Bull Astr Soc India (1990) 18, 229-238

Radio emission from binary systems

V. R. Venugopal*
Radio Astronomy Centre (TIFR), P O Box 8, Udhagamandalam 643 001

1. Introduction

Historically, the earliest attempt to detect radio radiation from a star was by Sir Oliver Lodge, sometime during 1897 to 1900, when he used a coherer to look for long wave radiation from the sun, although he did not succeed. The first successful detection of solar radiation was made independently in 1942 by James Hey in England when he correctly associated the strong noise-type of interference affecting second world war radar equipment operating at 60 MHz with the sun; and by G. C. Southworth in the United States of America when he observed radio radiation from the 'quiet' sun at centimetre wavelengths. It was also in 1942 that solar radio bursts associated with solar activity were investigated by Hey, and this component was attributed to the 'disturbed' sun. The development of solar radio astronomy, the observation of galactic radio emission—'the radio Milky Way'—and the discovery of discrete sources of rapidly fluctuating intensity led to the suggestion in 1946 that the cosmic radio waves result from the aggregate radiation of separate stars in the Galaxy giving rise to the 'Radio star hypothesis' for the origin of galactic radio waves. It was soon recognized that none of the bright stars in the Galaxy was a radio emitter and the great majority of the radio sources identified in the late 1940s and early 1950s were either extragalactic or associated with nebulosities in our Galaxy and therefore, 'Radio star' was a misnomer for these sources.

It is of interest to note that Unsöld (1949) had pointed out that the 'Radio stars' contributing to the galactic radio emission were stars of high activity—prolific in spot formation and flare production and having strongly variable magnetic fields accompanied by corpuscular streaming. Although his ideas of 'Radio stars' as contributors to Milky Way radio radiation were refuted soon after, in the light of progress in the field in the last two decades, it seems that his basic ideas were correct in formulating the characteristics of real stars that could be radio emitters as evidenced by the discovery of radio emission from RS CVn stars. Another prediction worthy of note on the possibility of observing radio emission from real stars was by Schatzman (1958) at the Paris symposium on radio astronomy. Basing his arguments on the association of strong radio emissions with solar flares, he suggested that non-stable stars, namely, T Tauri stars, UV Ceti type flare stars, SS Cygni stars, and novae may be possible candidates to search for radio emission. Following this suggestion, Lovell, in England,

---

*Present address : Visiting Professor, School of Physics, Madurai Kamaraj University, Madurai 625 021.

initiated a program of monitoring flare stars for radio emission in 1958 September with the 250-ft radio telescope at Jodrell Bank, and Slee *et al* in Australia commenced observations of flare stars in 1960 september using the north-south arm of the cross-type aerial at Fleurs near Sydney, and in 1962 April using the 210-ft steerable radio telescope at Parkes. Although these two teams reported several cases of simultaneous radio and optical flares (Lovell 1964; Slee, Higgins & Patston 1963; Slee, Solomon & Patston 1963, Higgins, Solomon & Bateson 1968) and radio flares of peak intensities at metre wavelengths of few Jansky and a few tens of Jansky, more recent observations have not confirmed such strong radio flares (Gibson 1983; Hjellming & Gibson 1980), and weak (< 100 mJy) microwave flares have been observed from red dwarf stars using VLA (Kundu & Shevgaonkar 1988). Such contradictory results have been obtained in respect of flare stars in stellar aggregates, Orion and Pleiades, also (Slee & Higgins 1971; Tovmassian *et al.* 1974; Sanamian, Venugopal & Chavushian, 1978; Bastian *et al.*, 1988).

Since the commencement of the monitoring of radio emission from flare stars in the late 1950s and the 1960s, many different types of stars have been detected to be radio stars. In his paper on 'Radio stars'. Hjellming (1976) lists seven categories of known radio stars. They are UV Ceti-type flare stars, M Supergiants; variable thermal emitters; steady thermal emitters; 'normal' radio binaries; radio emitting x-ray stars; and pulsars.

The initial search for radio emission from binaries started with red supergiants by Wade & Hjellming (1971) and their detection of a flare from α ScoB at 8 GHz on 1971 June 1, led them to search for radio emission from binaries with known mass exchange and emission lines culminating in their positive radio detection (on 1971 October 1) of Algol and β Lyrae at 8 GHz and 2.7 GHz. This was followed by a search for radio emission from many other Algol and β Lyrae-type binaries (Hjellming *et al.* 1972). A very astonishing result of this search was the large variability from 0.01 Jy to 0.32 Jy within a few hours displayed by Algol. Subsequently came the successful detection of radio emission from AR Lacertae (Hjellming & Blankenship 1973) while searching for radio emission from binary stars with period jumps or evolving periods and from UX Arietic (Gibson & Hjellming 1975) suggested by D. Hall because of its close similarity to AR Lac. These positive detections indicated that RS CVn-type binaries to which AR Lac and UX Ari belong should be radio stars (Gibson 1975). Since then systematic survey of RS CVn stars have been undertaken at the Algonquin Radio Observatory and the VLA. The extensive observational results obtained by several workers on radio emission from a wide variety of stellar systems induced the Herzberg Institute of Astrophysics (Canada) to organize a workshop on radio stars in Ottawa in 1979 June. From the report from this workshop (Feldman & Kwok 1979) it is seen that 'radio stars' include Algol-type systems, x-ray emitting radio stars, compact radio sources in the direction of supernova remnants, RS CVn stars, emission line stars, symbiotic stars, novae and supergiants. It is immediately seen that these are all binary/triple systems. Gibson (1980) has examined the question of binarity as a factor in stellar radio emission and has stressed its importance while underlining that the specific aspects of binarity which affect the radio emission process are far from clear. Thus, recognizing that binarity is an important factor in stellar radio emission, it is appropriate that we review 'Radio emission from binary systems' at this colloquium on 'Binary stars and stellar atmospheres'. Considering the active interests of the astronomers of the Centre for Advanced Study in Astronomy, the constraints of time and kindly feelings to the audience lest they should feel too heavily loaded, I shall restrict myself to reviewing radio emission from three systems RS CVn stars, Algol and Algol-type systems; and x-ray binaries

2. RS CVn Stars

Radio emission at centimetre wavelengths has been discovered in more than 20 RS CVn binary stellar systems, this emission is observed to be highly time variable and circularly polarized. The polarization is also variable and occasionally components with only one frequency and one circular polarization, parts of which show oscillations with periods of about four minutes, have been observed Systematic surveys of RS CVn binaries have been carried on at the Algonquin Radio Observatory by Feldman since 1976 and by Gibson and others using the NRAO facilities (91m, Green Bank interferometer, and VLA) and the Jodrell Bank Mark I-Mark III interferometers since 1974. These surveys have provided extensive data primarily on V711 Tau ((HR 1099) whose radio flares are quite strong, and moderate amount of data on AR Lac and UX Ari, and meagre amount of data on a few other RS CVn binaries [see *Astr. J.* (1978) **83**, No. 12]. From the series of strong radio outbursts in 1978 February the following observational results are obtained.

(i) RS CVn binaries produce strong variable centimetric radio emission. Detailed 'light curve' obtained on nine days of flaring of HR 1099 with at least one flaring occurring per day.

(ii) Radio flares do not appear to be correlated with any specific orbital phase (observations indicate minimum of photometric wave occurs in the vicinity of orbital phase 0.55-0.60). No correlation with radio flaring apparent in the 10.5 GHz data.

(iii) Component stars of HR 1099 rotate synchronously. Because of chance occurrence of radio flares with orbital phase the size of the radio emitting region is probably larger than the active star ($R_* \sim 3R_\odot = 2 \times 10^{11}$ cm).

(iv) The radio flares evolve on a time scale of hours. Data show both rise and decay.

(v) Linear decay of flux density with time fairly common. More gradual decay $\sim 3^h$; (flare after 20^hUT on 1978 February 25). This $\tau_d \approx 10^4$s seems somewhat shorter than previous reports on RS CVn binaries.

(vi) The rise times are of considerable interest and they characterize the high energy injection phase of the flares. The time of rise varies from 30 min to 2 hr, the best observational evidence favouring 2 hr. Previous estimates of τ_r are an order of magnitude longer. Rise time is somewhat shorter than decay time scale.

(vii) Evidence for shorter time scale variability definitely present in 10.5 GHz data—significant changes occur with mean epochs $\sim$ 10 min apart.

(viii) Combining coincident ARO and Haystack observatory data the radio spectrum is found to be flat ($\alpha = 0$) at short centimetre wavelengths (2 cm to 4 cm) in the injection and peak flux phases of major flares. Spectrum is flat also during relatively quiescent periods.

(ix) Peak near 0^hUT 1978 February 24 second most intense flare observed at 10.5 GHz—this is marginally less intense than the flare at 20 hr UT 1978 February 21. This is the first flare of February series caught and followed on the rise and well observed by cooperating optical astronomers. Also, observed at both very low and very high radio frequencies (ARO and Haystack). Low frequency radio spectrum of HR1099 during rise portion at 22 hr (orb phase 0.97) flat ($\alpha = 0$) at short centimetre wavelengths became optically thick at longer wavelengths High frequency radio spectrum shows that the radio flare emission is consistent with nonthermal magnetobremsstrahlung. The combined radio spectrum is remarkably similar to post-optical microwave spectra of giant type IV solar radio bursts.

(x) The radio luminosity of HR 1099 during these outbursts peaked seven times at $\sim 10^3$ LU (1 LU $= 10^{15}$ ergs s^{-1} Hz^{-1}). This luminosity is an order of magnitude more intense than the mean peak radio flares of other RS CVn stars. This is also $\sim 10^5$ times more intense than the greatest type IV solar microwave burst ever recorded.

(xi) Observations by Brown & Crane (1978) during 1978 February 21 to 26 with the NRAO four element interferometer operating at 2695 MHz and 8085 MHz gave the following results:

(a) HR 1099 was quite active throughout the period, the flux density at 8085 MHz being always higher than at 2695 MHz *i.e.* spectral index $\alpha > 0$ ($S \propto \nu^a$).

(b) Source was more active at 8085 MHz than at 2695 MHz.

(c) Variations at the two frequencies in the same sense at the same time.

(d) HR 1099 was circularly polarized at both the frequencies. The magnitude of the polarization $\sim 40\%$ and the rapid changes in the polarization are unprecedented. Earlier values reported are $\sim 8\%$ at 8085 MHz and not polarized at 2695 MHz (Owen, Jones & Gibson 1976) and $\sim 20\%$ at 1400 MHz (Spangler 1977). Nearly always the circular polarization is greater at the lower frequency.

(e) Correlation of circular polarization with variations in total intensity not systematic but erratic--when spectrum is steep, sometimes degree of polarization large and at other times negligibly small – sometimes the sense of polarization is the same at both the frequencies and other times there is change in sense. The presence of circular polarization suggests that the emission mechanism involves a process in a structured magnetic field The differences in the degree of polarization at the two frequencies help to investigate the magnetic conditions within the source

(f) During active periods at the lower frequency (2695 MHz) the activity is only in a single sense (LCP) but at 8085 MHz it is in both (LCP and RCP).

(g) At 2695 MHz, during times of large circular polarization large flux density changes (factor of two) in left circular component occur in short intervals (2 min) and characteristic sinusoidal modulations seen with a period of ~ 4 min recurring on intervals of 4 to 6 min. No significant periodicities in either 2695 MHz RCP data or in 8085 MHz data.

(h) Large circular polarizations occur at zero phase (*i.e.* at conjunction with the more active component in front).

(i) The sense of polarization at 8085 MHz changes at conjunction.

The nonthermal character of the radio emission has been better established by the 1978 February events. The emission process is a magnetic phenomenon, almost certainly magnetobremsstrahlung (gyrosynchrotron radiation from mildly relativistic electrons). This conclusion is based on the nonthermal radio spectrum, high percentage of circular polarization, the high flux density level of radio emission and rapid time variability and absence of hard x-ray emission during the period of radio outbursts. This assumption of gyrosynchrotron radiation process enables estimation of physical parameters of the radio flare process (Spangler 1977; Owen, Jones & Gibson 1976). The characteristic decay time of 10.5 GHz radio flares is $\tau \sim 10^4$. This is mainly due to gyrosynchrotron radiation losses. Then the magnetic field is ~ 75G which is consistent with the circular polarization observations of Brown & Crane (1978). From the low frequency cut off of the radio spectrum of HR 1099 due to synchrotron self-absorption, the source radius $R \approx 3 \times 10^{14} B_{10}^{1.4}$ (B_{10}—magnetic field in units of 10G) The optically thin part of the spectrum is flat ($\alpha = 0$). The distance to HR 1099 is 35 pc. Hence, for $B = 75$ Gauss, $R = 5 \times 10^{11}$ cm. This is consistent with $c\tau \sim 2 \times 10^{12}$ cm from observed minute to minute variations. This estimate of linear size corresponds to ~ 2 milliarcsec at x-band The size is comparable to values derived for AR Lac (Owen & Spangler 1977) and UX Ari (Backer & Sramek quoted in Hall 1978). This angular size is consistent with VLBI results obtained for HR 1099, UX Ari and HR 5110 (Resch *et al.* quoted in Hall 1978; Owen, Jones & Gibson 1976; Lestrade *et al.* 1984a; Mutel *et al.* 1984; Lestrade *et al.* 1984b). The derived linear size indicates that the emitting region is comparable to or smaller than the overall size of the binary system. For $R = 5 \times 10^{11}$ cm the observed 10 5 GHz bursts of 1978 February and 1 65GHz VLBI observations of 1983 February yield brightness temperature of ~ 10^{10}K. This explains the negligible inverse Compton radiation The radio emission from RS CVn stars has close similarities to solar radio events, at least at centimetre wavelengths. The RS CVn events are typically 10^2-10^4 times more luminous.

Hall (1972, 1976) and others have put forward model incorporating giant spot groups and other scaled up physical manifestation of the magnetically active sun. Also, a simple kinematic dynamo model has been put forward (Hall & Shore 1978) which has been reasonably successful in explaining a number of the observed peculiarities of the source.

The increased radio luminosity of the RS CVn stars has a bearing on their binarity in the sense that the enhanced dynamos and the strong tidal effects increase the magnetic field strengths (Gibson 1980). Because of tidal effects stars orbit synchronously and this causes the rotational velocities to be typically 10 times larger than in the solar type single stars. Because of this, greatly increased dynamo action in the convective envelope is caused which enhances the magnetic fields. The result of the increased dynamo action and tidal distortion effects is the occurrence of large star spots on the RS CVn systems covering 25% to 50% of the cooler component. The migration of star spots with stellar longitude over a period of years is responsible for energetic particles, analogous to the solar phenomenon, which give rise to the radio. events.

From the VLBI observations of UX Arietis and HR 1099 (Mutel *et al.* 1984), it seems the gyrosynchrotron model with power law energy distribution of electrons can reasonably explain the observed brightness temperature and the polarization properties and there is no need to invoke coherent mechanisms such as electron cyclotron maser.

However, it should be pointed out that higher angular resolution observations will yield detailed information on the size and shape of the emission region which will enable better modelling and therefore better understanding of these interesting binary systems.

3. Algol-type systems

The prototype of this class of radio binaries is the triple star β Persei (Algol) and includes close binary systems such as CC Cas, b Per, AR Lac and possibly β Lyrae. Among these the best studied is Algol with lot of observational information. The characteristics of an 'Algol-type' event, according to Hjellming (1972), are a flat radio spectrum before the flare, with higher flux levels at high frequencies during the flare and decay of the flare event until a relatively flat spectrum is reached at low flux levels We discuss a few members of the class before considering Algol itself.

CC Cassiopeae

It is a massive close binary with both components more than 10 $M_\odot$ Radio emission was searched for from this system using the NRAO interferometer operating simultaneously at two frequencies 2695 and 8085 MHz The observations were made in 1973 September and 1974 March (Gibson & Hjellming 1974) and the radio emission was detected from the source on three days in September The other observations failed to detect any emission This, perhaps, is indicative of 'cycles of activity' observed in Algol

The observations clearly reveal that when the source is active it is stronger at the higher frequency or has a flat spectrum. these characteristics assign CC Cas, which consists of two 09 IV stars, to the 'Algol type' system.

AR Lacertae

This system consists of the spectral types, G2 IV-V and KO IV. First detected as a radio emitter in 1973 January and February (Hjellming & Blankenship 1973) it was again observed in 1973 October using the NRAO interferometer (Gibson & Hjellming 1974). The 'Algol-type' radio event observed during October 16-18 reveals most interesting data with strong flux densities which enable detailed quantitative interpretation. This event has similarities with typical 'Algol-flare' events: The duration of AR Lac event was about 24 hr (Algol 16 hr). Rise time for AR Lac event is seen to be faster than typical Algol events. The spectral index increased more rapidly and reached higher values than those obtained for Algol events. The rapid rise time in AR Lac event may be suggestive of the sudden onset (discontinuities) of radio emission on time scales of minutes seen in Algol. Such sudden spurts may point to the sudden reenergization of radio emitting regions with sizes of the order of tens of light minutes or less.

Gibson & Hjellming (1974) discuss the radio properties of the six systems for which the binarity is definite viz. CC Cas, AR Lac, β Per, β Lyr, b Per and HDE 226868 (Cyg X-1)

The initial suggestio . (Hjellming 1972) of interpreting the Algol-type radio events as thermal emission from a hot and transient plasma has not been found to be tenable by the extensive observations of these events: occasional events with nonthermal spectra have been detected; thermal interpretation warrants detection of appreciable amounts of x-rays which are not seen to accompany radio flares in Algol; the angular size of Algol derived from high resolution radio observations during major radio events leads to lower limit of brightness temperature of 2×10^7 K which makes the x-ray emission requirement untenable. Gibson & Hjellming have calculated the brightness temperatures on the assumption that the radio sizes of the binary systems are of the order of their size scales and find that the brightness temperatures are quite high with 1.2×10^{12} K in the case of Cyg X-1. This suggests that if the sizes are of the order of the stellar discs T_b would be much greater than 10^{12} K requiring coherent mechanisms to account for the radio emission. This would require inverse compton scattering effects to be caused with the production of hard x-rays. It is therefore interesting that the one system with the highest brightness temperature HDE 226868 (Cyg X-1) is an x-ray source.

Another very interesting correlation discovered by Gibson & Hjellming (1974) is that between the maximum radio luminosity at 8085 MHz (L^{Max}_{8085}) and the mass of the binary system. This, according to them, supports the conclusion that the source of energy supply, for the processes that eventually result in variable emission, is the gravitational energization of matter falling on or near the surface of one of the binary components. Of course, there is need for more such observations to establish firmly the validity of this conclusion.

β *Persei (Algol)*

Algol can be considered as the prototype of the radio stars because of the extensive observations on it including VLBI observations of the radio-flaring region in two events and the very high levels of flaring recorded. The variation in flaring level is clearly seen from the observations made during four years from 1971 to 1975 (Hjellming 1976) although this is too short a period to draw any conclusions on the cycle of activity similar to solar activity cycles. Perhaps such variations could explain the non-detection of radio emission from similar radio binaries at any time.

Algol radio variations fall into three recognizable classes.

(i) The single peaked flare event where the decay time is typically twice the rise time. Occasionally double peaks are seen. Flux density at higher frequency greater than at lower frequency; (ii) featureless variability with flat spectrum, and (iii) rare non-thermal events.

Each of the three non-thermal Algol events recorded is unique.

(i) 1975 January 23 : a clearly decaying non-thermal event was followed by a more typical event. (ii) 1972, January 11 . a very short event, duration 2 hr, decaying rapidly (exponentially) as a non-thermal source. (iii) 1974 September 12 : typical high frequency dominated flare evolving into a non-thermal decay.

Similarity of different Algol events (Gibson 1975):

(i) Shape quite similar with decay times longer than rise times. (ii) Major parameter distinguishing different peaking events is the flux density at the peak. (iii) The typical life time from initial rise to final decay is 16 hr.

The most important radio observations of Algol are the two VLBI measurements of the evolving radio source:

(i) The 0.7 Jy event of 1974 May 4-5 (Clark *et al.* 1975)

- 8 GHz; 20×10^6 wavelength baseline
- Slightly resolved source, angular size ~ 0.004 arcsec (~ 0.1 A.U.)
- $T_B \sim 4 \times 10^8$K
- Data consistent with either a source expanding at 500-1000 $\mathrm{km\,s^{-1}}$ or a stationary elliptical source

(ii) The 1Jy event 1975 January 16 (Clark *et al.* 1976)

- 8 GHz; 20×10^6, 85×10^6 and 100×10^6 wavelength baselines
- source size ~ 0.0018 arcsec (~ 0.045 A.U.)
- $T_B \sim 10^{10}$K.

From these it is clear that the radio source was larger than the size of each star (0.03 A.U.) and was about the size of the environment between the stars. Thermal model is not tenable for these events.

Most reasonable working hypothesis for the Algol radio emission is incoherent synchrotron radiation from relativistic electrons in a relatively dense environment.

Recently Lastrade *et al* (1988) have presented results of dual frequency (2.3 GHz and 8.4 GHz) and dual polarization (left and right circular) VLBI observations of the Algol stellar system. Eight radio telescopes in the USA, one in Spain and one in West Germany formed the elements of the VLB array and the observations at three epochs : 1983 March 20 – 8.4 GHz, 1983 May 11 – 2.3 and 8.4 GHz simultaneous and 1983 October 16 – 1.65 GHz dual polarization. Their observations provide strong evidence that all the three mechanisms gyrosynchrotron, synchrotron and coherent radio emission processes (electron-cyclotron maser) operate in the Algol system. They have suggested a simple physical model which includes all the three mechanisms.

4. X-ray emitting radio stars

Cygnus X-3

The best studied of this class of radio stars is Cygnus X-3. This was first detected as a highly variable radio source at 1415 MHz with the Westerbork Synthesis Radio Telescope during observations in 1971 July and October and 1972 March by Braes & Miley (1972) and confirmed by observations in 1972 April and May with the NRAO interferometer by Hjellming *et al* (1972). In 1972 September, two giant radio outbursts were observed from Cyg X-3 described as 'the most impressive outburst ever witnessed by radio astronomers' (Gregory *et al.* 1972). The extensive data triggered a spate of studies leading to many interpretations. These have shown that the outbursts are nonthermal and are most likely produced by the sudden injection of relativistic electrons into an expanding plasma cloud containing non-relativistic gas (Seaquist & Gregory 1977; Mascher & Brown 1975). The relativistic electrons may be produced in the plasma clouds from high energy γ-rays emitted by a central engine in the source (Vestrand 1983). This suggests an expansion of the radio source soon after the outburst. In September 1982 Cyg X-3 flared up with a series of giant outbursts. The observations of these bursts made with the VLA and VLBI by Geldzahler *et al.* (1983) indicate an expansion rate of 0.010 arcsec per day which corresponds to linear expansion at a speed of $\gtrsim 0.35c$.

The MERLIN, VLA, and Cambridge 5-km observations of the bursts of 1983 October (Spencer *et al.* 1986) seem to favour a rate of 12 milliarcsec per day. They suggest that a model of symmetrical expansion about the star at a velocity of 0.35c, with a later outburst accompanying the formation of hot spots in the jet possibly by means of interaction with a surrounding gas shell best fits the observations. Johnston *et al.* (1986) report on the flux density variations of Cygnus X-3 for the period 1982 October through 1985 March at 11 cm and 3.7 cm. The flaring events observed during the period may be attributed to variable accretion rate on to the collapsed star of the binary system. They mention a possibility of a 120d periodicity in the large flaring events. This periodicity may be the result of the modulation of the accretion rate by a third body. The remarkable event of 1983 September-October, monitored at 6 cm, displayed variations on time scales of minutes to hours. The 6 cm data did not reveal any periodicity of ~ 4.8 hr in the radio emission with amplitude greater than 50 mJy.

In the recent *IAU Circular No. 4798* Waltman *et al.* report that V1521 Cyg (Cygnus X-3) is flaring. It reached a peak of 17 Jy at 8.085 GHz on June 2 and 14 Jy at 2.7 GHz on June 3. By June 5, it had dropped to 3 Jy. This is the first major flare after 1985. It could flare up in the following weeks.

Sco X-1

Sco X-1 was one of the first x-ray sources to be recognized (Giacconi *et al.* 1962). This was detected as a weak radio emitter by Andrew & Purton (1968) and a radio variable by Ables (1969). The NRAO three element interferometer observations by Hjellming & Wade (1971) have revealed this to be an unusual radio source with three components, one coinciding with the x-ray star and the other two on opposite sides of it within 2 arcmin from it. The variability was noticed to be highly erratic at 11.1 cm. The radiation during the flare is stronger at longer wavelength than at shorter wavelength suggesting that it is nonthermal. Both the radio spectrum and emitted power are variable. Intensity variations on timescales of ~ 10 min have been observed. This binary system is the only known galactic object exhibiting radio morphology similar to extragalactic double radio sources. Geldzahler *et al.* (1981) have brought out its triple morphology from their 1980 VLA observations. In order to understand the energetics and the kinematics a 5 yr monitoring has been carried on by Geldzahler & Fomalont (1986) with the VLA at 4.85 GHz with resolution of 0.4 arcsec. They have found three components . an unresolved (< 0.1 arcsec) radio core coincident with the stellar binary system; an unresolved lobe ~ 1 arcmin north-east of the core; and an extended (10 arcsec) lobe, ~ 1 arcmin south-west of the core. The NE lobe is moving away from the core at a velocity of 36 ± 5 km s^{-1} and the relative velocity of a hot spot in the SW lobe relative to the core is < 70 km s^{-1}. The flux densities of the lobes vary by ~ 20% over time scales of a year and the variations between the lobes seem to be correlated. They invoke partially coherent processes to explain the flux density variations.

Velusamy & Subrahmanya (1989) have presented new observations of Sco X-1 at 327 MHz with OSRT and at 843 MHz with MOST. Their observations show that the NE component exhibits a spectral turn over at ~ 1.5 GHz. The central component is not seen at these frequencies. The SE component shows a power law spectrum with $\alpha = -0.75$ between 0.3 and 5 GHz. The radio structure and spectra resemble those of extragalactic double radio sources. The spectral turnover indicates a size of < 1 milliarcsec for the NE component which poses difficulties for ram pressure confinement. Two other sources collinear with the triple source, 18.5 and 31.6 arcmin from the central source have been found. These are discussed in the light of models with magnetic focussing.

Hjellming & Johnston (1988) have developed kinematic and physical models for the evolution of synchrotron radio emission in conical twin jets. These models are shown to have the characteristics needed to explain the variety of radio properties of x-ray binaries.

5. Conclusion

In this review, the radio emission from a few of the binary systems has been discussed. It is evident that high resolution and high sensitivity observations, especially VLA and VLBI have revelaed very interesting aspects of radio emission from the binary systems and increased our knowledge of these systems. It is, therefore, possible that higher sensitivity and higher resolution and simultaneous multiwavelength observations will not only help in understanding these systems better but may reveal many exciting physical phenomena.

References

Ables, J G (1969) *Proc astr Soc Aus.* **1**, 237.
Andrew, B H & Purton, C R (1968) *Nature* **218**, 855
Backer & Sramek in Hall (1978) *Astr J* **83**, 1469.
Bastian, I S, Dulk, G A & Slee, O B (1988) *Astr J.* **95**, 794
Braes, L. L E & Miley, G K (1972) *Nature* **237**, 506
Brown, R L & Crane, P C (1978) *Astr J* **83**, 1504
Clark, B G Kellermann, K I and Shaffer, D B (1975) *Ap. J* **198**, L123
Clark, T A *et al* (1976) *Ap J* **206**, L107
Feldman, P A & Kwok, S. (1979) *J R astr Soc. Can.* **73**, 271.
Geldzahler, B J *et al.* (1981) *Astr J* **85**, 1036
Geldzahler, B J *et al* (1983) *Ap J.* **273**, L65.
Gibson, D M & Hjellming, R M (1974) *P A S P* **86**, 652
Gibson, D M (1975) *PhD thesis*, Univ of Virginia
Gibson, D M *et al* (1975) *Ap. J.* **200**, L99
Gibson, D M (1980) in *Close binary stars* (eds: M. J Plavec, D. M. Popper & R K. Ulrich), p. 31.
Gibson, D. M (1983) *IAU Coll. No. 91*, 273
Gregory, P *et al.* (1972) *Nature* **239**, 440
Hall, D S. (1972) *P A S.P* **84**, 323.
Hall, D S (1976) *IAU Coll. No 29.*
Hall, D S & Shore, S N (1978) *Bull Am. Astr Soc.* **10**, 418.
Higgins, C S. Solomon, J D & Bateson, F. M. (1968) *Aus. J Phys.* **21**, 725
Hjellming, R M & Wade, C M (1971) *Ap. J* **164**, L1
Hjellming, R. M (1972) *Nature, Phys. Sci* **238**, 52
Hjellming, R M *et al* (1972) *Nature* **236**, 43
Hjellming, R M & Blankenship, L 1973 *Nature, Phys Sci* **243**, 81
Hjellming, R M (1976) *The physics of non-thermal radio sources* (ed · G Setti), Reidel, p. 209
Hjellming, R M & Gibson, D. M. (1980) in *Radio physics of sun* (eds M R. Kundu & T. K. Gergely) p. 209.
Hjellming, R M & Johnston, K. J (1988) *Ap. J.* **328**, 600.
Johnston, K J *et al.* (1986) *Ap. J.* **309**, 707.
Kundu, M R. & Shevgaonkar, R K. (1988) *Ap. J* **334**, 1001
Lestrade, J F *et al.* (1984a, b) *Ap J.* **279**, 1984, (Lett) **282**, L23.
Lestrade, J F. *et al* (1988) *Ap. J.* **328**, 232.
Lovell, B (1964) Observtory **84**, 191.
Marscher, A. P. & Brown, R L (1975) *Ap J.* **200**, 719
Mutel, R L *et al* (1984) *Ap J.* **278**, 220.
Owen, F. N., Jones, T W. & Gibson, D. M. (1976) *Ap J.* **210**, L27.
Owen, F N. & Spangler, S. R. (1977) *Ap. J.* **217**, L41.
Resch *et al.* in Hall (1978) *Astr. J.* **83**, 1469.
Sanamian, V. A, Venugopal, V. R. & Chavushian, O. S (1978) *Astrofizika* **14**, 283.
Schatzman, E. (1958) in *Paris Symp. on Radio Astronomy* (ed R N. Bracewell) Stanford Univ. Press, p. 552.
Seaquist, E R. & Gregory, P C. (1977) *Ap. Lett.* **18**, 65.
Slee, O. B., Higgins, C S. Patston, G E (1963) *Sky & Tel.* **25**, 83.
Slee, O. B., Solomon, L. H. & Patston, G E. (1963). *Nature* **199**, 991.
Slee, O. B. & Higgins, C. S. (1971) *Aus. J. Phys.* **24**, 247
Spangler, S. R. (1977) *Astr. J.* **82**, 169.
Spencer, R E. *et al* (1986) *Ap. J.* **309**, 694.
Tovmassian, H. M. *et al.* (1974) *Astrofizika* **10**, 337.
Unsold, A. (1949) *Z Ap.* **26**, 176.
Velusamy, T. & Subrahmanya, C. R (1989) *M.N.R.A.S.* **239**, 281.
Vestrand, W. T. (1983) *Ap. J.* **271**, 304.
Wade, C. M & Hjellming, R. M. (1971) *Ap. J* **163**, L65.