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DETECTION OF A SUB-MILLIARCSECOND RADIO COMPONENT IN THE RS CVn SYSTEM HR 1099

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ABSTRACT

The RS CVn system HR 1099 was observed with a five station VLBI array at a frequency of 8.4 GHz during a strong radio outburst of approximately 400 mJy. The data are consistent with a circular Gaussian source of 0.8 ± 0.12 milli-arcsec (FWHM), corresponding to a linear size of $4 \pm 0.6 \times 10^{11}$ cm. This is comparable to the distance between the surfaces of the two stars, or to 75% of the diameter of the chromospherically active K star. Extrapolation of published photometric data shows that the starspot formation of HR 1099 was facing toward us at the times of observations. The high equivalent brightness temperature, approximately 10^{10} K, is consistent with gyrosynchrotron emission from a power-law energy distribution of electrons in a magnetic field of strength $B \sim 30$ gauss.

Subject headings: interferometry — radio sources: variable — stars: binaries — stars: chromospheres — stars: radio radiation

I. INTRODUCTION

Variable radio emission at centimeter wavelengths has been discovered in 21 RS CVn binary stellar systems (Hall 1976; Wendker 1982). The radio emission of RS CVn systems is highly time variable and often circularly polarized. Observed flux densities range from 1 mJy to 1 Jy, although a typical outburst is below 100 mJy. The most commonly discussed emission mechanism is gyrosynchrotron radiation from mildly relativistic electrons (Owens, Jones, and Gibson 1976; Spangler 1977), although some short-duration, highly circularly polarized events of the type reported by Brown and Crane (1978) may be the result of a coherent process, such as an electron-cyclotron maser (Melrose and Dulk 1982).

In an effort to measure the source size of the radio emission region, we are conducting a series of multistation, high-sensitivity VLBI observations at various centimeter wavelengths on the most active RS CVn systems. Our first successful VLBI observations were of HR 5110 at 8.4 GHz with an angular resolution of 5 milli-arcsec (Lestrade *et al.* 1984) and of UX Arietis and HR 1099 at 1.65 GHz with an angular resolution of 11 milli-arcsec (Mutel *et al.* 1984).

In this *Letter* we report on observations of the system HR 1099 during an intense radio outburst using a five telescope continental VLB array.

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II. OBSERVATIONS AND DATA ANALYSIS

The observations were conducted on 1983 March 20 at 8.4 GHz using five radio telescopes: Deep Space Station 14 (DSS 14, 64 m, Goldstone, California); Deep Space Station 13 (DSS 13, 26 m, Goldstone, California); Owens Valley Radio Observatory (OVRO, 40 m, California); G. R. Agassiz Radio Observatory (GRAS, 26 m, Texas); Westford (WESTF, 18 m, Massachusetts). All five telescopes utilized maser frequency standards and received right circular polarization. The recorded frequency band was 56 MHz wide, from 8.389 to 8.445 GHz. The data were recorded using Mark III VLBI systems and were correlated at Haystack Observatory using the NASA-NSF Mark III VLBI processor (Rogers *et al.* 1983).

The observing schedule was a sequence of "snapshots" on 14 radio stars (mainly RS CVn systems). We detected HR 5110, σ CrB, II Peg, Algol, LSI 61°303, UX Arietis, and HR 1099 on the two shortest and most sensitive baselines (Goldstone 64 m/26 m, Goldstone 64 m/Owens Valley). Algol was also detected on the Goldstone 64 m/G. R. Agassiz R. O. baseline. The strong radio outburst of the RS CVn system HR 1099 was detected on all baselines, and it is this event we report here.

The observations consisted of three scans of 11 minutes on HR 1099 followed by 2 minutes on the calibrator source CTA 26. The fringe spacings of the array ranged from 2 milli-arcsec on the Goldstone-Westford baseline to 360 milli-arcsec for the short baseline (20 km) within the Goldstone complex. This short baseline provided a correlated flux density which was assumed to be identical to the total flux density.

Calibration of the cross-correlation amplitudes to obtain correlated flux density was done by applying the measured system temperatures and aperture efficiencies in the standard manner (Cohen 1975). Baseline aperture efficiencies were derived for each baseline from VLBI observations and quasi-simultaneous total flux density measurements, made with the 64 m radio telescope at Goldstone, of the compact sources 0016+731 and 0235+162, which were assumed completely unresolved (Pearson and Readhead 1984; Jones, Davis, and Unwin 1984).

III. RESULTS

At times of our VLBI observations, the total flux density of HR 1099 was very high, reaching a peak value of 404 mJy. We have searched for evidence of total flux density variation on a time scale of a few minutes by analyzing the correlated flux density in 1 minute intervals, but no variation similar to the observations of Brown and Crane (1978) was found.

The correlated flux densities versus baseline length are plotted for all three scans in Figure 1. They show clear resolution of the source on the longest baselines. We have separately fitted the data from each scan to single Gaussian brightness distributions and find angular sizes between $\theta_s = 0.67 \pm 0.11$ and $\theta_s = 0.84 \pm 0.09$ milli-arcsec, corresponding to linear sizes of 3.5 and 4.4×10^{11} cm, at a known distance of 35 pc. Table 1 summarizes the angular and linear sizes for each scan, along with the total flux measurements and derived brightness temperatures. Note that the apparent source size has decreased between 20 : 30 and 23 : 55 UT, accompanied by a 25% total flux decrease. It is unlikely that this corresponds to a physical decrease in the size of the emission region which, on physical grounds, is more likely to expand as the outburst evolves. Rather, the decrease may be understood by optical depth effects in an expanding core-halo brightness distribution, as discussed below. As a consistency check on our results, we have inspected the closure amplitudes which are independent of calibration and must deviate from unity for partially resolved sources. The closure amplitudes calculated between the three Californian stations and the Texas station yield unity, while closure amplitudes, including instead the station at Westford in the eastern US, typically yield 0.7 ± 0.15.

The closure phases for HR 1099 on the long baseline triangles significantly depart from zero (e.g., $33° \pm 8°$ on WESTF-GRAS-OVRO triangle). Zero closure phase on all the baselines would be expected if the source brightness distribution were a single elliptical Gaussian. The departure from zero on long baselines indicates an asymmetry in the brightness distribution on a scale of 1 milli-arcsec, such as would be obtained from two (or more) distinct "components." Of course, the lack of (u-v) plane coverage does not allow us to use the

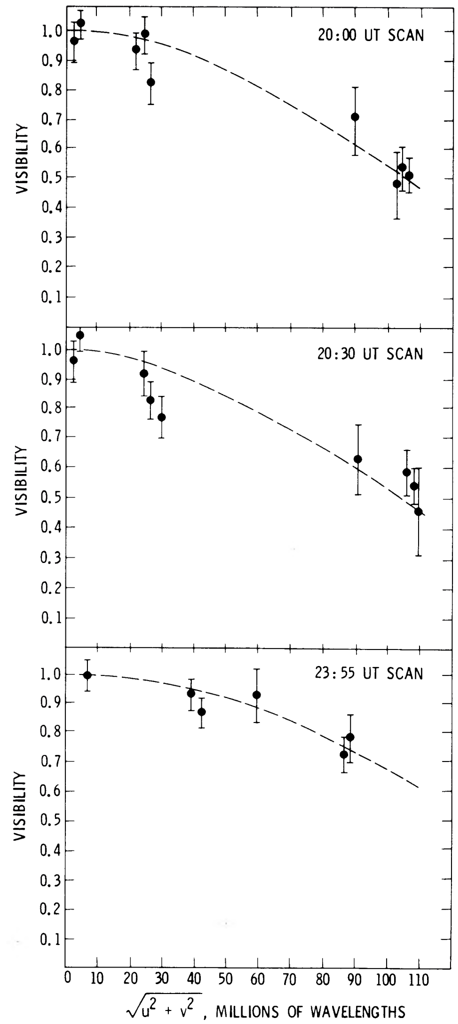

FIG. 1.—Correlated flux densities of the RS CVn system HR 1099 plotted vs. baseline lengths. Three observations were conducted at 20 : 00 UT, 20 : 30 UT, and 23 : 55 UT on 1983 March 20 at 8.4 GHz with a five station VLBI array. The dashed lines show the visibility functions of circular Gaussian sources with FWHM of 0.84, 0.82, and 0.67 milli-arcsec respectively.

TABLE 1

SIZES AND BRIGHTNESS TEMPERATURES OF THE RS CVn SYSTEM HR 1099[a]

Mean Times (UT)	Total Flux Densities (mJy)	Visibilities	Baseline Lengths ($10^6 \lambda$)	Angular Sizes (FWHM) (milli-arcsec)	Linear Sizes (cm)	Brightness Temperatures (K)
20 : 00	393 ± 30	0.53 ± 0.08	104	0.84 ± 0.09	$4.4 \pm 0.4 \times 10^{11}$	$9 \pm 3 \times 10^9$
20 : 30	404 ± 30	0.53 ± 0.10	106	0.82 ± 0.12	$4.3 \pm 0.6 \times 10^{11}$	$9 \pm 3 \times 10^9$
23 : 55	312 ± 15	0.75 ± 0.07	87	0.67 ± 0.11	$3.5 \pm 0.6 \times 10^{11}$	$12 \pm 5 \times 10^9$

[a] Derived by fitting a circular Gaussian brightness distribution to the observed visibilities.

closure phase measurements in any quantitative analysis of the source brightness distribution.

IV. DISCUSSION

In previous VLBI observations of radio emission from RS CVn systems (Lestrade *et al.* 1984; Mutel *et al.* 1984), the sources were unresolved. This allowed us to place limits only on the angular sizes and brightness temperatures. The observations presented here are the first multistation VLBI measurements of source size for an RS CVn system. The measured angular size of roughly 0.8 milli-arcsec corresponds to a linear size of approximately 4×10^{11} cm, which is comparable to 75% of the diameter of the chromospherically active subgiant K star of 5.5×10^{11} cm, or about equal to the distance between the surfaces of the two stars according to the elements given by Fekel (1983).

The observed brightness temperature, approximately 10^{10} K, is too high for a thermal mechanism, and synchrotron radiation from ultrarelativistic electrons is generally ruled out because of circular polarization often reported for the radio emission of RS CVn systems. As was discussed for previous VLBI observations of these systems, we assume as a working hypothesis gyrosynchrotron radiation from mildly relativistic electrons (Ramaty 1969) of $E \gtrsim 1$ MeV ($T_{\rm eff} \gtrsim 10^{10}$ K) and use the numerical results of Dulk and Marsh (1982). We first note that the effective source temperature ($T_{\rm eff}$) of their paper is always greater than or comparable to the measured brightness temperature, i.e., $T_{\rm eff} \gtrsim 10^{10}$ K where the equality is obtained when the source is optically thick. Inspection of Figure 3*c* from their paper shows immediately that the only conditions for which an effective temperature of $\gtrsim 10^{10}$ K is allowed are for $f \gtrsim 100\, f_B$ (where f is the observing frequency and f_B is the electron gyrofrequency) and for the power-law spectral index $\delta \lesssim 3$ of the electron energy distribution $[N(E) \propto E^{-\delta}]$. The relation $f > 100\, f_B$ implies a magnetic field strength $B \leq 30$ gauss. Since the peak of the spectrum is at an optical depth of $\tau \approx 1$, it is probable that the emission we detect arises mainly from the $\tau = 1$ surface, so long as the overall optical depth exceeds unity. In this case, the estimate of $B \sim 30$ gauss is a measure of the field strength in the region of $\tau \approx 1$.

This value is significantly higher than the previous upper limit of $B < 6$ gauss obtained in the same manner for HR 1099 at 1.65 GHz during 1983 February (Mutel *et al.* 1984). The difference may be due to intrinsic variations in the magnetic field strengths for individual outbursts, or may be a result of emission at different frequencies arising from regions of different magnetic fields. For example, for gyrosynch otron emission, the peak emission frequency scales as roughly $B^{0.77}$ (for an energy spectral index $\delta = 3$) (Dulk and Marsh 1982), so that for equal electron column densities, observations at two given frequencies will produce flux maxima in regions whose magnetic fields differ by the ratio $B_1/B_2 = (f_1/f_2)^{1.30}$. Using $B_1 = 30$ gauss at $f_1 = 8.4$ GHz, we expect $B_2 \sim 3.5$ gauss at $f_2 = 1.65$ GHz, consistent with our previous upper limit of $B_2 < 6$ gauss. This rough estimate assumes that the observed emission at a given frequency is dominated by regions which have peak frequency (as determined by the local magnetic field) close to the observing frequency, and we have neglected variations in column density and electron energies. Future VLBI observations at two or more frequencies, particularly during a single outburst, will be necessary to distinguish between these two possibilities.

The apparent decrease in source size, from $\theta_s \sim 0.84 \pm 0.1$ milli-arcsec during the first two scans, to $\theta_s \sim 0.67 \pm 0.1$ about 3.5 hours later, is perhaps surprising at first, since expansion of the emission region would be expected during the evolution of an energetic outburst. In fact, in Algol, possible expansion of the source on a few hours scale has been observed by Clark, Kellermann, and Shaffer (1975). This decrease may be understood by expansion of an optically thin component. Since the correlated flux densities on the longer baselines were fairly constant on all three scans, this may be evidence of a core-halo structure, with a constant core of approximately 200 mJy flux and an optically thin expanding halo. For the simple case of an optically thin, adiabatically expanding source, the flux will vary as t^{-2}, where t is the expansion time. The characteristic expansion time is given by $\tau \sim L/V$, where $L \sim 4 \times 10^{11}$ cm is the source dimension and V is the expansion velocity. Since the "halo" component flux density decreased substantially over approximately 3.5 hours, the characteristic expansion velocity must be $V \sim 300$ km s^{-1}.

Finally, we note that the large outburst reported here may have been related to the orientation of the active starspot region of the K star at the time of our observations. The orbital phase of HR 1099 was 0.226 ± 0.003 at 20:00 UT and 0.286 ± 0.003 at 23:55 UT from the ephemeris of Fekel (1983), where zero-phase is defined as conjunction of the two stars with the K star nearer the observer. The quasi-sinusoidal modulation of the minimum light of RS CVn systems is currently interpreted as caused by large starspots darkening the hemisphere of the K star facing toward us, once every revolution. At the date of our observations, this minimum is found to occur at the orbital phase 0.37 ± 0.06 when extrapolated from the photometric data of HR 1099 taken between 1976 and 1980 and presented by Dorren and Guinan (1982). HR 1099 was then observed close to its position of minimum light indicating that the starspot formation was facing toward us at the time of the detection of the strong radio outburst. Thus the source might have originated from an active chromospheric zone above the starspots. This correlation has been found between seven optical flares and orbital phases of minimum light in the related RS CVn binary V 471 Tau by Young *et al.* (1983).

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