VLA OBSERVATIONS OF STELLAR FLARES: A 3-HOUR FLARE OF THE RS CVN STAR λ ANDROMEDAE AND A 5-MINUTE FLARE OF THE BP STAR HR 5942

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ABSTRACT

We describe high-sensitivity VLA observations of rapidly varying radio emission ('flares') from two stars of very different types, one of which (λ And) is a Long-Period RS CVn system, and the other (HR 5942) is a magnetic Bp star. In both cases, however, the physical mechanism producing the radio emission is most likely to be gyrosynchrotron radiation from mildly relativistic, power-law electrons.

Introduction

The NRAO Very Large Array has such high sensitivity ($\sim 100\mu$Jy at 6 cm) and spatial resolution (0.″25 at 6 cm in A configuration) as to have detected radio emission from many types of stars. The standard time resolution of VLA observations is 30 seconds, but faster sampling rates are possible. We describe VLA observations of rapidly varying radio emission ('flares') from two stars of very different types, but for which the physical emission mechanism is believed to be the same, namely gyrosynchrotron radiation from mildly relativistic, power-law electrons.

The March 11th 1984 radio flare of λ Andromedae

λ Andromedae is an RS CVn binary system in which the primary star is a G8 III-IV star; the orbital period of the system is 20.5 days, while the G star's rotational period is 54 days. It was first detected as a 65 mJy 6-cm radio source by Bath and Wallerstein (1976). Subsequent observations show that its more typical radio flux is $\sim$ 1 mJy, and hence imply that the first detection was during a radio flare or outburst. On March 11th 1984 from 18:56 to 23:52 UT, we observed λ And at 2 and 6 cm, using the NRAO Very Large Array in B/C configuration operating in a split-array mode with 13 antennas at each wavelength. The time-averaged 2- and 6-cm fluxes for the entire 5-hour VLA observations were 47.6 and 23.7 mJy, respectively, indicating that the source was in an outburst phase during this time period. We have analyzed the fluxes as a function of time split into 20-minute intervals and we show the results in Figures 1 and 2.

The λ And radio source was clearly in an elevated state (compared to its 1 mJy quiescent level) even at the start of the observing run, with average 2 and 6 cm fluxes of 28 and 14 mJy, respectively. Commencing at about 20:30 UT, a major outburst commenced, and by 22:00-22:20 UT the 2 and 6 cm fluxes had reached (peak) values of 75 and 29 mJy respectively. By the end of the observing run the 2 cm flux had declined to 32 mJy, close to its pre-outburst level, and the 6 cm flux had decreased to a 22 mJy level still significantly above its initial level. The flux at both frequencies showed a small amount of right-hand circular polarization: the 2 cm polarization varied between 4 and 9 %, while the 6 cm polarization varied between 2 and 7%. The 2 to 6 cm spectral index α, where $S_\nu \propto \nu^\alpha$, increased during the flare to a maximum value of 0.85, compared to pre- and post-outburst minima of 0.25 to 0.35. We summarize the properties of this radio flare in Table 1.

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Table 1: Properties of the 1984 March 11 flare of λ And

Rise Time: ~ 1.5 hours (N.B. 2-cm emission seems to lead 6-cm emission)
Duration: ~ 3 hours
Circular Polarization: Yes, slightly (< 10%) Right-Hand
Spectral Index: +0.85 at peak (cf. quiescent value of 0.3)
Maximum 2 Cm Luminosity: 5.6×10^{16} erg/sec/Hz
Maximum 6 Cm Luminosity: 2.2×10^{16} erg/sec/Hz
Maximum 2 Cm Brightness Temperature: $9 \times 10^{7}(R_{source}/R_{*})^{-2}$ K
Maximum 6 Cm Brightness Temperature: $3 \times 10^{8}(R_{source}/R_{*})^{-2}$ K
Total Radio Energy in Flare: 2.5×10^{30} erg

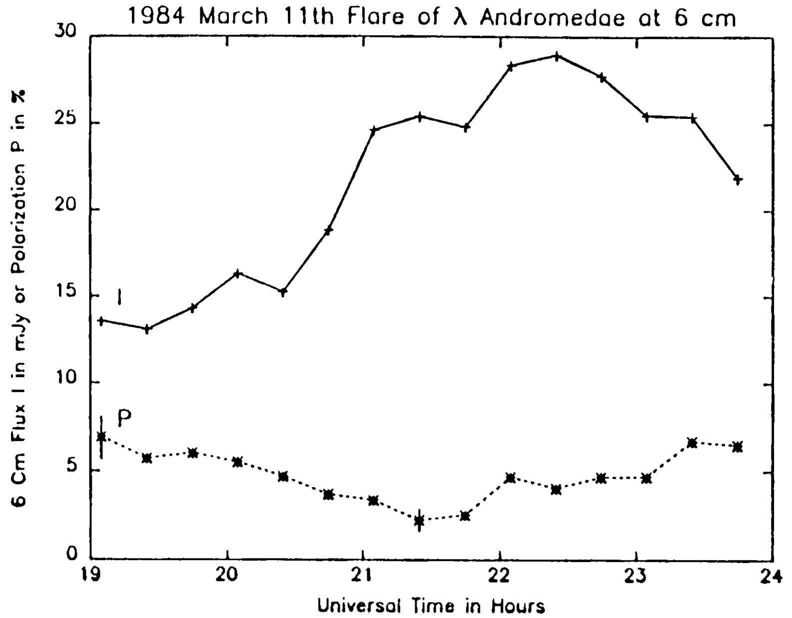

Fig. 1. The 6-cm light curve of λ And on 1984 March 11, showing the variation of total intensity I and circular polarization P as a function of time. Typical $\pm 1\sigma$ rms error bars are shown for the P values, while those for the I values are smaller than the size of the symbol used to plot them.

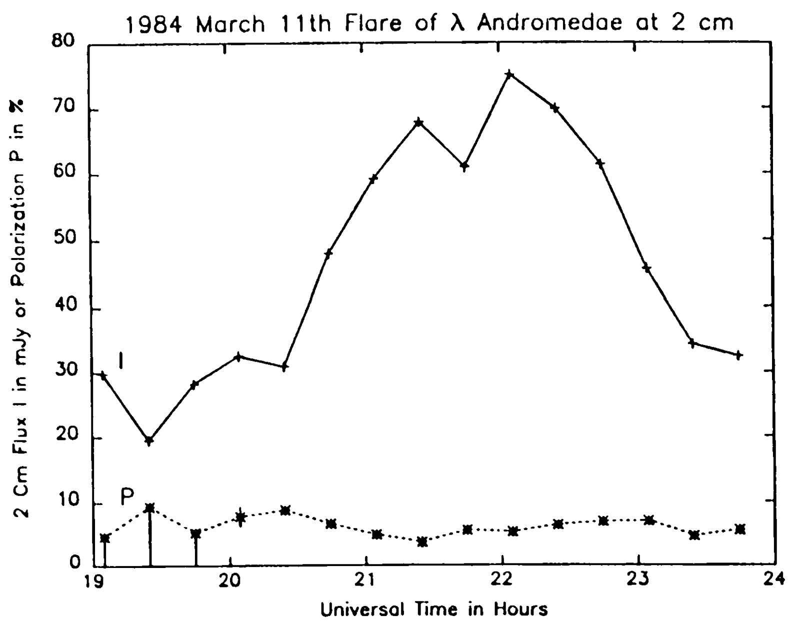

Fig. 2. The 2-cm light curve of λ And for the same time period as in Fig. 1. Note that the first three polarization points shown are 3σ upper limits.

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The generally accepted explanation for the radio emission from RS CVn systems is that it is produced by gyrosynchrotron radiation from mildly relativistic ($1 < \gamma < 10$) electrons spiralling in coronal magnetic fields $\sim$ 30 to 100 (cf. Spangler 1977; Borghi and Chiuderi-Drago 1985; Kuijpers and van der Hulst 1985; Mutel *et al.* 1985). The observed properties of the 1984 March 11th flare of λ And are completely compatible with the standard model: for example, Mutel *et al.* (1985) argue that, during 'active' phases ('flares'), RS CVn radio sources become optically thick due to synchrotron self-absorption and thence develop a positive spectral index and reduced circular polarization, as we observe for this particular flare. The observed rise time of the λ And flare of 1.5 hours is consistent with the synchrotron radiative loss lifetime of 1 to 5 MeV electrons in a magnetic field of 100 Gauss.

If λ And is similar to other RS CVn systems that have been resolved by VLBI observations, the brightness temperature of this flare is probably $\geq 10^{10}$ K, implying a source radius $\sim 20\% R_*$ and it originates from the 'core' component of the Mutel *et al.* core-halo model. The fluxes at 2 and 6 centimeters before and after the observed 'flare' were already enhanced by an order of magnitude compared to their quiescent values. It is probable that the 3-hour flare that we observed was superimposed on a much longer-period (days to weeks) of enhanced activity, probably associated with the 'halo' component described in Mutel *et al.* (1985), which should have a synchrotron radiative lifetime $\sim 10^6$ seconds.

Radio Observations of Magnetic Bp Stars

Surface magnetic fields of kiloGauss strength have been known to exist in the class of Ap and Bp stars for 40 years. Borra *et al.* (1982) conclude, in a recent review, that longitudinal magnetic fields of more than 0.2 kG are common in Ap stars of the Si and SiCrEu peculiarity classes, the Helium-Weak (He-W) stars, and the Helium-Strong (He-S) stars, with the latter class having much stronger fields than the other classes. The geometries of the magnetic fields in these stars have been generally regarded as fundamentally dipolar, with the magnetic axes inclined with respect to the rotation axes. The probability that, because of these strong magnetic fields, the Bp and Ap stars should be detectable non-thermal radio continuum sources *if* they had some reservoir of charged particles to be accelerated, has been recognized for at least 20 years. Pre-VLA radio surveys had rather high detection thresholds at centimetre wavelengths of 5 to 50 mJy, and of the $\sim$ 30 stars observed, there were no definite detections, and only 2 possible ($2-3\sigma$) detections: Babcock's Star ($\equiv$ HD 215441; Kodaira and Fomalont 1970), which has the strongest known magnetic field (a 34 kG mean surface field) that has ever been observed in a non-degenerate star, and was a possible 50 mJy source at 6 cm; and κ Dra (Trasco *et al.* 1970) , which was a possible 20 mJy radio source at 6 cm.

We have been conducting VLA studies of Bp and Ap stars over the last 4 years (Drake *et al.* 1985, 1987, 1988); because of the VLA's high spatial resolution and sensitivity, we have been able to improve significantly on previous radio studies. Our results to date are as follows:

(i) We have detected 3 (out of 9 observed) *bona fide* He-S stars as radio sources with radio luminosities $L_\nu \sim 10^{17.4} - 10^{17.9}$ erg/s/Hz. We present detailed models for the radio emission from these stars in Drake *et al.* (1987), where we argue that the emission is produced by gyrosynchrotron emission from electrons with a power-law distribution of energies. Thermal emission processes can be ruled out since the emission has a flat or negative spectral index and is seen to vary on a timescale of several hours.

(ii) We have detected *no* (out of 13 observed) classical Ap stars as radio sources, with upper limits to L_ν as low as $10^{14.5-15.0}$ erg/s/Hz. (Drake *et al.* 1987). Lang (1986) has similarly detected *no* radio sources among 11 classical Ap stars that he observed with the VLA at 6 cm.

(iii) We have detected 8 (out of 20 observed) He-W/Si stars as radio sources. (Drake *et al.* 1987, 1988). This class of magnetic star is rather heterogeneous, and blends into the related 'classical' Ap stars with no well-defined boundary. It is not surprising then that the radio sources found among this class of star are also rather varied in their properties: for example, Babcock's Star has an inferred L_ν of $10^{17.9}$ erg/s/Hz, making it as radio-luminous as the He-S radio sources (but still 50 times weaker than its previous possible detection by Kodaira and Fomalont, implying that the initial detection may have been a radio flare).

Four of the other detected He-W/Si radio sources are in the nearby ($D \sim 160$ pc) Sco-Cen Association, and have $L_\nu \sim 10^{16} - 10^{17}$ erg/s/Hz. Variability on a timescale of minutes has been discovered in the 6 cm emission of HR 5942 (see Fig. 3), and (possibly) 3 Sco. [The radio emission of 3 Sco may also be slightly circularly polarized ($\sim 6\%$ level), but this needs to be confirmed.] Such fast variability suggests that HR 5942 may have been flaring, although there is no evidence for any impulsive-rise component in our 25-minute observation of this star. The fastest systematic variation of the radio flux occured between 0.1236 and 0.1238 days (a period of 3 minutes), when the 6-cm flux of this star decreased by a factor of two. If this variability is attributable to synchrotron losses, then we can use equation (16) of Drake *et al.* (1987) to infer a source size of $1.6R_*$, assuming that the same radiation belt model is valid for HR 5942 as for the He-S stars. Thus, we would predict that VLBI observations of the HR 5942 radio source will find it to be compact (angular size $< 0.''0005$). We plan to make further VLA observations of this star in October 1988 and therefore defer any detailed modelling of this radio source until after these multi-frequency radio data are analyzed.

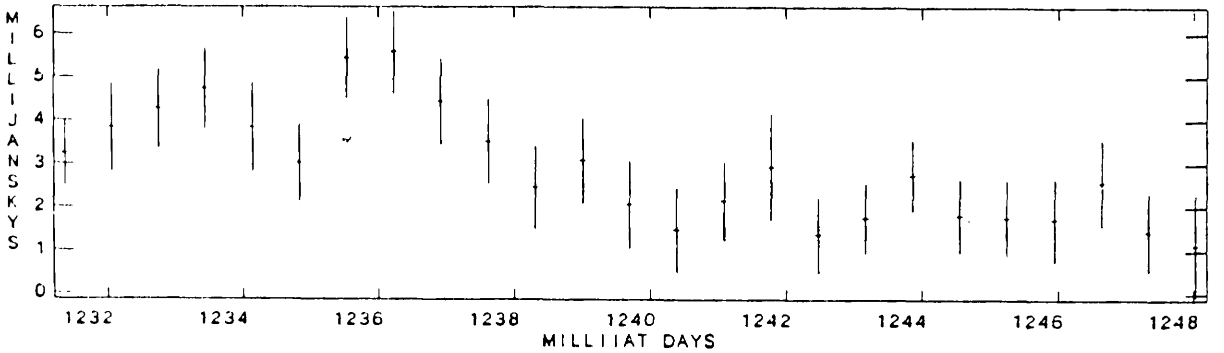

Fig. 3. 6-cm observations of the Bp star HR 5942 covering a 25-minute period, with the data binned in 1-minute averages. The radio flux is $\sim 3 - 6$ mJy for the first 10 minutes of the scan, but has decreased to a level of $\sim 1 - 2.5$ mJy by the final 10 minutes.

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