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AN EXTREMELY VARIABLE RADIO STAR IN THE RHO OPHIUCHI CLOUD

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ABSTRACT

During a multi-epoch radio continuum survey of the ρ Ophiuchi star formation cloud performed with the Very Large Array, rapid radio variability was seen in the young star DoAr 21. Typically present at levels of 2–5 mJy, it rose up to 48 mJy at 5 GHz on time scales of hours on 1983 February 18, during which the spectrum was steeply inverted. Interpretation in terms of mass loss, which is usually invoked to explain T Tauri star radio emission, encounters difficulties. (Gyro)synchrotron radiation from energetic electrons in a magnetic loop several times larger than the star provides a better model. The event is very similar to the largest radio flares seen on RS CVn stars. This is the first report of such a microwave flare on a pre–main-sequence star and adds to the growing body of evidence that young stars exhibit very high levels of magnetically induced surface activity.

Subject headings: stars: flare — stars: pre–main-sequence — stars: radio radiation — stars: variables

I. INTRODUCTION

Radio continuum surveys of low-mass pre–main-sequence (PMS) stars have revealed about a dozen T Tauri stars with detectable emission (Cohen, Bieging, and Schwartz 1982; Bertout and Thum 1982; Felli *et al.* 1982). The radio emission is generally interpreted to be free-free emission from ionized portions of stellar winds with $\dot{M} \gtrsim 10^{-7}\ M_\odot\ \mathrm{yr}^{-1}$, though some have recently been shown to have nonthermal spectra (Bieging, Cohen, and Schwartz 1984). There is also a growing body of evidence that PMS stars possess enhanced solar type activity compared to late-type main-sequence stars. Indications of flares and starspots from optical photometry (e.g., Worden *et al.* 1981; Schaefer 1983) and spectroscopy (e.g., Herbig and Soderblom 1980) have been strongly confirmed in X-ray studies of PMS stars (see review by Feigelson 1984). Their X-ray emission, typically 10^3–10^4 times that of main-sequence stars, is unrelated to the emission-line winds and can be highly variable on time scales of hours or minutes. The X-ray evidence for powerful flares motivated us to conduct a search for variable flare-generated nonthermal radio emission from PMS stars.

The ρ Ophiuchi star formation cloud (Barnard 42) was chosen for study because of its proximity ($d \approx 160$ pc) and concentration of 50–70 X-ray variable PMS stars within a few square degrees (Montmerle *et al.* 1983, hereafter MKFG). A number of centimeter band radio sources, some coincident with highly reddened stars, have been found in the cloud (Brown and Zuckerman 1975; Falgarone and Gilmore 1981). They have been interpreted as H II regions around embedded B stars, although the far-infrared flux from the cloud does not allow the presence of many such stars (Fazio *et al.* 1976; Elias 1978). Complete results from our multi-epoch, multifrequency survey of the cloud with the NRAO Very Large Array will be given elsewhere (T. Montmerle *et al.*, in preparation). This paper concentrates on a particular PMS star that exhibited extremely variable radio intensity and spectrum. The star, one of the brightest in the cloud at infrared and X-ray wavelengths, is known by a variety of names: Oph 10 from the radio survey of Falgarone and Gilmore (1981); GS-23 from the 2 μm survey of Grasdalen, Strom, and Strom (1973); Haro 1-6 and DoAr 21 from Hα emission-line surveys (Haro 1949; Dolidze and Arakelyan 1959), and ROX-8 from the X-ray survey of MKFG. We adopt the most common appellation, DoAr 21.

II. RADIO OBSERVATIONS AND FINDINGS

Snapshots of DoAr 21 were obtained on 6 days between 1983 February and September with the VLA. Table 1 gives the observation dates, the array configuration, the frequency, the resulting flux density, and uncertainty. The radio source lies at $\alpha = 16^{\mathrm{h}}23^{\mathrm{m}}01^{\mathrm{s}}\!.6$ and $\delta = -24°16'50''$(1950.0) and is coincident with the optical star to within $2''$. Antenna phases were adjusted to the calibrator source 1622−297 and gains were calibrated to 3C 286. Standard VLA bands, 50 MHz or 25 MHz bandwidths, and A/C intermediate frequency data were used. Observing conditions were satisfactory during all runs except for antenna shadowing in June due to the compact configuration and southern declination of the source. Fourier transformed maps of the entire primary beam were made and "cleaned" using the UV-subtraction method that permits sidelobe removal from all parts of the dirty map. Flux densities were then evaluated by parabolic interpolation of the local peak. The uncertainties reported in Table 1 are the rms deviations in source-free portions of the cleaned maps; all

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TABLE 1

VLA OBSERVATIONS OF DoAr 21

Date (1983)	Array	Frequency (GHz)	Flux Density (mJy)
Feb 17	C	1.4	6.3 ± 0.4
Feb 18	C	1.4	(7.2 ± 0.5)–(11.2 ± 0.4)
		4.9	(33.6 ± 0.4)–(48.3 ± 0.3)
Apr 13	C	1.4	< 1.8 ...
		4.9	4.6 ± 0.2
Jun 17	D	1.4	2.3 ± 0.5
		15.0	< 3.4 ...
Jun 18	D	1.4	3.2 ± 0.5
		4.9	3.4 ± 0.1
		15.0	3.3 ± 0.6
Sep 2	A	1.4	2.6 ± 0.3
		4.9	1.8 ± 0.3
		15.0	< 2.3 ...

upper limits are 3 × rms. Systematic uncertainties due to calibration, cleaning, and different source flux estimation procedures ranging up to ±1 mJy may be present but are not included in this analysis.

As shown in Figure 1, the source was dramatically brighter on 1983 February 18 than during the other observations, including February 17, by factors $\gtrsim 3$ and $\gtrsim 10$ at 1.4 GHz and 4.9 GHz, respectively. Figure 2 (Plates L1 and L2) shows the effect visually by comparing wide-field 1.4 GHz maps of February 18 and April 13 side by side. If February 18 is excluded from consideration, the source still exhibits variability at 1.4 and 4.9 GHz, though at a low level (e.g., 4.6 ± 0.2 mJy on April 13 compared to 1.8 ± 0.3 mJy on September 2 at 4.9 GHz). The apparent spectral index is also clearly changing. The slope between 1.4 and 4.9 GHz was steeply positive with $\alpha = +1.23 \pm 0.05$ ($S_\nu \propto \nu^\alpha$) on February 18, but it was flat or negative at other times.

DoAr 21 was examined for short time scale variability on February 17 and 18 when snapshots spanning several hours were obtained (Fig. 3). The source showed no variation on February 17 at 1.4 GHz, with an upper limit to the variability of ±1 mJy over 5 hr. An increase in flux from 7.2 ± 0.5 mJy to 11.2 ± 0.4 mJy is seen between February 18.470 and February 18.668 at 1.4 GHz, though the effect is somewhat confused by the sidelobes of Oph 1 which is far off-axis (see Fig. 2*a*). However, a large and definitive increase in flux occurred at 4.9 GHz: from 33.6 ± 0.4 mJy to 48.3 ± 0.3 mJy between February 18.518 and February 18.617 (about 2.5 hr). At this frequency, DoAr 21 is the only source in the field and thus is not subject to sidelobe contamination. The rise can not be attributed to instrumental gain variations since the calibrator (1622−297) was observed during this interval and exhibited random variations of only ±0.3% (1519–1528 mJy range). A search for polarized flux during the February 18 high state was made, but no signal was detected. The 3 σ upper limits to the linear and circular polarization fractions of DoAr 21 are 1.4% at 4.9 GHz and 9% at 1.4 GHz. The values are probably valid even though detailed antenna polarization calibration was not made.

III. OPTICAL AND X-RAY PROPERTIES OF DoAr 21

DoAr 21 is one of the brightest stars associated with the ρ Ophiuchi cloud in the red and near-infrared bands ($R = 11.6$, $K = 6.1$) though it is faint in the blue ($U = 17.6$, $B = 16.2$, $V = 13.9$) due to strong interstellar reddening (Rydgren, Strom, and Strom 1976; Elias 1978). Its original Hα emission has disappeared in recent decades. The line was "strong" and variable within several weeks in 1949 (Haro 1949, star 6), "weak" in 1958 (Dolidze and Arakelyan 1959, star 21), "weak" in 1960 (Hidajat 1961, star 13), and absent in ~ 1973 (Rydgren, Strom, and Strom 1976), 1980 (equivalent width ≤ 0.5 Å; MKFG), and 1983 (E. Feigelson, unpublished observations at Black Moshannon Observatory).

A reliable optical spectral type for the star has never been established (cf. Rydgren, Strom, and Strom 1976; Chini *et al.*

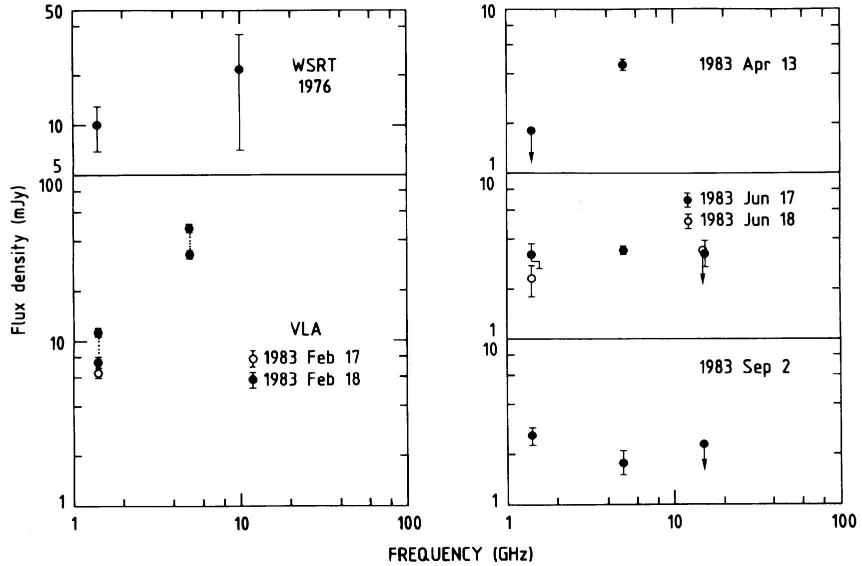

FIG. 1.—VLA observations of the PMS object DoAr 21. The Westerbork results are from Falgarone and Gilmore (1981). The dotted lines for February 18 note the range of variations.

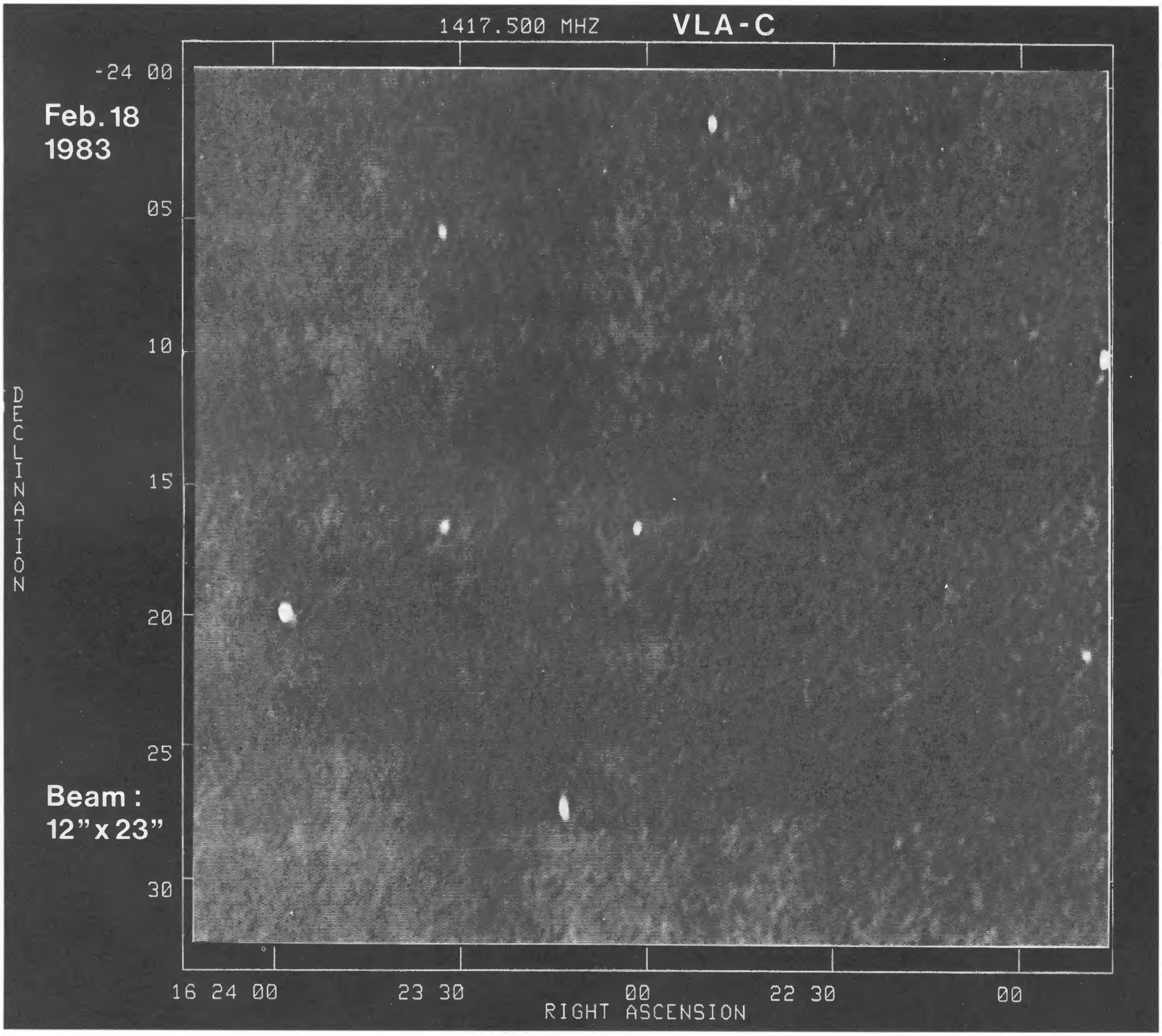

FIG. 2*a*

FIG. 2.—1.4 GHz VLA maps of the central region of the ρ Ophiuchi cloud. DoAr 21 is the bright source near the center during the 1983 February 18 observation (Fig. 2*a*, *left map*) that has disappeared in the 1983 April 13 observation (Fig. 2*b*, *right map*). The bright source at the right edge is source Oph 1 of Brown and Zuckerman (1975), while the extended diffuse faint feature between DoAr 21 and Oph 1 is the H II region surrounding the B2 V star HD 147889. Other sources in the field include Oph 4 and Oph 6, which may also be associated with low-mass PMS stars, and several unidentified (presumably extragalactic) sources.

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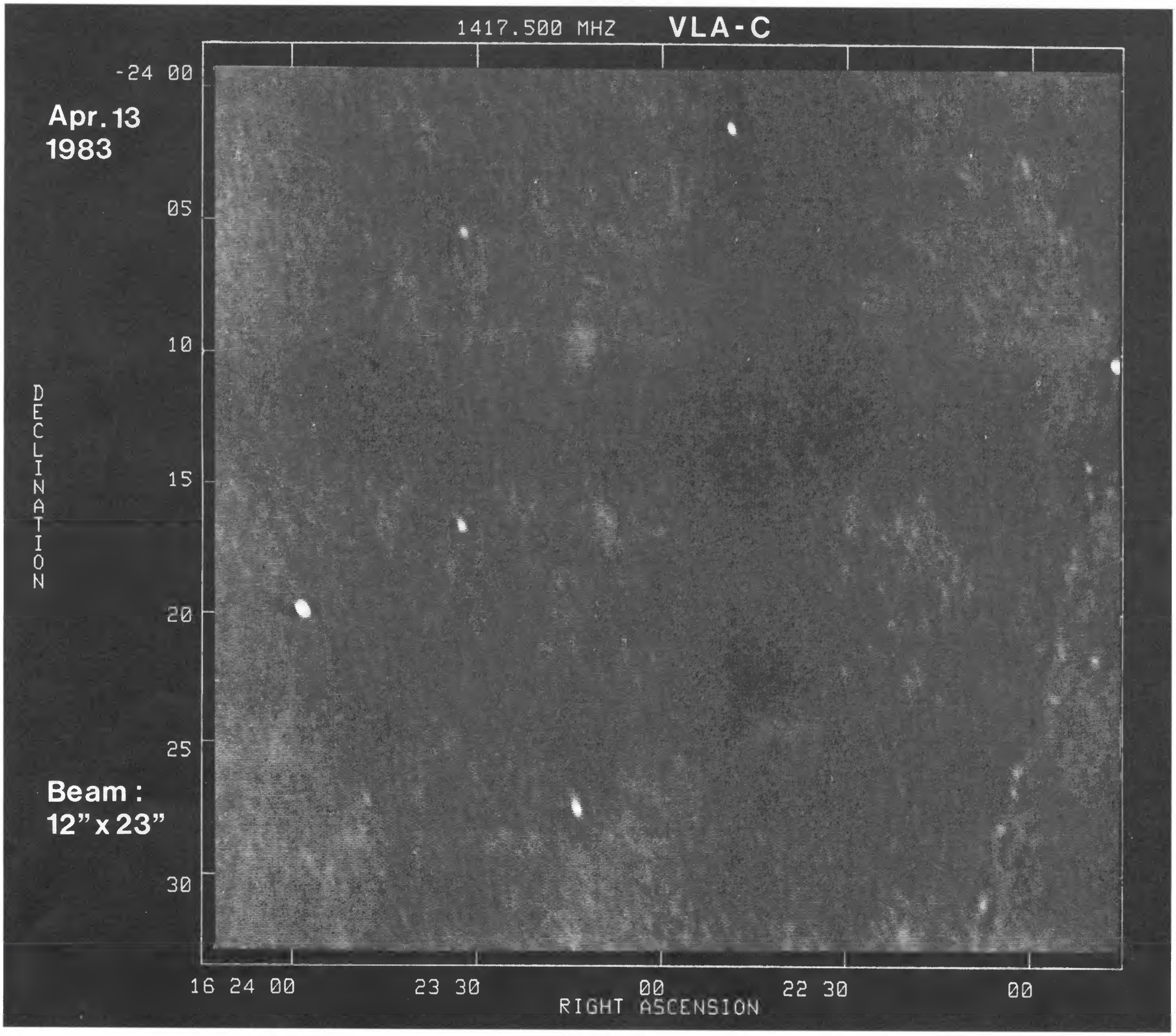

FIG. 2*b*

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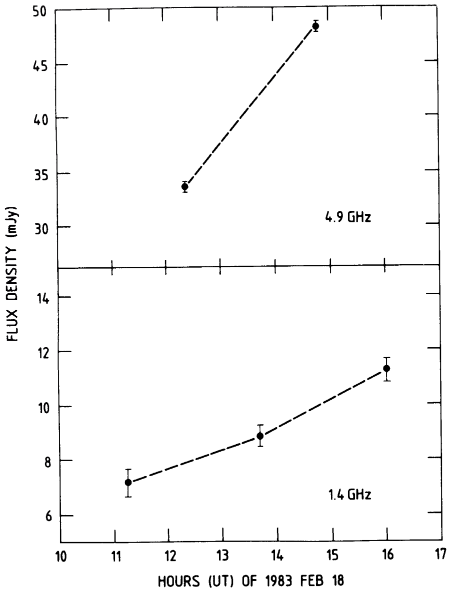

FIG. 3.—The short time scale variability of DoAr 21 during 1983 February 18.

1977). Figure 4 shows a spectrum kindly made available by J. E. Grindlay. The only clear absorption feature is around 6180 Å with equivalent width of 2 Å at the location of a strong diffuse interstellar band (DIB). Several OB stars with $A_V = 4$–6 exhibit their strongest DIB absorption feature at 6177 Å with similar equivalent widths (Herbig 1975), and weaker (EW $\lesssim 0.3$ Å) DIB features have been seen in some late-type T Tauri stars (Meyer and Ulrich 1984). A second DIB feature at 6284 Å and weak Na D absorption may also be present in DoAr 21. Although a definitive spectral classification based on this spectrum is not possible, we have confidence in excluding stars of type F or earlier due to the absence of Balmer absorption lines, and type M0 or later due to the absence of TiO bands. Wilking and Lada (1984) have recently reported near-infrared photometry of DoAr 21 and derive a spectral type of G0 and bolometric luminosity of $\approx 25\ L_\odot$. If DoAr 21 is therefore taken to be a G star with luminosity 25 $L_\odot$, it has $A_V \approx 5$ and is located 3–4 mag above the ZAMS among the more luminous classical T Tauri stars in the Hertzsprung-Russell diagram (Cohen and Kuhi 1979). The corresponding blackbody radius is $R_* \approx 5\ R_\odot$. Optically, DoAr 21 thus appears to be a late-type T Tauri star that has (temporarily?) lost its dense emission-line wind.

Among the many ρ Ophiuchi X-ray sources discovered by MKFG, ROX-8 = DoAr 21 is somewhat unusual in that its maximum observed IPC X-ray count rate is severalfold higher than the average ROX source. It is moderately variable with a maximum observed variation of a factor of 2 in 3 days. Specifically, the corrected count-rates, in 10^{-3} IPC counts s^{-1}, are 116 ± 9 (1979 March 8), 103 ± 9 (1979 September 8), 59 ± 7 (1981 February 7), 80 ± 13 (1981 February 8), 132 ± 9 (1981 February 10), 75 ± 6 (1981 February 12). The X-ray spectra at maximum is fit by a thermal spectrum $kT = 2$ keV with an absorption column density of $N_H \approx 1.5 \times 10^{22}$ cm^{-2}. Both spectral parameters are determined within a factor ~ 2 and are typical of ROX sources. The corresponding maximum and minimum intrinsic X-ray luminosities are 2.6×10^{31} ergs s^{-1} and 1.2×10^{31} ergs s^{-1}, respectively.

IV. INTERPRETATION OF THE FEBRUARY 18 EVENT: WIND OR FLARE?

The radio emission from late-type PMS stars like DoAr 21 is usually attributed to free-free emission from a steady spherically symmetric, ionized stellar wind. If the wind has a constant velocity, the theoretical spectral index will be $\alpha = 0.6$ (Wright and Barlow 1975; Panagia and Felli 1975). More steeply inverted spectra, such as $\alpha = 1.2$ seen on DoAr 21, can be produced if the wind is accelerated or has an adequate

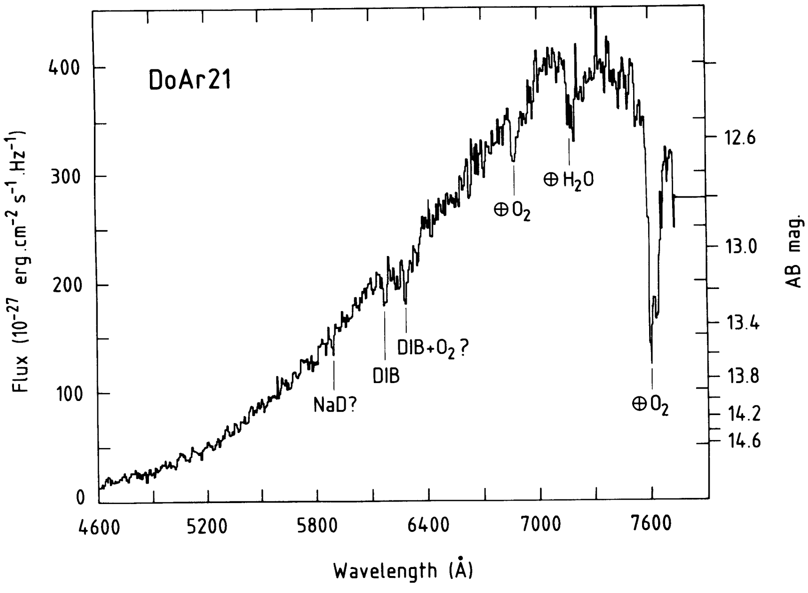

FIG. 4.—CTIO 4 m SIT Vidicon spectrum of DoAr 21 obtained on 1980 May 16 by J. E. Grindlay. Some probable spectral features are indicated.

discontinuity. In the case of an accelerated spherical outflow, we follow the formulation of Panagia and Felli (1975) and consider a velocity law of the form $v(r) = v_\infty (r/R_{\mathrm{GHz}})^{\beta-2}$, reasonable values for the wind temperature ($T = 1 \times 10^4$ K) and terminal velocity ($v_\infty = 300$ km s^{-1}). The parameter R_{GHz} is the radius at which the 1 GHz emission emerges. Given $S(1.4 \text{ GHz}) = 11$ mJy and $\alpha = 1.2$ from the February 18 data, the resulting model parameters are $\beta = 2.1/(2 - \alpha) + \frac{1}{2} = 3.2$, $\dot{M} \simeq 1 \times 10^{-6}$ $M_\odot$ yr^{-1}, and $R_{\mathrm{GHz}} \approx 7 \times 10^{14}$ cm. This wind model has several serious problems: the calculated mass loss rate exceeds values estimated for even the most extreme T Tauri stars; the radio emission from such a wind should vary on time scales $t \gtrsim R_{\mathrm{GHz}}/v_\infty \approx 2 \times 10^7$ s, far longer than the observed time scale $t \approx 10^4$ s; and there is no clear way the star can continuously inject energy to accelerate the wind $\gtrsim 10^3$ radii from its surface. To avoid having unreasonably large values of $v(r)$ at large distances (or, equivalently, a yet larger $\dot{M}$) the wind must be truncated at $R_0 \lesssim R_{\mathrm{GHz}}$ (Simon *et al.* 1983; Montmerle 1984).

The main difficulty of thermal wind models for DoAr 21 is perhaps the apparent absence of Hα line emission during the last 10–20 yr. In a steady wind, the mass loss rate and radio flux depend on the Hα luminosity approximately as $\dot{M} \approx L_{\mathrm{H}\alpha}^{1/2}$ (DeCampli 1981) and $S_\nu \approx L_{\mathrm{H}\alpha}^{1}$ (Felli *et al.* 1982). The Hα equivalent width of DoAr 21 is $\gtrsim 100$ times less than that seen in strong T Tauri winds and thus is far too low to account for the February 18 event or even the quiescent radio emission. The only acceptable thermal model would be one that invokes a highly inhomogeneous flow where the radio variations are due to the passage of strong gradients of density and/or ionization fraction through the appropriate emission regions. In that case the observed spectral index $\alpha = 1.2$ does not correspond to an actual power law, since the observed flux densities are then a consequence of the detailed structure of the inhomogeneity rather than of any calculable large-scale property of a quasi-steady wind.

The principal alternative to wind models is that DoAr 21 undergoes solar-type microwave flares such as those seen on dMe and RS CVn stars. The spectral index of the February 18 event is similar to 1–10 GHz indices seen on the Sun ($0 \lesssim \alpha \lesssim 4$ with the most frequent occurrences at $\alpha \simeq 1.4$; Schoechlin and Magun 1979). However, the peak observed power, 1.5×10^{18} ergs s^{-1} Hz^{-1} at 4.9 GHz, is 10^7 times greater than that produced by the most powerful ($\sim$ 500 SFU) solar flares. The total radio output is greater still since the DoAr 21 event lasts $> 2 \times 10^4$ s whereas solar events typically last 10^1–10^2 s. For comparison, the X-ray emission from ROX-8 = DoAr 21, all or much of which is attributable to flarelike events, is $\sim 1 \times 10^{13}$ ergs s^{-1} Hz^{-1} at 1 keV or 10^4 times greater than the strongest solar flares.

The DoAr 21 event closely resembles radio flares seen in some RS CVn stars. These flares exhibit peak luminosities of $\sim 1 \times 10^{18}$ ergs s^{-1} Hz^{-1} (though levels of 10^{16}–10^{17} ergs s^{-1} Hz^{-1}, like the quiescent level of DoAr 21, are more typical), spectral indices $-0.6 \lesssim \alpha \lesssim 1.0$, and variation time scales of 10^4 s (Feldman *et al.* 1978; Owen and Gibson 1978). The main inconsistency is that RS CVn flares nearly always show circular polarization at levels significantly higher than the limits found for DoAr 21. Whether this reflects a fundamental difference in emission mechanism or some incidental characteristic (e.g., magnetic field orientation) is not clear.

We can make rough estimates of the physical conditions implied by the February 18 event by considering a simple model of (gyro)synchrotron emission from nonthermal electrons having an energy distribution $E^{-\gamma}$ above some threshold E_0, radiating in a homogeneous plasma of density n and magnetic field B filling a spherical volume of radius R. Such conditions will produce a rising spectrum with $\alpha \gtrsim 2$ up to a frequency $\nu_{\max}$ due to various absorption processes, and a falling spectrum with index $\alpha = -(\gamma - 1)/2$ above $\nu_{\max}$ (see, e.g., Kundu and Vlahos 1982). The observed index $\alpha = 1.2$ implies that $\nu_{\max}$ is in the GHz range. If physical conditions in the plasma are not too different from solar, gyroresonance absorption will occur below a few harmonics of the gyrofrequency $\nu_B = eB/(m_e c^2) = 3 \times 10^{-3} B$ GHz, where B is in gauss. For $\nu_B \lesssim 1-2$ GHz, $B \lesssim 500$ G which is similar to values seen in solar flares. Razin-Tsytovitch suppression will operate below $\nu_R \approx n/B$ Hz; assuming its absence implies $n \lesssim 3 \times 10^{10} (B/500 \text{ G})$ cm^{-3}. Gyrosynchrotron absorption may occur below $\nu_{\max} \approx 5(B/500 \text{ G})^{1/5} (S_{\max}/50 \text{ mJy})^{2/5} [R/(2 \times 10^{12} \text{ cm})]^{-4/5}$ GHz (Ramaty and Petrosian 1972).

L. Klein (private communication; see Klein and Trottet 1984) has kindly made numerical calculations of gyrosynchrotron flux from an energetic electron population with $\gamma = 2$, $n = 5 \times 10^9$ cm^{-3}, $B = 500$ G in a homogeneous source at a distance of 160 pc. The threshold energy E_0, radius R_5 of the $\tau \approx 1$ surface at 5 GHz, and emergent flux S_5 at 5 GHz are kept as free parameters. For E_0 in the MeV range, his results may be approximated by $S_5 \approx 45(E_0/1 \text{ MeV})(R_5/10^{12} \text{ cm})^2$ mJy which suggest the need for a large emission region and electrons more energetic than in solar flares, where E_0 is in the keV range. The February 18 event can thus in all likelihood be explained as (gyro)synchrotron emission by MeV electrons in a magnetic loop $\sim 1 \times 10^{12}$ cm in size, or a few times the stellar radius. If the field strength is of order a few 10^2 G at these heights, surface fields are likely to be $\approx 10^4$ G. The duration of the flare, $\sim 10^4$ s or longer, implies that *in situ* particle acceleration takes place in the loop. Since the observed radio power, spectrum, and rise time are identical to flares occasionally seen in RS CVn systems, the physical parameters are likely to be similar as well. This similarity raises the possibility that DoAr 21 is either a close binary or a rapidly rotating single star.

V. CONCLUSIONS

The radio behavior of DoAr 21, along with an event recently seen in the rapidly rotating PMS star V410 Tau (Bieging and Cohen 1984), constitutes the first evidence for microwave flares in low-mass pre–main-sequence stars. It directly supports the accumulating evidence, based on X-ray and other data (Feigelson 1984), that PMS stars are characterized by extremely high levels of magnetically induced surface activity. An important question is whether or not DoAr 21 is unusual in its radio emission, perhaps because of

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rapid rotation or its recent loss of $H\alpha$ emission. Alternatively, all ρ Oph PMS stars may exhibit occasional radio flares. Our failure to detect a second flare from DoAr 21 in several tries, combined with the X-ray evidence that several dozen ρ Oph stars are flaring (MKFG), suggests that other radio stars may be found. Our VLA survey of the ρ Oph cloud (T. Montmerle *et al.*, in preparation) has uncovered as many as 11 possible additional radio emitting PMS stars.

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