 (e [ ], D)	
M2–9 (e [ ], D)	HBV 475 (Pec)	
HD 167362 (WC [ ], Dn)	Cyg X-2 (sdGpec)	
Vy2-2 (e [ ], D)	LkHα 101 (e [ ], Dn)	

and π Aur. These attempts at detection were made following a suggestion by Weymann and Chapman that the free-free emission from the corona formed by ejected matter from these stars might be detectable at radio frequencies. The stars show circumstellar lines in their spectra, indicating expanding gas over several hundred stellar radii.

Recently, Altenhoff and Wendker (1973) using the Bonn 100-m dish detected α Ori at a flux density of 7 ± 1 mJy. Efforts to detect the star with the Westerbork Synthesis Radio Telescope at 1.4 GHz and with the Green Bank three-element interferometer at 2.7 and 8.1 GHz did not yield a positive result. So strictly speaking, it remains uncertain whether α Ori has been detected at radio wavelengths. Certainly it remains uncertain whether it is a variable radio star as suggested by the data. Maybe it occasionally undergoes brief radio flares.

III. Binary Stars

I've also listed all the radio stars that are known to be binary. For all these binaries there are indications of mass loss or mass exchange in the system. It is tempting to believe there is a relationship between such gas-streaming phenomena and the production of radio emission. The radio emission from most of these objects is very faint.

Only Algol, β Persei, is bright enough to be studied in some detail. This has been done at Green Bank. It appears from the Green Bank observations that the radio behavior of Algol is erratic, showing both long quiescent periods and occasional periods of flaring. During quiescent periods the spectrum remains flat, but during most of the flares it increases at the higher frequency. This led Hjellming (1972) to propose that these flares are due to bremsstrahlung from a partially self-absorbed hot plasma with the following parameters: $T_e \sim 10^8$ K, $n_e \sim 10^{10}$ cm^{-3}, $D \sim 0.3$ AU. The value of the diameter he gets, 0.3 AU, is of the order of the separation of the close binary pair of the system (Algol is a triple system consisting of A B, and C components). This indicates that the radio emission originates from that close pair and not from the C component. Pooley and Ryle (1973), using the Cambridge 5-km telescope, came to the same conclusion. They found a variation of the right ascension of the radio source with time, suggesting orbital motion with respect to the C component.

There's one difficulty with the Hjellming model, and that's the high temperature of 10^8 K. From such high temperatures one would expect Algol to be an X-ray source during the radio flares, and that has not been observed yet. So this failure to detect Algol in the X-ray region, together with the occurrence of occasional nonthermal events, led Canizares *et al.* (1973) to reject Hjellming's model. They suggest that most of the radio emission must be ascribed to complex nonthermal phenomena.

Since its detection in October 1971, Algol has shown progressively stronger and more frequent radio flaring. Hjellming *et al.* (1972) suggest there may be a connection between this recent radio activity and a change in period of the binary system. The period of Algol is variable. It is known that period changes occur in the system on the average once every 25 yr. Hjellming believes that these period changes indicate sudden mass losses in the system, what he calls 'starquakes'. He believes that the radio flares we are detecting are the direct result of such starquakes. He suggests the rare occurrence of such activity might explain why radio emission has been detected in only a few objects out of roughly 50 binaries observed at Green Bank. There are more objects of variable period in Table I, and from all these objects Hjellming found radio emission similar to that from Algol.

Antares, α Scorpii, is a quite different system. It's clearly variable at 8.1 GHz, but at lower frequencies there is no significant, if any, change with time. So maybe here we are dealing with a two-component radio source, one component due to the envelope surrounding the supergiant in the system and a variable component associated with the early-type star. We know from the Green Bank observations that this 8.1 GHz emission originates from this *B* component. RY Scuti and R Aquarii may be similar systems, though Hjellming *et al.* (1973) prefer to call them radio nebulosities because of the lack of short time scale flux variations. They may, however, represent the same case as α Sco, with constant radio emission from a circumstellar envelope and variable radio emission at higher frequencies from the binary system.

IV. Related Peculiar Objects

The related peculiar objects include the well-known X-ray sources Sco X-1 and Cyg X-2, nova-like variables like P Cygni, and so-called stellar planetaries, mainly from Minkowski's lists, Minkowski 1–11, 2–9, etc. These objects show the spectral characteristics of early-type emission-line stars and compact planetary nebulae. The list also contains very peculiar systems like V1016 Cygni, which in the literature has been described as a symbiotic star, a slow nova, or a planetary nebula in an early stage of formation. Most of these stars show forbidden lines in their spectra. Most of them occur in Allen's (1973) infrared catalog of early-type emission stars, from which the types in Table I have been taken. '*F*' means that the observed infrared color indices fall close to the range of values expected from an early-type star combined with optically thin free-free radiation from the star's ionized hydrogen envelope. '*D*' means that the color indices are too large to be accounted for by hot free-free radiation. The IR excess is ascribed to re-radiation from circumstellar dust clouds. The '*n*' means that there is a visible nebulosity associated with the star. Probably we are dealing here with objects that have just arrived on the main sequence and are still surrounded by part of the parent interstellar material.

The best-studied object is MWC 349 (Greenstein, 1973). According to Olnon (preprint) its radio spectrum ($\alpha \sim 0.8$) can be explained by adopting an inhomogeneous density distribution. With a distance of 2.1 kpc and $T_e = 10^4$ K, he finds $n_e = 0.73\, r^{-2.15}$ cm^{-3}, where r is the distance from the center of the object in pc. He estimates the observed radio flux originates in layers at a distance of more than 0.002 pc from the center, radiation from the deeper levels being effectively absorbed. So we do not get any information about the density inside the sphere with that radius. But using the volume emission measure computed from the Hβ flux he derives a mean electron density of 7×10^6 cm^{-3}.

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DISCUSSION

Hughes: I can confirm that our observations to date on RY Sct at 2.8 cm show that the radio emission is constant to within about 20%. There was a numerical error in one of the values for flux density as listed in a recent publication in *Nature*. Some caution needs to be exercised when selecting radio sources according to their optical properties. We have observed a number of stars for radio emission at 2.8 cm. Under one classification, we chose Bep stars showing P Cyg profiles and an infrared excess, as contained in the list by Geisel. This included β Lyr, MWC 349 and RY Sct. β Lyr shows large radio variability and small angular size, while the latter two are constant to within about 20%, the radiation originating in a radio nebulosity which surrounds the star. Clearly we have two types of radio source.

Macrae: A comment about Algol. If one looks into the history books one finds a very surprising thing – that this star was not known to be variable in light until about 400 yr ago. This was only about 150 yr before Goodricke's recognition of Algol as an eclipsing pair. β Per was a well-known star in all of the principal constellations and there had been many assiduous observers over the centuries. Perhaps we have evidence that pronounced changes took place in Algol as recently as four centuries ago. If so, the time scale of the phenomena we are discussing may be shorter than generally assumed.

Van Woerden: If MacRae's suggestion is correct, then certainly the same case should be made for Mira Ceti, which at maximum is roughly as bright as Algol but has a much larger amplitude, and still was only discovered as variable around 1600. I doubt whether the arguments for profound changes around 1600–1700 would be strong. In medieval (and earlier?) times one tended to believe that the stellar heavens were unchangeable. The discovery of variable stars after 1600 might rather be due to the breakthrough of an experimental approach to physical science.