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RADIO OBSERVATIONS OF THE 1985 OUTBURST OF RS OPHIUCHI

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ABSTRACT

We report observations of the first radio source observed in association with a recurrent nova event, the 1985 January 26 outburst of RS Ophiuchi. Measurements at some or all of four VLA frequencies were made at 32 epochs from 1985 February 24 to 1986 January 31, indicating a rapidly evolving spectrum with at least two components. After peaking in flux in early March, the radio source exhibited complex decay at all four frequencies. The radio source was resolved in the early 15 GHz observations, indicating an angular extent expanding at a rate of $0''.0015$ (or $0''.003$) per day, corresponding to a velocity of 2100 (or 4200) km s^{-1} if the expansion is symmetric (or asymmetric). H I absorption measurements found $(2.4 \pm 0.6) \times 10^{21}$ hydrogen atoms per cm^2 for the line of sight to RS Oph, implying a distance of 1.6 kpc. The rapidly expanding radio source is probably synchrotron emission, and the remnant radio source, dominating during the apparently optically thin decay, may be gyrosynchrotron emission of 300–500 keV electrons radiating in a magnetosphere in the RS Oph binary system.

Subject headings: stars: individual — stars: novae — stars: radio radiation

I. INTRODUCTION

The first detection of radio emission from a recurrent nova after an outburst was made by Padin, Davis, and Bode (1985*a*) 18 days after the 1985 outburst of RS Ophiuchi. Padin, Davis, and Bode, (1985*b*) observed ~ 20 days of the rise of the radio source, noted that these data indicated high brightness temperatures, and suggested a nonthermal origin analogous to Type II supernovae (Chevalier 1982).

We report VLA measurements of the rise, peak, and decay of a two-component, four-frequency radio spectrum; a resolved radio source indicating both angular size and rate of expansion; and 21 cm hydrogen absorption.

II. CONTINUUM OBSERVATIONS OF THE RS OPHIUCHI OUTBURST

VLA observations of the RS Oph radio source from 1985 February 24 through 1986 January 31 at frequencies of 1.49, 4.85, 4.885, 14.94, and 22.46 GHz, made with 24–27 antennas operating with 50 MHz bandwidth and average system temperatures of 60, 60, 100, and 500 K, respectively, are listed in Table 1.

In Figure 1 we plot the radio light curves of RS Oph using the data in Table 1 and 5 GHz data from Padin, Davis, and Bode (1985*b*). The radio source flux peaked on March 3 and March 8 at 5 and 1.49 GHz, respectively. The peak occurred on or before March 5 at 15 GHz, while the peak at 22 GHz may have occurred before March 5, or was a roughly constant maximum between March 5 and March 15. Also in Figure 1 are line segments corresponding to power laws, $(t - t_0)^\alpha$, with α's indicated near each solid line. At 1.49 GHz a power law with $\alpha = -1.68$ was in effect from 60 to 220 days after outburst, with a change to -1.02 at about 220 days. At 4.9 GHz a power law with $\alpha = -1.26$ began after about 80 days and continued through 340 days. At 15 GHz a power law decay with $\alpha = -1.1$ started after about 60 days, but changed to a much steeper -2.09 at about 140 days.

We also plot the RS Oph radio spectra in Figure 2 where the earliest spectrum is in the upper right and spectra for different dates are displaced downward and to the left to indicate the time sequence. Figure 2 indicates at least two radio components existed from roughly March through July: one with a negative spectral index between 1.4 and 5 GHz; and another with a positive spectral index above 5 GHz. In

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TABLE 1

VLA FLUX DENSITIES FOR THE RS OPHIUCHI RADIO SOURCE

	FLUX DENSITY (mJy)			
JD − 2,446,000	1.49 MHz	4.85 MHz	14.94 MHz	22.46 MHz
120.59	38 ± 2	50 ± 2	61 ± 2	65 ± 3
129.70	61 ± 2	58 ± 3	68 ± 3	75 ± 3
132.49	63 ± 2	61 ± 2	65 ± 3	...
137.52	62 ± 2	56 ± 2	61 ± 2	71 ± 3
139.49	59 ± 2	51 ± 2	58 ± 2	72 ± 3
144.46	54 ± 2	47 ± 2	56 ± 3	66 ± 3
151.52	44 ± 2	41 ± 2	52 ± 4	60 ± 3
156.39	41 ± 2	37 ± 2	45 ± 2	56 ± 3
159.36	38 ± 2	...	...	...
161.35	36 ± 2	34 ± 2	43 ± 2	51 ± 3
165.52	...	...	43 ± 3	...
168.35	33 ± 2	30 ± 2	42 ± 2	47 ± 3
174.29	26 ± 2	23 ± 2	37 ± 2	...
178.48	...	...	36 ± 2	43 ± 3
189.31	20 ± 2	18 ± 2	31 ± 2	...
194.33	20 ± 2	17 ± 2	29 ± 2	39 ± 3
208.40	15 ± 2	15 ± 2	25 ± 2	34 ± 3
222.38	13 ± 1	13 ± 1	22 ± 2	30 ± 3
224.42	12 ± 2	...	...	...
239.23	10 ± 1	11 ± 1	19 ± 2	25 ± 3
248.21	9 ± 1	10 ± 1	17 ± 2	22 ± 2
265.17	8 ± 1	8.8 ± 0.5	14 ± 2	18 ± 2
278.14	7 ± 0.5	8.1 ± 0.5	12 ± 1	14 ± 2
287.21	6.2 ± 0.5	7.8 ± 0.5	11 ± 1	13 ± 2
303.25	5.5 ± 0.5	6.9 ± 0.5	10 ± 1	11 ± 2
320.17	5.3 ± 0.5	6.5 ± 0.5	7.9 ± 0.5	...
336.04	4.8 ± 0.5	5.8 ± 0.4	6.5 ± 0.5	...
358.04	4.4 ± 0.5	5.3 ± 0.4	5.5 ± 0.4	...
384.99	4.0 ± 0.5	4.5 ± 0.4	4.6 ± 0.4	...
417.72	3.7 ± 0.5	3.9 ± 0.4	3.8 ± 0.4	...
451.65	2.1 ± 0.5	3.1 ± 0.4	3.0 ± 0.4	...
461.64	2.3 ± 0.5	...	...	...

August the component with a positive spectral index became completely dominant in the decaying spectrum. The spectral index between 4.9 and 15 GHz rose linearly from ~ 0.1 at the 1985 March 5 peak to ~ 0.5 about 60 days after outburst, then declined linearly until it was ~ 0 about 270 days after outburst. The spectral index between 1.49 and 4.9 GHz remained at about −0.08 from the peak on March 5 until 100 days, then rose roughly linearly in time, reaching 0 at about 130 days and 0.2 at about 200 days, after which it declined roughly linearly with time until it was ~ 0.1 at 330 days.

The RS Oph radio source position is $\alpha_{1950} = 17^h47^m31^s.530 \pm 0^s.01$, $\delta_{1950} = -6°41'39''.7 \pm 0''.2$; it was determined assuming that the calibrator 1741−038 has a position of $\alpha_{1950} = 17^h41^m20^s.619$, $\delta_{1950} = -3°48'48''.88$.

III. DIRECT MEASUREMENT OF CHANGING SIZE SCALE

The observations from 1985 February 24 through March 13 were made with the VLA in its largest (35 km) configuration. The data at 15 GHz showed that the radio source was both resolved and expanding at high velocity. Unfortunately, after that the VLA was moved to smaller configurations at an average rate slightly faster than the probable rate of expansion of the radio source. In Figure 3 we plot normalized visibility functions for 1985 February 24, March 13, and April 10 as a function of antenna separation (in units of wavelengths). The solid curves correspond to circular Gaussian models with half-power widths of 0''.042, 0''.059, and 0''.11. The plotted data are a subset of the extensive observations listed in Table 1 which indicate a rate of (symmetric) expansion of 0''.0015 per day, which corresponds to a velocity of 2100 km s^{-1} if the distance is taken to be 1.7 kpc (Payne-

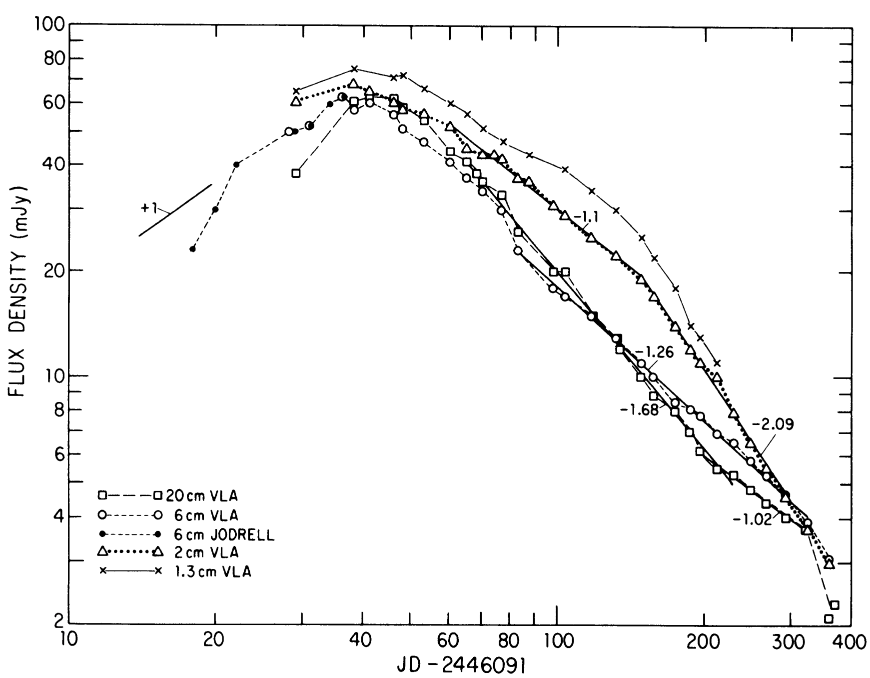

FIG. 1.—Radio flux densities of RS Ophiuchi are plotted as a function of time since outburst (on 1985 January 26, JD 2,446,091) for the period between 1985 February 24 and 1986 January 31, for frequencies of 1.49 GHz (VLA, *open squares*), 4.9 GHz (VLA, *open circles*), 5 GHz (Jodrell data from Padin *et al.* 1985*b*, *filled circles*), 15 GHz (VLA, *triangles*), and 22 GHz (VLA, *crosses*). The data for each frequency are connected with dashed lines, and solid lines indicate power-law segments with nearby numbers corresponding to the power-law exponent.

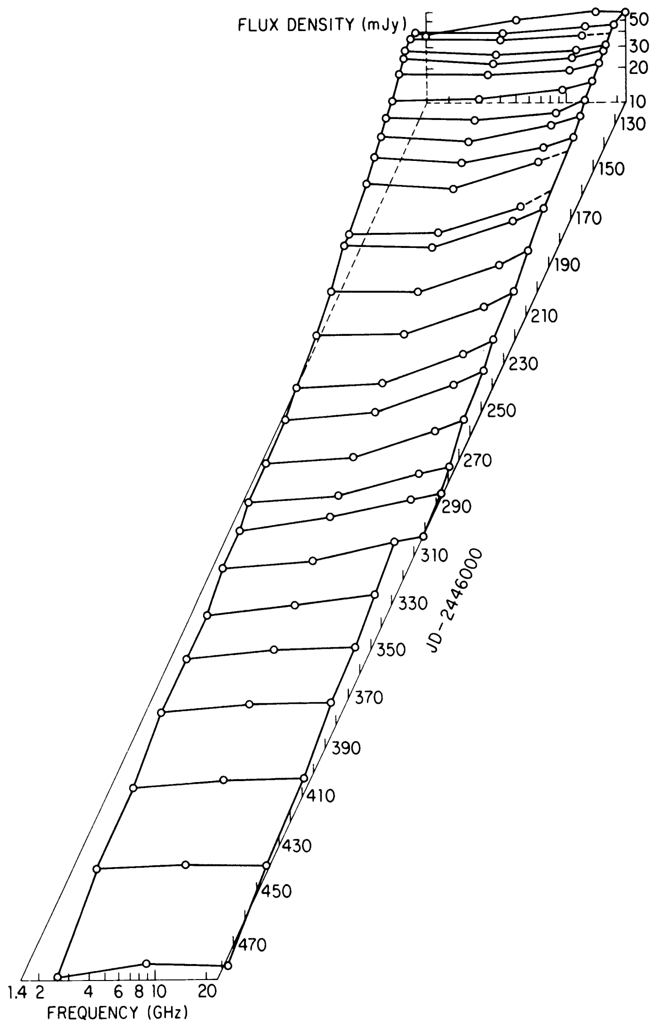

FIG. 2.—Radio spectra for the VLA frequencies of 1.49, 4.9, 15, and 22 GHz are shown with each spectrum connected by solid lines. The spectra for different days are displaced from upper right to lower left in a linear sequence in time.

Gaposchkin 1957). There are indications of asymmetry, with the source more resolved in the east-west direction, but the low degree of resolution allows no firm conclusions. However, either the radio emission was expanding symmetrically (in 1985 February–April) with respect to the center at 0″.0015 per day, or part(s) of the source were moving asymmetrically with respect to the rest at 0″.003 per day.

Using the inferred angular size scales and the observed flux densities, one obtains average 1.49 GHz, 4.9 GHz, and 15 GHz brightness temperatures of 1.2×10^5, 1.5×10^6, and 1.2×10^7 for 1985 February 24, and 1.2×10^7, 9.5×10^5, and 1.1×10^5 for March 13. Because radio sources can appear larger at lower frequencies, the definitive result is that of *measured* average brightness temperatures at 15 GHz of $\sim 10^5$ K, with inferred or probable values of 10^6–10^7 K if the radio source sizes are the same at all frequencies. Preliminary measurements from the European VLBI network indicate brightness temperatures of 10^6 to 10^7 K at 1.5 GHz.

In 1985 October an attempt was made to image RS Oph using a hybrid VLA with six antennas spanning 35 km, and the rest in a 3 km configuration. Most of the 15 GHz radio emission was in a source $< 0''.1$ in size, indicating that the central RS Oph radio source had expanded by less than 0″.0004 per day. Extended emission was marginally detected, but needs confirmation.

IV. H I ABSORPTION-LINE MEASUREMENTS AND THE DISTANCE TO RS OPHIUCHI

Figure 4 shows H I spectral line obervations made with the VLA on 1985 April 1 and 4, with Figure 4*a* showing the RS Oph absorption spectrum and Figure 4*b* showing the absorption spectrum for a neighboring source located 13′ away at $\alpha_{1950} = 17^h46^m39^s.04$, $\delta_{1950} = -6°41'46''$. The hydrogen column densities (N_H) to RS Oph and the neighboring source were $(2.4 \pm 0.6) \times 10^{21}$ cm^{-2} and $(3.1 \pm 0.8) \times 10^{21}$ cm^{-2}, respectively, assuming the spin temperature, T_s, is 100 K. Taking $N_H/T_s = 1.59 \times 10^{19}$ cm^{-2} K^{-1} kpc^{-1} (Dickey *et al.* 1983) this implies a distance of 1.6 kpc. Cassatalla *et al.* (1985) have summarized distance determinations for RS Oph, with different methods giving between 1.3 and 2.4 kpc and argued for the smaller values in this range because they failed to detect any ~ 20 km s^{-1} interstellar lines produced by the Carina arm at a distance of 1.5 to 2.3 kpc. Our H I absorption distance is close to the distance of 1.7 kpc given by Payne-Gaposchkin (1957), so we adopt it in this paper. The +15 km s^{-1} feature in the spectrum of the neighboring source, but not in RS Oph, is also seen in the absorption spectrum of 1730–130 (Dickey *et al.* 1983). The more distant ~ 15 km s^{-1} hydrogen beyond RS Oph has about the correct velocity (Cassatalla *et al.* 1985) to be due to the Carina arm.

V. CONCLUSIONS

The radio data for the 1985 outburst of RS Oph is not easily interpretable in terms of the free-free emission of normal nova shells, nor is it clearly like the self-absorbed synchrotron radio sources related to shocks as suggested by Padin, Davis, and Bode (1985*b*) and Bode and Kahn (1985).

The RS Oph radio source differs from those of classical novae (Hjellming *et al.* 1979) in four ways: the occurrence of brightness temperatures $\gg 10^4$ K; light curves with time scales of < 1 yr rather than several years or decades; decay power laws in the range -1 to -2 rather than -2.3 to -2.5; and spectral indices during the decay that are not the simple -0.1 of an optically thin free-free source. A difference between classical and recurrent novae is that recurrent nova explosions occur inside the wind of the red giant companion. This leads to the deceleration phenomena well known for RS Oph whereby the optically emitting shell starts out with velocities of the order of 4000 km s^{-1} but is decelerated by ram pressure effects to < 1000 km s^{-1} in ~ 25 days, and < 300 km s^{-1} after 100 days (Pottasch 1967).

Explosions in dense wind environments occur for some radio supernovae (Weiler *et al.* 1986), for which power-law decays ranging from -0.6 to -1.6 are found. However, in the case of radio supernovae, and for the shocked synchrotron emission model, one would expect the radio source to evolve to a single power-law decay with a clearly synchrotron source spectral index, whereas Figure 1 shows a complicated set of frequency-dependent decays.

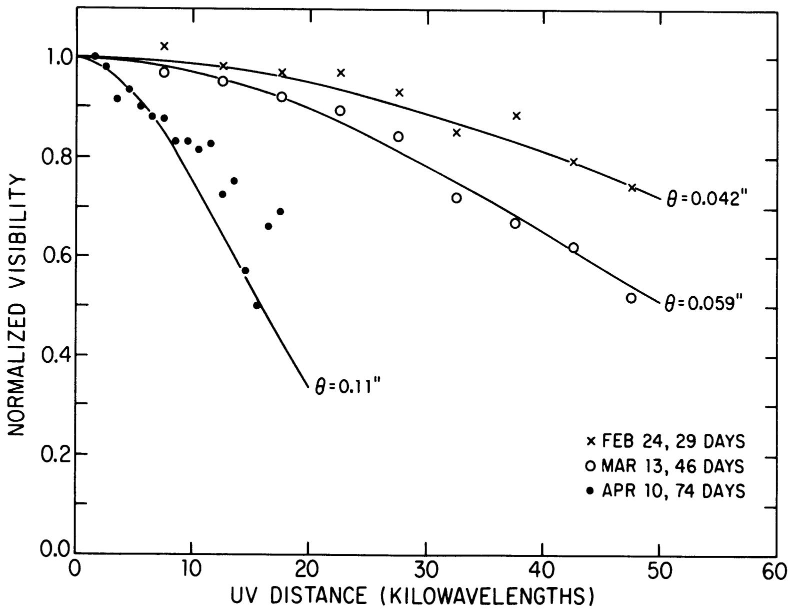

FIG. 3.—Visibility data from 1985 February 24, March 13, and April 10 VLA observations at 15 GHz are averaged in radial rings in the aperture plane, showing the radio source is both resolved and exhibiting either symmetric expansion at a rate of 0"0015 per day or asymmetric expansion at 0"003 per day. The solid curves correspond to Gaussian models with half-power widths (θ) of 0"042, 0"059, and 0"11 for the 3 days of plotted data.

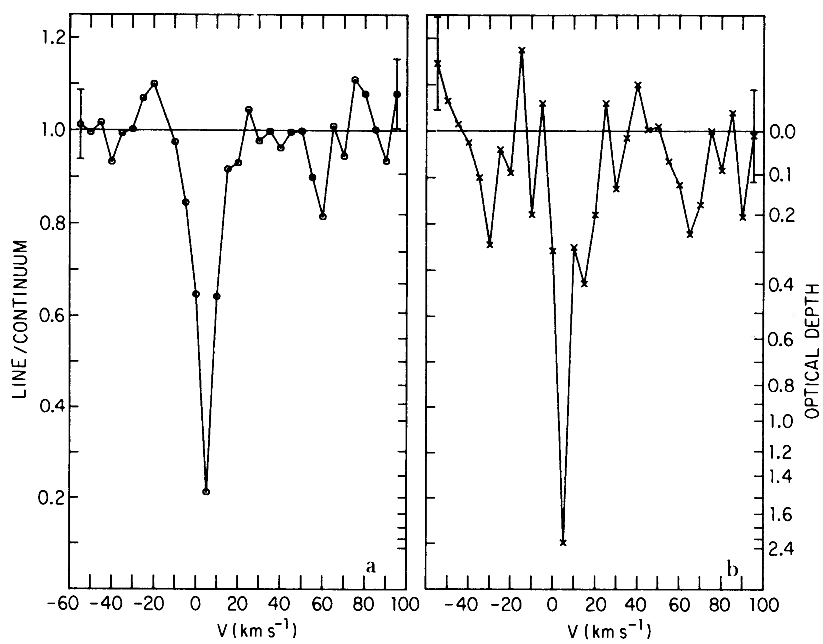

FIG. 4.—Neutral hydrogen absorption spectra obtained with the VLA on 1985 April 1 and 4 are shown for (*a*) the RS Oph radio source, when it was ~ 40 mJy at 1420 MHz; and (*b*) a neighboring radio source 13′ east of RS Oph. The line to continuum ratio (left ordinate), and line-of-sight optical depth (right ordinate) of each channel are plotted as a function of LSR velocity.

The two- (or more) component nature of the RS Oph radio source can explain some of the complexities. It is very likely that the material ejected with velocities ≥ 2000 km s^{-1}, which presumably occurred because of some combination of geometry, greater momentum, and less external ram pressure, is associated with a nonthermal component prominent in the radio spectra for about the first 150 days. The physics of this component is presumably similar to that of high-velocity, synchrotron-emitting material normally encountered in radio jet sources. However, the inverted spectrum component that decays by a factor of ~ 20 while its spectral index changes from to ~ 0.5 to ~ 0, may be a fortuitously self-absorbed synchrotron radio source, or, if the observed high-frequency component is optically thin as it appears to be, the emission mechanism may be gyrosynchrotron similar to that found in the magnetic cataclysmic variable AM Her (Chanmugam and Dulk 1982; Dulk, Bastian, and Chanmugam 1983). In the latter case there is a remnant of 300–500 keV electrons, with changing energy spectra in the range E^{-1} to $E^{-1.4}$, trapped in a magnetosphere in the binary system with fields up to 5000 G, with these electrons emitting gyrosynchrotron emission at harmonics $\sim$ 20–80 of the cyclotron frequency. While self-absorbed synchrotron models with complicated geometries can be made to have the observed spectrum characteristics, the RS Oph radio source has appeared to be in a state of complex, optically thin decay since it peaked 1985 March 5. For this reason a gyrosynchrotron emission model is an alternative for the remnant radio source. The complicated behavior of the RS Oph radio source indicates that complex models and extensive use of X-ray, infrared, and optical data will be essential in understanding this unique radio event.

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