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CIRCULAR POLARIZATION IN T TAURI STARS. II. NEW OBSERVATIONS AND EVIDENCE FOR MULTIPLE SCATTERING

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ABSTRACT

New observations with different instrumentation confirm the detection of circular polarization in three T Tauri stars reported earlier by Nadeau and Bastien (1986). Data on three other stars are also reported. In agreement with the recent interpretation of patterns of aligned vectors in linear polarization maps of young stellar objects in terms of multiple scattering in optically thick disks, the circular polarization in T Tauri stars is attributed to multiple scattering. Scattering of linearly polarized light by aligned grains cannot explain our observations satisfactorily.

Subject headings: polarization — radiative transfer — stars: circumstellar shells — stars: pre–main-sequence

I. INTRODUCTION

T Tauri stars form a group of young, low-mass stars, whose main defining characteristics are spectroscopic (Herbig 1962). Recent reviews of their general properties have been given by Bertout (1984) and Cohen (1984). These young stars are generally found in association with dark clouds and are very often surrounded by nebulosities, which are the remnants of the clouds out of which they formed. The dust grains in these nebulosities are responsible for infrared excesses (Cohen and Kuhi 1979) and linear polarization (Bastien and Landstreet 1979). The infrared excess and the linear polarization in two visual bandpasses are indeed correlated (Bastien 1982, 1985). The linear polarization vectors are found to be within 30° of being perpendicular to the bipolar outflow (CO and/or optical) for 11 (48%) or perhaps 14 (61%) sources out of 23 (Bastien 1987).

Nadeau and Bastien (1986, hereafter Paper I) reported recently the detection of circular polarization in three T Tauri stars, RY Tau, T Tau, and SU Aur, with a signal-to-noise ratio of 5–6. They suggested that both multiple scattering by dust grains and scattering by aligned nonspherical grains were required to explain their data, one mechanism being dominant in some stars and the other in other stars. Multiple scattering is expected at least in some cases where the intrisic linear polarization is too large ($>2\%$) to be explained by single-scattering models without blocking some of the direct, unpolarized, stellar light. Aligned dust grains have been considered in the past few years to explain the pattern of aligned linear polarization vectors which is observed in about 60% of the polarization maps made so far of young stellar objects (YSOs), which include some T Tauri stars, some hotter Herbig emission stars, and young infrared sources. A list of polarization maps with references is given by Bastien and Ménard (1988, hereafter BM). A detailed review of the polarization properties of T Tauri stars and other YSOs has been given recently by Bastien (1989).

The models for explaining the polarization properties of these stars in relation to the jets and disks which surround them can be divided into two groups: (1) models where grains scatter the light from the star and the nearby line-emission region (many different distributions of the grains have been considered) and (2) models with aligned nonspherical grains distributed in a disk configuration. Arguments in favor and against both types of models were discussed by Bastien (1987). While there are many observed polarization properties of T Tauri stars which cannot be explained by models with aligned grains (see Table 5 in Bastien 1987, and § IV), only one argument was found against the scattering models: the explanation of the linear polarization maps where aligned polarization vectors are observed. These maps clearly cannot be explained by single scattering only.

However, more recently a new interpretation for the patterns of aligned polarization vectors was proposed by BM. These patterns can be explained by scattering of light on optically thick, flat surfaces which are presumably the surfaces of circumstellar disk structures. Near such surfaces, locally, the photons move in a preferred direction which is not the direction from the star but rather the direction perpendicular to the density gradient, or the surface. This results in a preferred direction parallel to the surface for the linear polarization vectors of the light scattered toward us. Such a property is sufficient to explain satisfactorily all the patterns of aligned linear polarization vectors observed so far, as explained in BM. This new interpretation now allows us to be more specific about the mechanism responsible for the circular polarization in these young stars.

II. OBSERVATIONS

New observations of the three T Tauri stars detected earlier have been obtained with the Minipol polarimeter of the University of Arizona (Frecker and Serkowski 1976) at the Cassegrain focus of the 1.02 m telescope on Mount Lemmon during the period 1986 October 30–November 1. A quarter-wave plate was inserted in front of the rotating half-wave plate for measuring circular polarization. The filter used for these observations gives a bandpass, when combined with the photomultipliers, of 2700 Å FWHM centered at 7550 Å. The diaphragm used has a diameter of 12″.7.

Additional circular polarization observations of stars not observed by us previously, namely, SR 9, V1121 Oph, and V1057 Cyg, have also been obtained with a Pockels cell polarimeter at the Cassegrain focus of the 1.6 m Ritchey-Chrétien telescope on Mont Mégantic, the same equipment used for the

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TABLE 1

CIRCULAR POLARIZATION DATA

Star Name (1)	Julian Date (2,446,000+) (2)	λ (Å) (3)	q ($\times 10^{-4}$) (4)	σ_q ($\times 10^{-4}$) (5)	Source (6)
RY Tau	389.654	7925	6.4	1.0	1
	735.843	7550	7.1	1.6	3
T Tau	386.606	7925	−5.5	1.0	1
	482.578	7925	−6.0	2.5	1
	734.966	7550	−5.4	1.1	3
DG Tau	386.856	7675	0.6	1.1	1
SU Aur	386.721	7925	4.9	1.0	1
	734.853	7550	2.4	0.9	3
FU Ori	391.846	7925	0.8	1.3	1
SR 9	578.752	7675	−0.1	1.8	2
V1121 Oph	585.742	7675	−2.9	1.2	2
V1057 Cyg	580.794	7675	1.8	1.2	2

SOURCES.—(1) Nadeau and Bastien 1986; (2) 1.6 m telescope on Mont Mégantic; (3) 1.02 m telescope on Mount Lemmon.

observations reported earlier in Paper I. The bandpass is also the same as the broadest of the two bandpasses used in Paper I, $\lambda_c = 7675$ Å, $\Delta\lambda = 2450$ Å FWHM. These observations were carried out with a diaphragm of 8″.3 diameter during the period 1986 May 28–June 5. The observational procedure for these observations was described in Paper I.

The data are presented in Table 1 along with the measurements from Paper I for comparison. Columns (1)–(6) give, respectively, the name of the star, the Julian Date corresponding to the middle of the observation, the central wavelength of the bandpass, the normalized circular polarization in units of 0.01%, the standard error, and a key to the reference or equipment used. The standard error was computed from photon statistics for the Mont Mégantic observations (sources 1 and 2), and from fitting sine curves through the data for the Minipol observations (source 3).

As can be seen in Table 1, the previous detections of RY Tau, T Tau, and SU Aur are confirmed by the new measurements with a different instrument and a different telescope. The circular polarization of RY Tau and T Tau did not vary significantly, but that of SU Aur was, at the end of 1986 October, about half of its value in 1985 November. We note the possible detection of V1121 Oph, but only at the 2.4 σ level. The circular polarization of SR 9 and V1057 Cyg was consistent with zero at the time of the observations.

III. DISCUSSION OF INDIVIDUAL STARS

a) SU Aurigae

Except for the *IRAS* points, the energy distribution of this star can be well fitted by an accretion disk model (Bertout, Basri, and Bouvier 1988, hereafter BBB). These authors have found that even though this star has only moderate ultraviolet excess, a chromosphere alone cannot reproduce it. The multiple scattering expected in the accretion disk is most likely responsible for the circular polarization in this star. The inclination angle of 40°, which best fits the data according to the BBB model, and the fact that SU Aur is suspected of being a spectroscopic binary system (Bouvier *et al.* 1986), could explain the rather small, but quite variable, linear polarization (Paper I). The position-angle variations are particularly large, >30°, which by itself is a good argument for excluding aligned grains as a possible explanation. If SU Aur is indeed a binary, the circular polarization might also be variable. However, the data presently available (cf. Table 1) do not allow this conclusion.

b) T Tauri and RY Tauri

The flat far-infrared energy distributions of these two stars cannot be fitted by an accretion disk model even though the rest of the spectrum is well fitted (BBB). This may not be surprising, since T Tau is a triple system which includes an infrared companion with large extinction. Multiple scattering is therefore quite likely, but the geometry of the system is poorly known. The morphological and spectroscopic properties of the surrounding Burnham's nebula and of the Herbig-Haro emission to the west of the star have been studied recently by Bührke, Brugel, and Mundt (1986). High-velocity blueshifted gas is found only near the line joining T Tau and this Herbig-Haro knot, which suggests that outflow is occurring from one of the stars in the system to the knot. The inclination angle of the brightest optical companion is well determined, 15°, from $V \sin i$ and the rotation period of 2.8 days (Herbst *et al.* 1987). RY Tau shows large variations in both the magnitude and the direction of the linear polarization vector. Multiple scattering seems required to explain its linear polarization, which can reach 6% at times (Paper I).

c) DG Tauri

This extreme T Tauri star has a flat, far-infrared spectrum, which is discussed by Adams, Lada, and Shu (1988). A classical accretion disk model does not reproduce well the whole energy distribution (BBB). In Paper I it was not possible to decide whether the polarization of this star can be explained by aligned grains or by multiple scattering. However, in view of its large linear polarization (Bastien 1982), the second largest observed among T Tauri stars, and the fact that aligned grains do not seem suitable for producing large polarization in young stars (BM), one must conclude that multiple scattering in a disk seen edge-on or near to edge-on is the most likely explanation. In the case of an edge-on disk, the BM model produces effectively a large linear polarization, perpendicular to the jet, and no circular polarization, in good agreement with the observations. This explanation would be fine if it were not for the large radial velocities, −150 to −250 km s^{-1} (Mundt and Fried 1983), observed in the short (only 8″ long) jet extending at a position angle of 226° from DG Tau (Mundt and Fried 1983; Strom *et al.* 1986; Bastien 1987). A short jet with large radial velocities suggests rather that the jet is coming toward us and that we are looking at the disk from a direction close to the pole. One possible explanation would be that the jet is bent in our direction close to the star.

d) FU Orionis

The linear polarization of this star does not seem to be variable (Bastien 1985), and its circular polarization seems to be negligible (see Table 1). Although the wavelength dependence of its linear polarization has apparently not yet been measured (Bastien 1989), it is possible that a significant fraction of it is of interstellar origin. The position angle of 19 stars within a circle of 6° in radius around FU Ori (from Mathewson *et al.* 1978) is 126° unweighted, or 120° when a weight inversely proportional to the angular distance to FU Ori is used. For more details on the method for estimating interstellar polarization see Bastien (1985). For comparison, the average observed position angle is 130° in two bands centered at 5895 and 7540

Å (Bastien 1982). On the other hand, the average ratio of $P/E(B-V)$ from the same neighboring stars is 2.72 (no weight) or 2.48 (weighted). This yields a polarization close to 0.5% for $E(B-V) = 0.2$. The average observed polarization is 0.71%, 0.76%, and 0.83% in bands centered at 5895, 7540, and 8410 Å, respectively. Clearly, most of the extinction ($A_V = 2.5$ according to Cohen and Kuhi 1979, or 1.8–2.2 according to Kenyon, Hartmann, and Hewett 1988) is circumstellar in origin. Since the extinction as determined by these authors is so large, multiple scattering is quite likely. If so, the exact value of the extinction has little meaning because one does not know the fraction of the light which is scattered in our direction and which effectively reduces the value of A_V determined from the observations. The value of A_V is the most critical parameter to be determined in the accretion disk models of Kenyon, Hartmann, and Hewett (1988).

e) V1121 Ophiuchi and SR 9

The star V1121 Oph (=AS 209) has a strongly variable linear polarization (Bastien 1982); however, the circular polarization measurement presented in Table 1 is hardly significant. SR 9 has been measured only once in linear (Bastien 1982) and circular (Table 1) polarization. Both of these stars deserve further polarimetric observations.

f) V1057 Cygni

The outburst in this FU Orionis object has been interpreted recently by Hartmann and Kenyon (1985, 1987*a*, *b*) as the result of accretion of protostellar disk material onto a central T Tauri star. From fitting their model calculations to the data, Kenyon, Hartmann, and Hewett (1988) favor a small inclination, $<30°$, in agreement with arguments given by Goodrich (1987) based on the morphology of the associated reflection nebulosity that this object is observed nearly pole-on. A small inclination is consistent with the fact that V1057 Cyg might have a small, nonzero linear polarization, which was suspected by Bastien (1982) to be present in addition to a large interstellar contribution. An accretion disk seen at a large inclination is expected to produce a significantly larger linear polarization.

Wolstencroft and Simon (1975) reported the detection of variable circular polarization in a broad blue filter (with $S/N \approx 3$). Their measurements in a broad red filter are consistent with zero, which is also the case for our own red measurement (cf. Table 1). They suggested scattering by aligned, elongated dust grains in a flattened disk seen pole-on to explain their observations. As mentioned in Paper I and below in § IV, we do not think their explanation is appropriate for this star.

IV. DISCUSSION

We can exclude an interstellar contribution to the detections of circular polarization reported in § II for exactly the same reason given in Paper I: the expected interstellar circular polarization is much smaller than the detected circular polarization. Therefore, we conclude that the circular polarization arises in the circumstellar environment of these young stars, and proceed to discuss further the mechanisms considered in Paper I.

Circular polarization can be produced in the circumstellar environment of YSOs by multiple scattering on spherical or nonspherical grains and also by single scattering on aligned nonspherical grains. Various mechanisms have been considered for aligning grains in a circumstellar environment. Dolginov and Mytrophanov (1978) have evaluated time scales for alignment by various mechanisms in a region with physical parameters typical of the circumstellar shell in a pre–main-sequence star such as V1057 Cyg. They found that the most likely mechanisms for aligning both oblate and prolate grains are the outflowing gas and the magnetic field which is frozen into the plasma. The specific case of V1057 Cyg was discussed in Paper I, and it appears unlikely that this model is able to produce circular polarization and little linear polarization, since the value of $V \sin i$ observed by Hartmann and Kenyon (1985), 45 km s^{-1}, is too large for the star to be seen pole-on. If one assumes that the alignment is by a magnetic field, then one can put constraints on its geometry from the polarization observations (Bastien 1987). However, the BM model suggests that magnetic fields are not efficient at aligning grains in the circumstellar environment of young stars.

Aligned nonspherical grains have been proposed by many workers to explain linear polarization maps in which a pattern of aligned vectors is observed. In this model, the linear polarization pattern is produced by dichroic extinction by aligned nonspherical grains in a circumstellar disk of either background light or light from the YSO reflected behind the disk somehow (see, e.g., Wolstencroft 1985). However, this model cannot explain many other polarization properties of YSOs (Bastien 1987; BM): (1) the large linear polarization, typically 10%–15%, observed in the region of aligned vectors; (2) the correlation between polarization and brightness variations in RY Lup (Bastien *et al.* 1989); (3) the various wavelength dependences of linear polarization observed in T Tauri stars; (4) the linear polarization reversals as a function of wavelength; and (5) the large ($\Delta P > 1\%$ and/or $\Delta\theta > 30°$), and rapid ($\Delta t <$ 1–3 days) polarization variations. Another difficulty with this model concerns the circular polarization observations reported here, in Paper I, and by Ménard, Bastien, and Robert (1988, hereafter MBR) for R Mon. For producing circular polarization with extinction by aligned grains, one needs (at least) two slabs of grains with different alignment, or a continuous medium with changing alignment along the line of sight. This would imply a rather complicated magnetic field geometry if a magnetic field were responsible for the alignment. But, more important, this same complicated magnetic field geometry required to explain the circular polarization would no longer be able to explain the pattern of aligned linear polarization vectors. We conclude that aligned nonspherical grains cannot be responsible for the circular polarization observed in T Tauri stars and YSOs.

On the other hand, the multiple-scattering model can explain all the polarization properties of YSOs: (1) By changing the grain composition and size distribution, and to a lesser extent its spatial distribution around the star, the great variety of observed wavelength dependences of the linear polarization (e.g., Bastien 1981, 1985) can be accounted for. (2) There is a correlation between polarization and brightness variations in RY Lup (Bastien *et al.* 1989). (3) The temporal variations of position angle of the linear polarization can be explained by changing the way that the grains are illuminated by the central star and its immediate surroundings, which might include a hot and luminous boundary layer between the accretion disk and the star, as in the models of BBB. (4) Both the pattern of aligned linear polarization maps and the magnitude (10%–15%) of the linear polarization in the regions where the vectors are aligned are well explained by the BM model.

In addition, a characteristic circular polarization pattern was predicted in a circumstellar disk (Bastien 1988) from the same model used to explain the linear polarization maps (BM). According to this prediction, the circular polarization changes sign in each adjacent quadrant as defined by the outflow axis and the perpendicular passing through the star. Recently circular polarization was indeed detected in a diaphragm centered on R Mon (MBR) with a different sign in a large diaphragm (8") than in a smaller one (4"). Measurements obtained at positions in the nebulosity close to R Mon, where the linear polarization maps show a pattern of aligned vectors, also showed definite circular polarization. These observations confirm the model of multiple scattering in an accretion disk; they cannot be explained by models with aligned grains.

The model can be used to obtain important information about the circumstellar disks whose presence is inferred from the polarization observations (Bastien and Ménard 1989). The size of the area where the pattern of aligned polarization vectors are observed gives us the size of the disk or, more specifically, of that part of the disk where the optical depth in the bandpasses used for the observations is ≥ 1. Comparison of the observed polarization pattern with a grid of computed patterns yields the value of the inclination of the disk. Reliable values can be obtained for inclinations from 90° (disk edge-on) to about 40°. For smaller inclinations, the resultant polarization pattern cannot be distinguished from a centrosymmetric pattern due to single scattering.

Disks around YSOs have been considered by many workers (Rucinsky 1985; Beall 1986; Adams, Lada, and Shu 1987, 1988; Bertout 1987; Kenyon and Hartmann 1987) in recent years to explain other properties of these objects, such as their ultraviolet and infrared energy distributions. Indirect evidence for the presence of disks is provided by the presence of blue-displaced, and lack of red-displaced, forbidden lines in the spectra of many T Tauri stars (Appenzeller, Jankovics, and Oestreicher 1984). The forbidden lines are formed in the outer, low-density, ionized regions of the stellar wind, and only blue-displaced line components are visible when a large inclined disk is present to absorb the radiation from the matter moving away from us. The energy distribution which can be well fitted for many T Tauri stars is also indirect evidence for an optically thick Keplerian accretion disk surrounding the star (BBB). Such fits yield many physical parameters of the disks.

According to our favored interpretation of polarization data in terms of multiple scattering in optically thick disks, linear polarization maps and circular polarization measurements such as those of R Mon (MBR) provide direct evidence for accretion disks around YSOs. The size and the inclination of the disks can be deduced from the polarization maps. Mode detailed calculations (currently underway) are required to eliminate some of the assumptions which were made by BM in testing the mechanism.

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