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CIRCULAR POLARIZATION IN T TAURI STARS

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ABSTRACT

We report the detection of circular polarization in the T Tauri stars RY Tau, T Tau, and SU Aur, with a signal-to-noise ratio of 5–7. Two other T Tauri stars (DG Tau, FU Ori) were also observed with the same accuracy, and the circular polarization was found to be essentially zero. An interstellar, or a mixed intrinsic-interstellar, origin seems to be excluded. Most likely, both multiple scattering and scattering by aligned nonspherical grains occur in different stars.

Subject headings: polarization — stars: pre-main-sequence

I. INTRODUCTION

Previous observations of circular polarization in the continuum in T Tauri stars reported in the literature are those of V1057 Cyg by Wolstencroft and Simon (1975) and RY Tau by Bastien (1982). The circular polarization of V1057 Cyg was consistent with zero in the red and was reported to be variable in the blue ($S/N \approx 3$), while the measurement of RY Tau is consistent with zero because of the large error. Although barely significant, Wolstencroft and Simon (1975) interpreted their results as due to changes in the alignment of elongated grain particles distributed in a disklike configuration which we are looking at from the pole. A spectrum of V1057 Cyg obtained by Herbig (1958) in 1957 August showed it to be a bona fide T Tauri star at that time; however, the star underwent an eruptive event in 1969–1970 (Welin 1971) similar to FU Ori in 1935 (Herbig 1977*b*). This peculiar nature of V1057 Cyg means that until now no circular polarization had been detected in "normal" T Tauri stars.

T Tauri stars are known to exhibit linear polarization which is typically 1%–2%, but which can be as large as 12% in the visible. This polarization is variable in at least 60% of the stars for which sufficient data exist (Ménard 1986; Ménard and Bastien 1986). It was attributed by Bastien and Landstreet (1979) to scattering of radiation from the stars and their surrounding gas-emitting regions in external circumstellar dust envelopes. Two surveys of linear polarization observations covering the northern and southern hemispheres (Bastien 1982, 1985) have been used to study the general characteristics of the polarization and to search for correlations with other properties. A strong correlation was found between the linear polarization and the infrared excess, indicating that both are due mostly to dust. Mie scattering theory has been used in single scattering models to reproduce successfully the wavelength dependence of polarization. However, it is not possible to get large enough polarization from these models to explain the most highly polarized stars without blocking some of the direct, unpolarized, stellar light. Thus, multiple scattering models appear to be required.

Recently, polarization maps of the jets and nebulosities surrounding young stars have been published for, e.g., L1551 IRS 5 (Draper, Warren-Smith, and Scarrott 1985), R Mon and NGC 2261 (Gething *et al.* 1982; Aspin, McLean, and Coyne 1985), R and T CrA (Ward-Thompson *et al.* 1985), and the Serpens Nebula (King, Scarrot, and Taylor 1983). In some of these stars, aligned nonspherical particles seem to be required to explain the observations. The polarization vector is parallel to the disk, which requires the long axis of the grains to be oriented perpendicular to the disk. Those grains could be aligned by a predominantly toroidal magnetic field, the general mass outflow, or the radiation field. Since both multiple scattering by spherical grains and single scattering by aligned grains can give rise to circular polarization, we decided to search for it in a few T Tauri stars.

II. OBSERVATIONS

The observations were carried out during the periods 1985 November 15–21 and 1986 February 20–21 at the Cassegrain focus of the 1.6 m Ritchey-Chrétien telescope of the Mont Mégantic observatory. We used a two-channel photoelectric polarimeter with a Pockels cell as modulator. The polarizing efficiencies as measured with a red circular polarizer made of an HR Polaroid followed by a quarter-wave plate for 0.8 μm, were in the range 93.5%–97.0% throughout the observing period for the broad passbands used. The measurements were taken at two positions of the polarimeter differing by 90° with respect to the telescope in order to eliminate conversion of linear to circular polarization in the polarimeter. Two filters were used, Schott RG 645 and RG 695, which give, when combined with the response of the RCA 31034A photomultipliers, bandpasses centered at 0.7625 and 0.7925 μm and with full widths at half-maximum of 0.245 and 0.195 μm, respectively.

Tests of the polarimeter for measuring high-accuracy circular polarization were performed in 1985 June. Two standard linearly polarized stars were observed in a blue bandpass and the results agree within the errors with the circular polarization expected for that wavelength, as computed from the values of $P_{\max}$, $\lambda_{\max}$, and G given by Martin and Campbell (1976) according to the method given in Martin (1975).

TABLE 1

CIRCULAR POLARIZATION DATA

Star	JD −2,440,000.0	λ	V/I		Reference
V1057 Cyg	1984.5	6250	−0.9 ±	2.4	1
		4500	−14.0	6.0	
	2012.5	6250	−1.9	2.6	
		4500	−1.3	1.7	
	2193.5	6250	+1.2	2.4	
		4500	−3.7	1.4	
	2247.5	6250	−4.0	3.6	
		4500	+17.5	4.7	
RY Tau	3746.89	7543	+4.1	3.9	2
	6388.654	7925	+6.4	1.0	3
T Tau	6385.613	7925	−5.5	1.0	3
	6482.578	7925	−6.0	2.5	3
SU Aur	6385.731	7925	+4.9	1.0	3
DG Tau	6385.865	7675	+0.6	1.1	3
FU Ori	6390.859	7925	+0.8	1.3	3

REFERENCES.—(1) Wolstencroft and Simon 1975. (2) Bastien 1982. (3) This paper.

The criteria used for selecting the stars were brightness and known intrinsic linear polarization, as determined from both the polarization variations and the wavelength dependence. Only FU Ori is not known as a polarimetric variable, but was nevertheless included since it is the prototype of the FU Orionis stars.

Our data are presented in Table 1 with all other previously published circular polarization observations of T Tauri stars, for comparison. The columns contain respectively the name of the star, the Julian date corresponding to the middle of the observation, the central wavelength of the bandpass, the circular polarization V/I in units of 0.01%, the standard error from photon statistics, and a key to the reference. All our measurements were taken through a 13″.0 diaphragm, except one on JD 2,446,482 which was taken at 8″.3.

Definite circular polarization is detected in RY Tau, T Tau, and SU Aur, with S/N ratios of 6.4, 5.5, and 4.9, respectively. On the other hand, the data for DG Tau and FU Ori are consistent with zero circular polarization. Three σ upper limits for DG Tau and FU Ori are 3.0×10^{-4} and 3.3×10^{-4}, respectively. For comparison, the average linear polarization at 0.76 μm (Bastien 1982) can be found in Table 2 (sixth column). The errors given are the standard deviations of all measures from the mean and reflect the linear polarization variability mentioned above.

III. DISCUSSION

An interstellar (IS) origin for the detected circular polarization is to be excluded for the following reason. The maximum expected IS circular polarization for twisting alignment of IS grains along our line of sight, or for a two cloud model is (Kemp and Wolstencroft 1972; Martin 1974) $q_{\max} \approx \frac{1}{3} P_{\rm IS}^2$, where $P_{\rm IS}$ is the IS linear polarization evaluated as a fraction, rather than in percent. The IS linear polarization in front of the Taurus-Auriga and Orion clouds are of the order of 0.2% and 0.45%, respectively, as can be determined by linear polarization of foreground stars (see, e.g., Bastien 1985). This yields for $q_{\max}$ $1. \times 10^{-6}$, and 7×10^{-6} for Taurus-Auriga and Orion, respectively, much lower than the detected circular polarization.

Similarly, if the observed circular polarization were due to intrinsic linear polarization converted to circular polarization by foreground aligned dust, the maximum expected IS circular polarization would be $q'_{\max} = P_{\rm IS} P$, where P is the intrinsic linear polarization. The values of $q'_{\max}$ are 5×10^{-5}, 2×10^{-5}, 4×10^{-6}, 1×10^{-4}, and 2×10^{-5}, for RY Tau, T Tau, SU Aur, DG Tau, and FU Ori, respectively, as computed from the average linear polarization given in Table 2 and the $P_{\rm IS}$'s given above. These values of $q'_{\max}$ are less than 0.1 times the detected circular polarization. Since the linear polarization was not observed on the same night that the circular polarization was obtained, the linear polarization could have been higher than the average value at the time of observation, and hence also the value of $q'_{\max}$. However, it is very improbable that P was higher than the average value by a factor of 10. Furthermore, the star with the largest intrinsic linear polarization, DG Tau, was not detected in circular polarization. Therefore, this process does not seem to work well, because of insufficient foreground dust, or improper alignment, or both. Since most of the stars have variable linear polarization, careful monitoring of linear and circular polarizations will clearly resolve the problem in doubtful cases.

Therefore, we conclude that the circular polarization arises in the circumstellar environment of the stars. We now examine possible mechanisms giving rise to this polarization.

As mentioned in § I, the two most likely mechanisms are multiple scattering in an optically thick shell or disk, and single scattering by partially aligned nonspherical dust grains. These mechanisms are not mutually exclusive, and a combination of both is also possible.

In infrared stars where multiple scattering is thought to be occurring, the position angle of the linear polarization is

TABLE 2

GENERAL AND LINEAR POLARIZATION PROPERTIES

Star	Sp	$V \sin i$ (km s^{-1})	A_v	$\log L/L_\odot$	$\langle P(0.76) \rangle$ (%)	$P(t)$ (%)	$\psi(t)$	$\psi(\lambda)$	$\psi_*(\lambda)$
RY Tau	K1e IV, V (Li)	57 ± 7	1.88 ± 0.15	1.24	2.70 ± 0.22	$\Delta P > 1.0$	$\Delta\psi > 30°$	0° to ~ 23°	yes
T Tau...........	K0e IV, V (Li)	18^{+9}_{-5}	1.44 ± 0.10	1.45	1.17 ± 0.05	$\Delta P > 1.0$	$15° < \Delta\psi < 30°$	0°	no
SU Aur	G2 α (Li)	69 ± 6	0.93 ± 0.14	1.25	0.21 ± 0.05	$\Delta P < 0.5$	$\Delta\psi > 30°$	0° to ~ 20°	yes
DG Tau	C	...	...	≥ 0.88	5.99 ± 0.05	$0.5 < \Delta P < 1.0$	$\Delta\psi < 15°$	0°	no
FU Ori	F2 I	71^{+6}_{-9}	2.50 ± 0.22	2.43	0.76 ± 0.01	no	no	0°?	no?
V1057 Cyg	G2–5, I–II	45	3.1	...	1.67 ± 0.02	?	no	0°	(no)

frequently observed to be strongly wavelength dependent (Angel and Martin 1973; Serkowski 1973). This is also the case for some T Tauri stars and has led to the conclusion that the *intrinsic* position angle is in general a function of wavelength (Bastien 1981) and time (Bastien and Landstreet 1979). This is true of some of the stars considered here (see below).

Multiple scattering is required to explain the simultaneous polarimetric and photometric data of RY Lup obtained by Bastien *et al.* (1986). Both sets of data show periodic variations with a period of about 3.8 days. If the polarization data were due to dichroic absorption by aligned grains, then the polarization would not change as the stellar light changes by more than 1 mag due to large spots on its surface. Single scattering in an asymmetric envelope is not sufficient to explain the degree of linear polarization which reaches more than 3% at some phases.

In multiple scattering models, one expects also synchronous variations between linear and circular polarizations. There are no such observations available now, but they should clearly be looked for in the future.

Scattering by aligned, elongated dust grains in a flattened disk seen pole-on was preferred by Wolstencroft and Simon (1975) to explain their observations of V1057 Cyg. Dolginov and Mytrophanov (1978) pursued the analysis further: oblate or prolate grains are oriented by both the outflowing gas and the magnetic field which is frozen into the plasma. The circular polarization would change sign at variations in the velocity field of the stellar wind. The magnetic field implied at the stellar surface is ~ 200 G. However, the value of $V \sin i$ observed by Hartmann and Kenyon (1985), 45 km s^{-1}, is too large for the star to be pole-on. There remain the possibilities (1) that the stellar axis is not perpendicular to the disk which is indeed seen pole-on, or (2) that both are inclined at $\sim 40°-50°$ and that there is a small, nonzero, linear polarization. Bastien (1982) suspected an intrinsic component in addition to the large IS contribution, because his linear polarization observations, although constant during the period 1976–1978, were smaller by about 0.2%–0.3% than in 1971 (Rieke, Lee, and Coyne 1972; see Fig. 1 in Bastien 1981). However, the variable circular polarization of V1057 Cyg should be confirmed before making detailed models to explain it.

Models with magnetic fields have been proposed recently (Pudritz and Norman 1983; Pudritz 1985; Uchida and Shibata 1984*a*, *b*, 1985; Uchida *et al.* 1986) to explain the bipolar outflow phenomenon. In these models, the field is predominantly perpendicular to the disk, which would then predict the linear polarization vector to be along the jet axis, which is contrary to the observations. If alignment is by magnetic field, then a toroidal field in the disk seems required, or one may constrain the angle which the polloidal component of the field makes with the disk (see Bastien 1986).

IV. DISCUSSION OF INDIVIDUAL STARS

The linear polarization properties of the program stars are summarized in Table 2. These are from Bastien (1985) for the time variations and from a careful examination of a compilation of all previously published linear polarization data and also unpublished data (Ménard and Bastien 1986; Bastien and Le Van Suu 1986), for the wavelength dependence of the position angle ψ. The spectral types are from Herbig (1977*a*, *b*) and Cohen and Kuhi (1979). A "C," for continuous spectrum, appears in this column when no photospheric absorption features are visible. The rotational velocities are from Vogel and Kuhi (1981), and Hartmann and Kenyon (1985), and the A_v's and luminosities from Cohen and Kuhi (1979). The following columns give respectively the average linear polarization at 0.76 μm, the range of the temporal polarization variations, ΔP and $\Delta\psi$, where ψ is the position angle. The last two columns give the range of the observed position angle rotation with wavelength, and whether the *intrinsic* position angle depends on wavelength. The star FU Ori has not been observed polarimetrically as much as the other ones. The data available show that its linear polarization probably does not vary; it may in fact be interstellar.

a) *RY Tauri*

This star has showed in the past periods of great polarimetric activity, with large variations in P and ψ on time scales of 1 or 2 days, and also quiet periods during which the polarization hardly changed for 12 consecutive nights. Single scattering alone cannot explain the amount of linear polarization which at times reached more than 6%. The position angle variations are large, but still not completely random. The polarization is confined to some regions in the Stokes parameters (Q, U) plane. This star appears to be a good case for multiple scattering.

b) *T Tauri*

The position angle of the linear polarization in T Tau is usually perpendicular to the line joining components A and B, although variations have been observed. The polarimetric data are more difficult to interpret because of the multiplicity of this system. It appears at first sight that the main linear polarization contribution comes mostly from dust around component B illuminated by the optical companion, with either multiple scattering or single scattering by aligned grains.

c) *SU Aurigae*

A model of aligned dust grains in a disk which we observe from a low inclination, as was proposed by Wolstencroft and Simon (1975) for V1057 Cyg, would explain the available data for SU Aur. The linear polarization is very small but quite variable, and the circular polarization relatively strong, about 0.25 of the linear polarization. However, the large value of $V \sin i$, 69 ± 6 km s^{-1} (Vogel and Kuhi 1981), makes this geometry improbable. The extinction is also relatively large, $A_v = 0.93 \pm 0.14$ (Cohen and Kuhi 1979). A more detailed study is required.

d) *DG Tauri*

This star is a well-known jet source (Mundt and Fried 1983). The linear polarization in the visible (Bastien 1982), and the infrared (Hodapp 1984) is perpendicular to the jet. The linear polarization is one of the largest observed among T Tauri stars, after HL Tau, but there seems to be no associated circular polarization. Maybe we are looking at a disk edge-on, and the grains could be aligned perpendicular to the disk, or parallel to the jet. Presumably nonaligned grains could also explain the polarization with significant extinction in front of the star which decreases the amount of unpolarized light, although no specific value of A_v can be determined (Cohen and Kuhi 1979).

We have found that circular polarization is probably a common phenomenon in T Tauri stars as it was detected in three of the five stars observed. We have shown that this polarization arises in the immediate surroundings of the stars. The polarization is produced by partially aligned grains and/or multiple scattering in an asymmetric envelope.

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