PRELIMINARY RESULTS OF A FIVE-YEAR SURVEY OF RADIO EMISSION FROM RS CVn AND SIMILAR BINARIES

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This is a summary of the systematic program of λ3cm radio observations of RS CVn and similar binaries which has been carried out since 1977 at the Algonquin Radio Observatory*. The observations were made at X-band frequencies (10-11 GHz) with the 46m telescope using the same observing procedures described in Feldman et al. (1978). The detection limit is generally 25 mJy, although it is possible to do somewhat better than this if the star is located well off the galactic plane and if it maintains an elevated flux level (i.e. $\gtrsim$ 15 mJy) for several hours. The observing list has grown roughly four-fold since the start of the program in 1977. It now encompasses 65 of the 69 "bona fide" RS CVn binaries compiled by Hall (1982); the rest are suspected RS CVn binaries, BY Dra variables, Algol-type binaries, and W UMa binaries. To date, a total of some 85 observing days, representing more than 1000 hours of telescope time, has been devoted to this program.

When the program was first instituted, there were three main objectives: (1) to detect new radio binaries; (2) to study the physics of the radio sources by observing the complete rise and decay phases of at least several flares; and (3) to detect major flaring events early enough to enable useful collaboration with observers at other wavebands.

(1) Five new RS CVn binaries were detected at λ3 cm, adding substantially to the number of these systems known to emit radio waves. These are SZ Psc (detected independently by Owen and Gibson (1978); HR 5110 = BH CVn; HK Lac; HR 8575 = HD213389 = V350 Lac; and HR 9024, which is not a "bona fide" RS CVn binary

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according to Hall's criteria but which may be either such a system or an FK Comae star seen pole-on (Feldman and Fraquelli 1983). All the new detections reported here are restricted to sources with flux densities in excess of 25 mJy and for which extensive enough observing was done at different times and parallactic angles to give reasonable confidence in the results. In addition, several possible new detections have been made at the ≈ 15 to 25 mJy level, but these require further confirmation.

(2) The complete rise and decay profiles of individual RS CVn radio flares have now been observed many times (see, e.g., Feldman et al. 1978, Hjellming and Gibson 1980). The basic radiation mechanism at short cm wavelengths now seems firmly established as incoherent gyro-synchrotron radiation of electrons with Lorentz factors $\gamma \lesssim 10$ in magnetic fields $B \approx 30$-100 G. Coherent gyro-synchrotron or possibly plasma wave emission processes may be operative at longer radio wavelengths ($\lambda \approx 10$ to 20 cm) as evidenced by the high degree and rapid variability of the circularly polarized flux which are sometimes observed. However, these effects have not yet been found at the relatively short (λ3cm) wavelengths used in this study.

(3) A major goal and success of this program has been the early detection of major flaring events. This has enabled valuable "target-of-opportunity" collaboration with observers at other wavebands. The prime example of such joint efforts occurred during the 1978 February-March outburst of HR 1099 = V711 Tau (Feldman et al. 1978; see special issue of Astron. J., December 1978). However, several other RS CVn superflares have been observed extensively, especially the 1978 Dec. - 1979 Jan. flare of UX Ari and both major events of HR 5110 (see Table 1). In general, it has proved feasible to obtain timely, useful collaboration from ground-based optical spectroscopists and from IUE observers (under a pre-arranged "target-of-opportunity" program). However, it has not been possible to obtain radio "back-up" at short notice, especially after the NRAO interferometer ceased operation as a national facility several years ago. On rare occasions, unscheduled VLBI observations of major radio flares were arranged with difficulty, but the most useful VLBI measurements to date have resulted from a fortuitously pre-scheduled program (Cohen et al. 1983). For operational reasons "target-of-opportunity" X-ray observations could never be scheduled during the Einstein era.

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TABLE 1. Major Radio Flares of RS CVn Binaries observed at Algonquin Radio Observatory (1977-1981)

Star	Distance (pc)	Date	Peak Flux Density (mJy)	Observing Frequency (GHz)	Peak Radio Luminosity (Lu)*
UX Ari	55	1978 Dec.- 1979 Jan.	255	10.65	920
		1979 Dec.	140	9.90	500
HR 1099 = V711 Tau	33	1978 Feb.-Mar.	960	10.52	1300
		1979 July	1210	10.76	1600
HR 5110 = BH CVn	52	1979 May-June	460	10.52	1500
		1981 April	410	10.46	1300
AR Lac	47	1977 May	550	10.48	1500
HD216489 = HR 8703	200	1980 June	40	10.48	2000
SZ Psc	100	1977 May	65	10.48	780
		1977 Sept.	60	10.29	720
		1978 April	85	10.52	1000
		1979 Nov.-Dec.	110	10.82	1300
II Peg = HD224085	29	1979 Nov.-Dec.	255	10.82,9.90	260
		1980 Sept.	170	10.45	170

* 1 Lu ≡ 10^{15} erg s^{-1} Hz^{-1}

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The (daily-averaged) absolute radio luminosity distribution for RS CVn binaries was first determined at 5 GHz for five comparable systems (AR Lac, UX Ari, HR 1099, SZ Psc, and II Peg) by Owen and Gibson (1978). This survey was done with sensitive instruments and thus probably provides a good estimate of the low-luminosity ($\lesssim$ 250 Lu) portion of the radio luminosity function during 1974-1977. Owen and Gibson

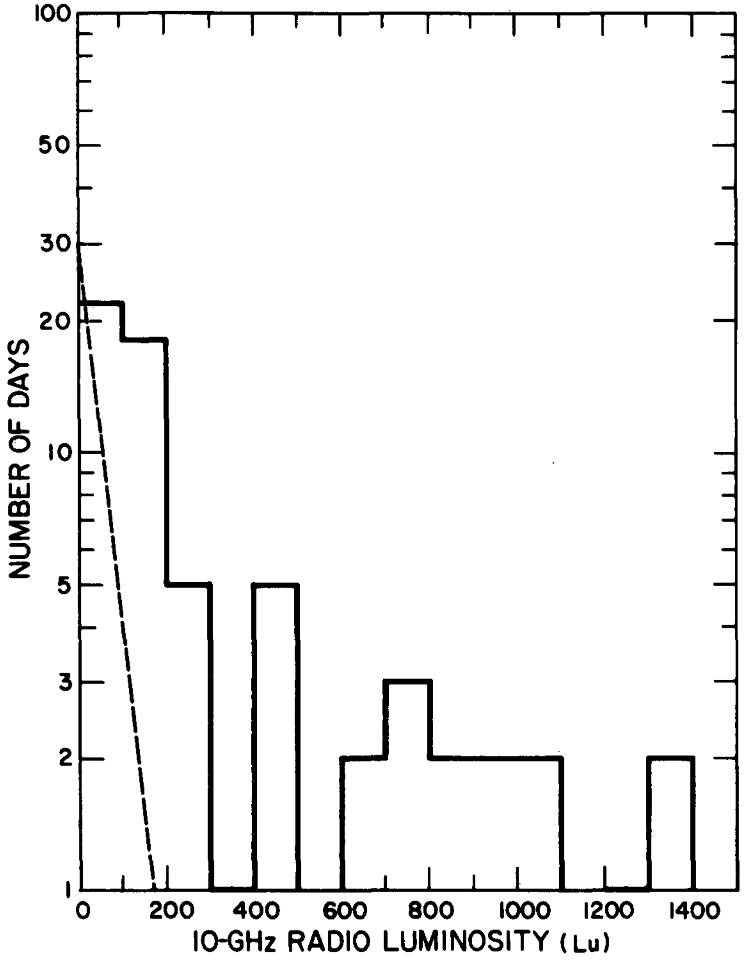

Figure 1. Cumulative differential 10-GHz radio luminosity distribution of six RS CVn binaries (UX Ari, HR 1099, HR 5110, AR Lac, SZ Psc, and II Peg). The ordinate is the number of independent days that these systems were detected with a daily-averaged radio luminosity given as the abscissa (in Lu, where 1 Lu $\equiv 10^{15}$ erg s^{-1} Hz^{-1}). The dashed line is the cumulative distribution obtained for five of these binaries (excluding HR 5110) at 5 GHz by Owen and Gibson (1978).

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approximated the distribution of radio luminosities above the median luminosity (37 Lu) as a simple exponential function with an e-folding luminosity of 50 Lu. Therefore, exceedingly long times would seem to be required before an observer can expect to detect a radio superflare (>250 Lu). For example, 1.3 million years of observing is formally estimated as needed before a 1000-Lu flare will be detected from one of the five RS CVn binaries considered! However, even before the Algonquin survey it was clear that RT Lac was substantially over-luminous with respect to Owen and Gibson's luminosity function. Thus it is perhaps no great surprise that many radio superflares have subsequently been detected from these (and other) systems.

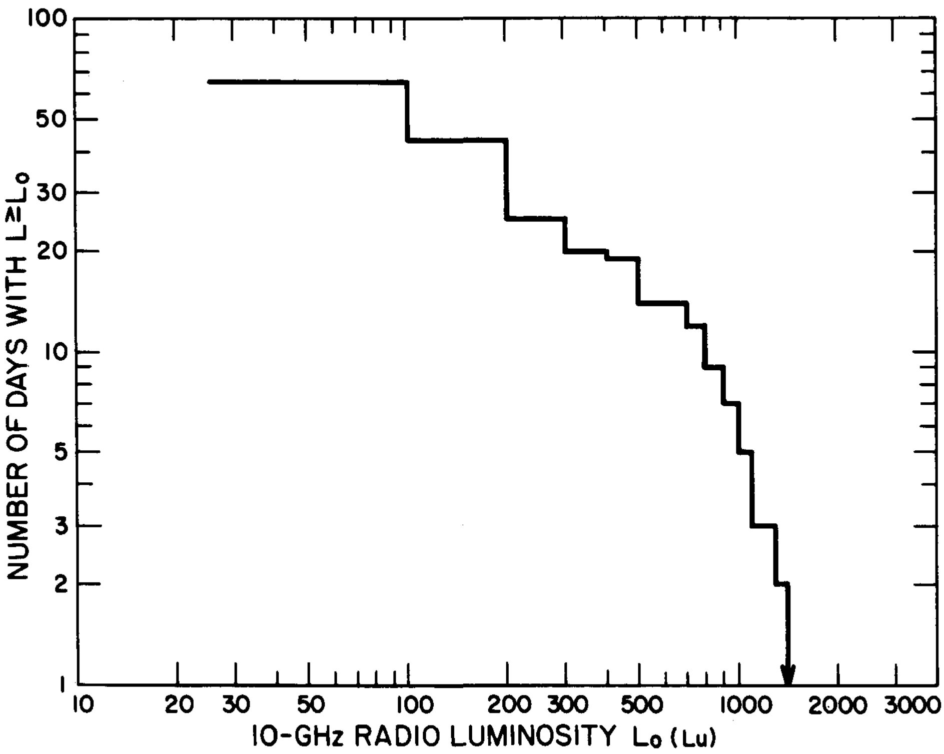

Figure 2. Cumulative integrated 10-GHz radio luminosity distribution of six RS CVn binaries (UX Ari, HR 1099, HR 5110, AR Lac, SZ Psc, and II Peg). The ordinate is the number of independent days that the daily-averaged radio luminosity equaled or exceeded the value given as the abscissa (in Lu, where 1 Lu ≡ 10^{15} erg s^{-1} Hz^{-1}). The arrow indicates that no (daily) events exceeding 1400 Lu have been recorded.

Figure 1 shows the cumulative differential radio luminosity distribution measured at λ3cm for the five binaries considered by Owen and Gibson plus HR 5110 which is a similar system. Daily averages were used to make the data more directly comparable with the earlier work. A conscious attempt was made to eliminate carefully measurements performed because earlier observations had shown certain stars to be flaring. As an example, in the case of HR 1099 the period 1978 Feb.-March is represented by only two data, corresponding to when this star would normally have been surveyed. It is obvious from the figure that the exponential distribution suggested by Owen and Gibson (1978) is inappropriate to describe the frequency of occurrence of major radio flares in RS CVn systems. Evidence is found for a cutoff in the absolute radio luminosity, at ≈ 2000 Lu. This is seen even more clearly in the cumulative integrated radio luminosity distribution, given in Figure 2, and in the peak radio luminosity results given in Table 1. The cutoff is probably due to the brightness-temperature limit imposed by the $\gamma \lesssim 10$ electrons themselves for radio sources of stellar dimensions (Feldman 1983). In plotting the radio luminosity distributions (Figs. 1 and 2) upper limits have been disregarded. These affect only the very low end (< 300 Lu) of our observed range of values and hence are insignificant to the basic conclusion that radio superflares are unexpectedly commonplace. A more complete version of these results will be published elsewhere (Feldman 1983).

Finally, the 1981 April outburst of HR 5110 is shown in Figure 3, as an example of a RS CVn radio superflare. A routine survey observation detected the binary in outburst at ≈ 240 mJy on 1981 April 4, and Mark III λ6cm VLBI observations were made on the two subsequent days (Feldman 1981). Unfortunately, much of the data was accidentally erased from our magnetic tapes before it could be processed, but some useful data survived for the April 6 observations. Preliminary reduction of these data (a one-baseline VLBI "snapshot") indicates that the fringe-visibility amplitude was approximately 0.5 with a fringe spacing of 3.7 milliarcsec. This implies that, during the later (plateau) portion of the outburst, half the radio flux was emitted from within a volume whose size scale was ≈ 3×10^{12} cm, or several times the binary star separation, with a brightness temperature $T_B > 3\times10^8$ K. This is in itself not surprising (cf. Feldman et al. (1978)). However, it also means that fully half the radio flux at 6cm was emitted over a size scale greater than this dimension. If we adopt the picture of interacting magnetic flux tubes in a binary system as proposed by Simon et al. (1980), the loops containing radiating MeV electrons would have to be disrupted on a very large scale indeed in the later stages of the flare. This is reminiscent of the behaviour of giant moving Type IV solar radio bursts, although the radio frequencies which are produced are, of course, quite different. IUE spectra taken coincident with the radio flaring (see Fig. 3) show evidence for hot gas with large line-of-sight motions, possibly indicating the infall of plasma onto one or both stars of the binary system (Linsky 1981). Similar behaviour was seen in the case of a superflare of UX Ari (Simon et al. 1980).

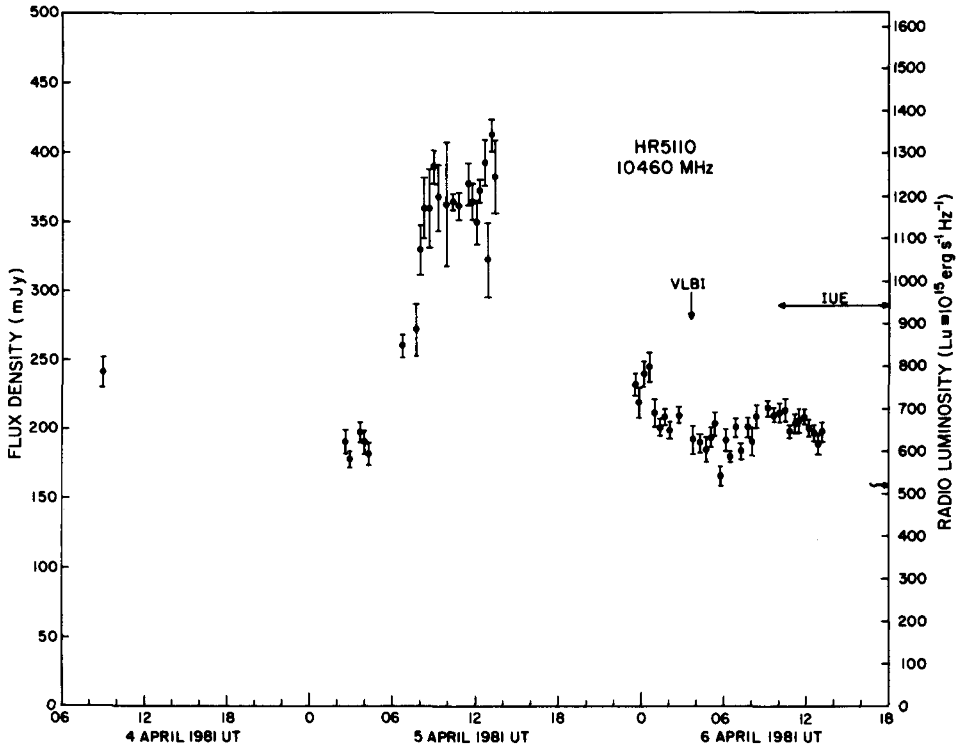

Figure 3. Radio "light curve" of HR 5110 during the 1981 April flare. The ordinates are the 10460-MHz flux density in mJy (1 mJy ≡ 10^{-26} erg s^{-1} Hz^{-1} cm^{-2}) and radio luminosity in Lu (1 Lu ≡ 10^{15} erg s^{-1} Hz^{-1}) measured at the Algonquin Radio Observatory as a function of UT. The vertical arrow indicates the time of the VLBI measurement; the horizontal straight arrows indicate the duration of the IUE observations. The wiggly arrow indicates the flux-density/radio-luminosity levels maintained for several days after 6 April.

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DISCUSSION

Kuijpers: Could you follow the time development of this flare with VLBI?

Feldman: The VLBI was unfortunately just a "snapshot" study. We had multiple baselines for only 15 minutes. However, verbal reports of unpublished work on such observations indicates that flares remain unresolved on an angular scale of 1 milli-arc sec in the early phases of the flare but may be partially resolved in the later phases. People all think of moving Type IV bursts in this context. I would anticipate that progress in this field will begin to show expansions during these events.

Venugopal: What is the lowest frequency at which the RS CVn stars have so far been detected?

Feldman: Dave Gibson would probably know this better than I would. However as far as I know the answer is about 21 cm. Would you like to comment, Dr. Gibson?

Gibson: Yes, 21 cm seems to be the longest wavelength at which RS CVn flares have been detected so far. I would like to add a comment in defence of your jabs at us that we must have made a mistake in our figures because we have observed a 1500 Luminosity units (Lu's) flare on RT Lac. That would bring us right to the top of your distributions (Figs. 1,2).

Feldman: But you did not include RT Lac in the figure which I referenced.

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Gibson: No, I may not have done but it should have been there. So we would not have concluded the same thing either.

Catalano: Have you any idea of the size of the coronal region in the BY Dra or short period RS CVn binaries?

Feldman: Not me because BY Dra binaries have not been observed in the radio to my knowledge.

Catalano: As I showed this morning there are differences in that one sees optical flares in BY Dra and short-period binaries but not in long-period ones. So are the radio flares you observe related to the magnetosphere outside the system or at least that which envelopes the entire system? Or could they arise from the photosphere in a way different from what is observed in the short-period systems or flare stars?