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POLARIZATION OBSERVATIONS OF THE T TAURI STARS RY TAURI, T TAURI, AND V866 SCORPII

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ABSTRACT

Observations of the wavelength dependence of linear polarization of the T Tauri stars RY Tauri, T Tauri, and V866 Scorpii are presented. These observations show that most of the polarization of these stars arises in extended circumstellar dust envelopes which lie outside the high-temperature gas-emitting regions. The distribution of this matter around the stars has no fixed axis of symmetry, such as is usually found in Be stars. Strong variations in the wavelength dependence of polarization are observed, which suggest large variations in the grain size in the dust scattering regions.

Subject headings: polarization — stars: circumstellar shells — stars: individual — stars: pre-main sequence

I. INTRODUCTION

Variable linear polarization in T Tauri stars was first reported by Vardanian (1964) and confirmed by Serkowski (1969, 1971). Breger (1974) measured the polarization with no filter for about 10 T Tauri stars and described the wavelength dependence of the polarization [$P(\lambda) = 1.6\ \lambda^{-1}$, λ in μm] of RY Tau on 1973 February 26. A joint program by Abuladze *et al.* (1975) included *UBVR* photometry, *BV* polarimetry, and spectroscopy in the near-infrared for RY Tau and T Tau. The polarization of some stars exhibits chaotic changes with time (Vardanian 1964; Serkowski 1969), although not all T Tauri stars are polarized (Hiltner and Iriarte 1958). The polarization may reach up to 12% (Strom 1977). The variability indicates that at least some of the polarization is intrinsic to the stars. The mechanism responsible for the polarization is unknown. The only wavelength dependence known is that of RY Tau in 1973. Breger (1974) suggested scattering by dust grains to explain it, while Strom (1977) has proposed scattering by electrons as a likely mechanism. Abuladze *et al.* (1975) found no correlation between their photometric and polarimetric data. They noticed that the intensity of the emission lines of the infrared Ca II triplet decreased as the magnitude of the polarization decreased in T Tau.

In order to study the polarization of these young stars in a more systematic way, a two-band polarization survey using 800 Å wide interference filters centered at 5900 and 7600 Å was initiated in 1976 at the University of Western Ontario, covering all the T Tauri stars north of −30° declination brighter (either in V or in m_{pg}) than thirteenth magnitude at maximum. The wavelength dependence of polarization was also measured in the range 0.34–0.86 μm for about one-third of those stars. The stars selected for measurement of wavelength dependence are the brightest ones which appear to have significant intrinsic polarization. We report in this *Letter* some first results of this survey. We present polarization data on three particularly interesting T Tauri stars, RY Tau, T Tau, and V866 Sco, from which we are able to draw some general conclusions about the polarization properties and the polarizing mechanism for T Tauri stars.

II. OBSERVATIONS

The observations were made with two photoelectric polarimeters similar to the one described by Angel and Landstreet (1970) on the 1.22 m telescope of the University of Western Ontario, and the *P*60 inch (1.52 m) telescope of the Hale Observatories. A set of broad interference and glass absorption filters and a narrow Hα interference filter have been used together with RCA C31034A photomultipliers to define the bandpasses. The central wavelengths and full widths at half maximum transmission of the bands used are (in angstroms): 3560(630), 4385(760), 5895(700), 7543(875), 8410(800), 6563(5), 5050(1100), 7830(2350). Filter widths are indicated in the graphs by horizontal error bars. The polarization measurements were corrected for instrumental efficiency and sky background; the correct operation of the polarimeters was checked by observing at least one polarized standard star every night. Further details will be given later (Bastien and Landstreet 1979).

Figures 1, 2, and 3 give for RY Tau, T Tau, and V866 Sco (=AS 205) respectively, the observed wavelength dependence of linear polarization in our standard bands on several nights as indicated by various symbols. Vertical error bars show ±1 standard deviation calculated from counting statistics. These stars have been chosen from the survey because they have been well observed and are representative of the general polarization properties of T Tauri stars.

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III. DISCUSSION

The data of Figures 1, 2, and 3 can be used to put constraints on the geometry of the material around T Tauri stars and to identify the mechanism(s) responsible for the polarization. The large time variations in the linear polarization indicate that at least some of it is intrinsic to the stars and their immediate surroundings, and that it is not all interstellar. Assuming that the polarization arises from scattering, this intrinsic linear polarization implies that the distribution of the scattering material surrounding T Tauri stars is not *spherically* symmetric.

We next consider whether the distribution of the matter responsible for the polarization in T Tauri stars has a fixed axis of symmetry, as is generally the case in Be stars. If it does, then the position angle of the intrinsic linear polarization should be constant in time, with the observed polarization changes coming from variations in the amplitude of the intrinsic polarization. The presence in general of some interstellar polarization complicates the situation. In the (Stokes components) *Q*-*U* plane, the intrinsic and interstellar polarizations add vectorially, so that when we consider one wavelength band, the various values of observed polarization should lie along a straight line in the *Q*-*U* plane if the intrinsic polarization has a fixed axis of symmetry and hence a constant position angle (see Fig. 1 in Poeckert, Bastien, and Landstreet 1979). Figure 4 shows a number of measurements for RY Tau in the *Q*-*U* plane, at two different wavelengths. Clearly, the position angle of the intrinsic polarization is not

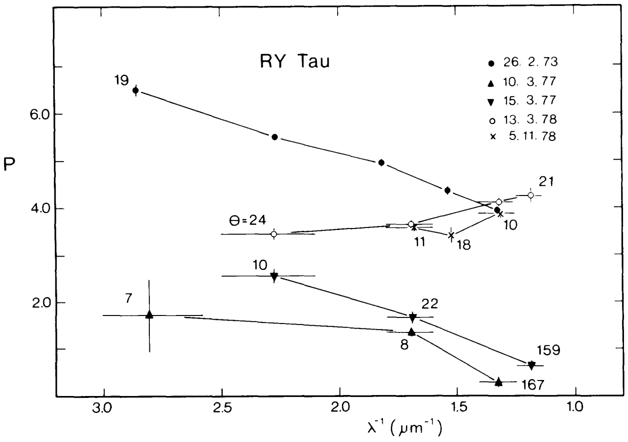

FIG. 1.—Wavelength dependence of linear polarization for RY Tau on the dates indicated. The corresponding equatorial position angles are indicated. The 1973 measurements are from Breger (1974).

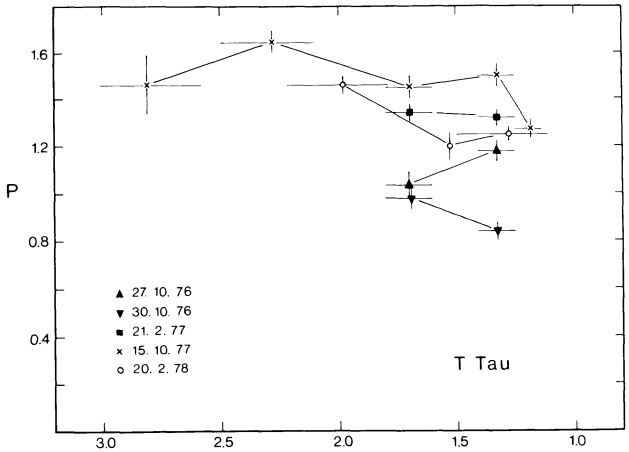

FIG. 2.—Same as in Fig. 1 for T Tau. The position angle is near 98° for all measurements.

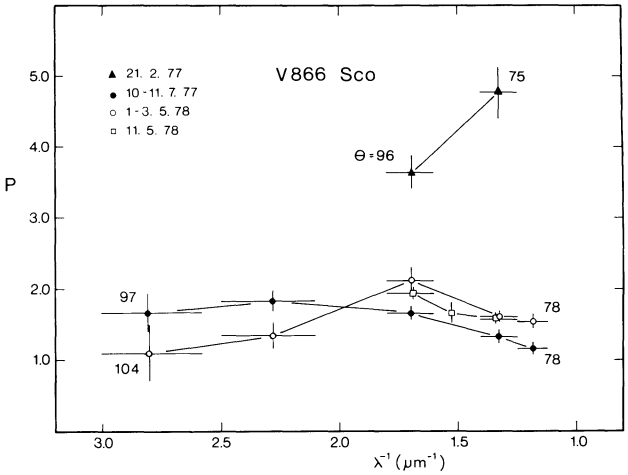

FIG. 3.—Same as in Fig. 1 for V866 Sco (=AS 205)

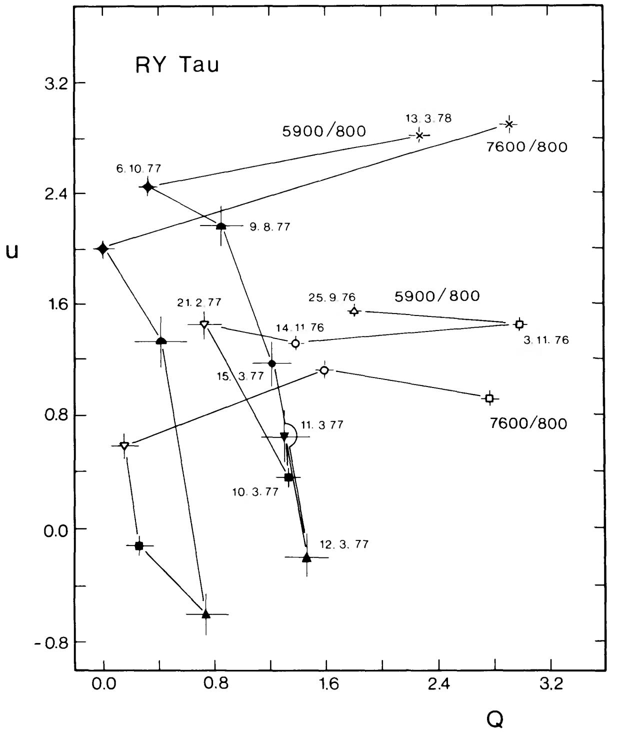

FIG. 4.—Polarization measurements of RY Tau in the *Q*-*U* plane in two bandpasses. See text for details.

constant in time. Hence, there is no fixed axis of symmetry for the scattering material. However, if we assume that the interstellar polarization of this star is small ($\ll 1\%$), the axis of intrinsic polarization wanders less than about ±30° away from a position angle of 15°, so that some tendency toward an axis is present. This would suggest blobs of material going around an axis.

Strom (1977) suggested that the polarization is produced by Thomson scattering of photospheric radiation in the inhomogeneous envelope region. This mechanism must be rejected as the main mechanism, although it may still make a small contribution in some cases (see the discussion for RY Tau below). The reasons are the following:

1. If the same electrons which are responsible for the emission lines are also responsible for the polarization, the emission lines should be "depolarized" as is the case for Be stars (Clarke and McLean 1974; Poeckert 1975). As may be seen from Figures 1–3, no such depolarization is observed across Hα for T Tau, RY Tau, or V866 Sco (or for several other stars to be discussed by Bastien and Landstreet 1979). At the time of the measurements reported here, the intensity in the Hα line (including continuum) measured with our 5Å wide filter was approximately 8 (T Tau), 11 (V866 Sco), and 2 (RY Tau) times that of the neighboring continuum. Therefore, any significant variations in the polarization at Hα should have been noticed.

2. The mass required to produce the polarization by Thomson scattering is too large. We consider a simple model where all the electrons are at the same position, at a distance r from a point source star and with an angle ϕ between the star-cloud line and the line of sight to the star. We take as many electrons as required to get the desired total polarization. The total polarization is obtained by multiplying the polarization due to the cloud $(1 - \cos^2 \phi)/(1 + \cos^2 \phi)$ by the factor $I_c/(I_* + I_c)$ to account for the dilution by the stellar radiation I_*. The radiation scattered by a cloud of N_e electrons is given by

$$I_c = I_* N_e \frac{3}{16\pi} \sigma_{\rm T} \frac{(1 + \cos^2 \phi)}{r^2} ,$$

where $\sigma_{\rm T}$ is the Thomson cross section. The total polarization of this "one-particle model" is therefore

$$P = \frac{N_e(1 - \cos^2 \phi)}{Cr^2 + N_e(1 + \cos^2 \phi)} .$$

The constant C is 5.637×10^{51} when r is expressed in terms of the astronomical unit of distance A. Taking typical values for the stellar radius ($R_* = 4\, R_\odot$) and a distance of 3 R_* to the cloud, and assuming that the cloud is in the plane of the sky ($\phi = \pi/2$) and that there is one proton for every electron in the cloud, then a mass of $1.0 \times 10^{-4}\, M_\oplus$ is required to produce 2% polarization. Different cloud masses can be obtained by changing r, since the mass varies with r^2. But r cannot be too small because the assumption of a point source star breaks down, and the polarization decreases due to the increasing solid angle subtended by the star at the cloud as r decreases. The minimum cloud mass for a given polarization occurs probably at values of r on the order of 2–3 R_*. The cloud must also have a size $\gtrsim R_*$ to be optically thin; otherwise its mass will have to be larger to produce the same total polarization. Clearly, the above estimate gives an unrealistically small lower bound on the cloud mass. If the material is distributed more uniformly around the star (in a ring, for example), then a more realistic estimate would be ~10 to 100 times the above value. This mass is too large since the total mass of the envelope responsible for the emission lines is about 1.5×10^{-6} to $1.5 \times 10^{-4}\, M_\oplus$ (Kuhi 1964; Kuan 1975). The theory agrees with the observations in showing that Thomson scattering produces a negligible contribution to the polarization in most cases.

3. The most likely cause for the excess radiation, both "blue veiling" and IR excess, is bound-free and free-free radiation in the immediate vicinity of T Tauri stars (see the review by Strom 1977). If the electrons involved in these processes (which are presumably the same ones responsible for the emission lines) were to scatter the stellar flux and produce the observed polarization, there should be a "depolarization" as the excess radiation increases relative to the stellar radiation toward the UV and the near-IR. This is not observed. For example, V866 Sco, a star with a relatively strong UV and blue emission (Kuhi 1970), shows no significant decrease in polarization at 3560 Å relative to 4300 Å (Fig. 3). In fact, if one allows for some interstellar polarization, the intrinsic polarization increases toward the UV. Furthermore, there is no indication that strong emission stars are less polarized on the average than other T Tauri stars (Bastien and Landstreet 1979).

Rayleigh scattering by circumstellar molecules is excluded because the expected wavelength distribution is not observed. By elimination, we are led to the conclusion that the polarization is due to dust grains. Those grains lie outside the gas emitting region, because they polarize the radiation from the circumstellar gas the same as the stellar radiation. The grains probably would not survive the temperature in the gas region, which is believed to reach 20,000 K or even higher (Kuan 195). An idealized estimate, similar to the one above but for dust grains, of the mass of a cloud required to produce the observed polarization, yields masses for the dust of the order of 10^{-6} to $10^{-4}\, M_\oplus$ for a variety of grain compositions and radii, taking a distance of 1 A between star and cloud. Rydgren, Strom, and Strom (1976) estimated a mass of silicate particles about 10^2–10^4 times higher to explain the observed 20 μm fluxes for seven T Tauri stars. There is certainly enough dust around these stars to produce the polarization.

Of all the T Tauri stars for which we have measured the polarization at Hα, only RY Tau showed a small but significant change at Hα with respect to the nearby continuum. There is a rotation of about 8° in the linear polarization at Hα. Two possible explanations suggest themselves. The gas emitting region contributes a substantial fraction of the total flux at Hα. If it is not spherically distributed around the star, its radiation when scattered by the circumstellar dust would not be polarized the same as the stellar continuum. Another possible explanation is that the electrons in the gas emitting region produce a small fraction of the polarization in the continuum, but essentially no polarization in the emission lines due to the "depolarization." When added vectorially to the main polarization component from the dust, this effect might produce the observed change in polarization at Hα.

Variations in the form of the wavelength dependence of the polarization occur for all three stars (Figs. 1, 2, and 3). The most spectacular change observed so far is that in RY Tau between 1973 February 26 (as observed by Breger 1974) and 1978 March 13 (Fig. 1). The polarization was increasing toward the UV in 1973 but in 1978 was increasing toward the red. Such variations in the wavelength dependence of polarization require variations in grain sizes. For example, silicate grains with radii $\sim 0.06\ \mu$m give the best fit to the 1973 data while large grains ($\gtrsim 0.3\ \mu$m) are required for the 1978 data. This is consistent with the suggestion that dust is currently forming around these young stars (Burke and Silk 1976).

IV. CONCLUSIONS

The linear polarization data for three T tauri stars shown in Figures 1, 2, and 3 allow us to make the following conclusions. The polarization is due to scattering of radiation from the stars and their surrounding gas-emitting envelopes in external circumstellar dust envelopes. The observed variations in position angle of the polarization indicate that this dust material has no fixed axis of symmetry, although some tendency toward retaining an axis is observed. Large variations in the grain size, which may be due to formation of dust around these young stars, is needed to explain the large variations in the wavelength dependence of polarization.

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