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MAGNETIC ACCRETION AND PHOTOPOLARIMETRIC VARIABILITY IN T TAURI STARS

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ABSTRACT

We investigate the photopolarimetric variability of a magnetic accretion disk model for pre–main-sequence T Tauri stars. In these dynamical models, material from a magnetically truncated Keplerian disk accretes along magnetic field lines onto the stellar surface at high latitudes, producing "hot spots" on the stellar photosphere. These spots have been proposed as the origin of the UV excesses in T Tauri stars. As the star rotates, the observed UV excess varies, as will the polarization arising from the intrinsically polarized spot the radiation of which is also scattered in the circumstellar disk.

We calculate the photopolarimetric variability for a simple magnetic accretion model in which the hot spots are two diametrically opposed, circular regions with temperatures much larger than the surrounding photosphere. Our Monte Carlo calculations show that the predicted amplitudes of the photopolarimetric variability are consistent with those observed in T Tauri stars. This model predicts correlations between the brightness and polarization that can be tested with synoptic observations. The model also predicts quasi-periodic variations if the hot spots remain relatively fixed on the stellar surface on timescales comparable to the rotation period.

Subject headings: accretion, accretion disks — polarization — radiative transfer — stars: magnetic fields — stars: pre–main-sequence — stars: rotation

1. INTRODUCTION

T Tauri stars are low-mass pre–main-sequence stars with effective temperatures of 3000–6000 K (Cohen & Kuhi 1979). These optically visible sources are commonly divided into two classes based on the shape of their spectral energy distributions (Lada 1987). Weak emission T Tauri stars (WTTS) resemble normal main-sequence stars with some emission from an active chromosphere (Walter et al. 1988; Herbig & Bell 1988), while classical T Tauri stars (CTTS) emit excess infrared (IR) and ultraviolet (UV) radiation compared to a stellar photosphere (Herbig & Bell 1988). The IR excesses require dust grains with temperatures of 50–2000 K to explain the roughly power-law energy distributions, $\lambda F_\lambda \propto \lambda^{-\alpha}$, from 2 to 100 μm (see, e.g., Cohen & Kuhi 1979; Rucinski 1985), and the UV excess can be explained in most cases by a hot, opaque source having $T \approx 10{,}000$ K and an area of 5%–10% of the stellar surface (see, e.g., Basri & Bertout 1989; Hartigan et al. 1991).

Most TTS are also low-amplitude variables on timescales of days to months (Herbst et al. 1994 and references therein). Two types of periodic variations are commonly observed. WTTS often have a regular, 0.1–0.5 mag, optical modulation with a period of 1–30 days (Herbst et al. 1994; Eaton, Herbst, & Hillenbrand 1995; Safier 1995 and references therein). These variations are caused by large dark spots, similar to sunspots, that rotate with the stellar photosphere. Some CTTS also display quasi-regular variations, but many fluctuate irregularly by 0.5–3 mag on timescales of days to years. Changes in the excess luminosity probably produce the larger irregular variations (Hartmann, Kenyon, & Hartigan 1993; Herbst et al. 1994; Safier 1995), while the quasi-regular 5–10 day variations in some cases can be caused by a bright spot (see, e.g., Herbst et al. 1994; Kenyon et al. 1994; Safier 1995; and references therein).

Circumstellar disks are popular explanations for many properties of CTTS, including the IR and UV excess emission (Adams, Lada, & Shu 1987; Kenyon & Hartmann 1987). An accretion disk naturally accounts for the 50–2000 K temperatures required for the 2–100 μm continuum. Disks also produce power-law energy distributions similar to those observed (Adams et al. 1987; Kenyon & Hartmann 1987, 1995). Although a boundary layer between the disk and stellar photosphere can emit a substantial UV excess (Kenyon & Hartmann 1987; Bertout, Basri, & Bouvier 1988), magnetic disk models may be more appropriate in many instances. If the central star has a 1 kG magnetic field, magnetic pressure truncates the disk several radii above the stellar photosphere. Disk material rises out of the disk midplane along magnetic field lines and then falls radially onto bright rings or spots at the stellar surface (Ghosh & Lamb 1979a, b and references therein). These spots rotate with the star and produce periodic or quasi-periodic modulations in the UV excess emission (Bouvier & Bertout 1989; Bouvier et al. 1993). This model can also explain the IR spectral energy distributions of many CTTS (Bertout et al. 1988; Kenyon, Yi, & Hartmann 1996) and may resolve the problem of low rotational velocities among CTTS (Bouvier et al. 1993; Edwards et al. 1993).

Many CTTS are intrinsically polarized ($P \approx 1\%$–5%) at optical and IR wavelengths (Hough et al. 1981; Schulte-Ladbeck 1982; Bastien 1982, 1985; Tamura & Sato 1989) and display temporal polarimetric variations of up to 2% on timescales of several days (see, e.g., Bastien 1985; Drissen, Bastien, & St-Louis 1989; Ménard & Bastien 1992). The polarization is usually attributed to dust scattering of starlight in surrounding circumstellar disks or envelopes (Bastien 1985; Grinin 1988), and its variability may result from changes in the scattering geometry, such as clumps in the mass inflow or outflow region (Gahm et al. 1974; Grinin 1988). This model works fairly well for polarization variations in some Herbig Ae/Be stars (see, e.g., Berdyugin et al. 1990), but the mecha-

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nism that produces a clumpy outflow or infall is not clear. Bastien (1985) suggested that intrinsic variations in the illuminating source—instead of changes in obscuration—might produce the 1–4 day polarimetric variations observed in several very active CTTS, but this proposal has not been explored in detail (see also Drissen et al. 1989).

In this Letter, we investigate a variable illumination model for polarimetric variations in CTTS. The hot rings or spots of the magnetic accretion geometry naturally produce a nonaxisymmetric illumination of the disk when the magnetic axis is not aligned with the rotation axis. The rotation of this illumination pattern with the stellar rotation period leads to a distinct modulation of both the photometry and the disk polarization. Using a simple magnetic accretion geometry with two hot spots, we find 0.25–1.5 mag photometric variations and 1%–2% variations in the optical polarization. These variations are consistent with the photopolarimetric variability observed in many CTTS.

We describe our simplified model for a disk illuminated by bright spots in § 2, report our results in § 3, and conclude with a brief discussion in § 4.

2. SPOT MODEL AND CIRCUMSTELLAR GEOMETRY

In a dipole magnetic field geometry, gas falling from an accretion disk along magnetic field lines should form two rings of emission at latitudes, $\pm b$ (Ghosh & Lamb 1979a, b; Königl 1991). If the magnetic and rotational axes are not aligned, the accretion ring is only partially filled with infalling gas (Cropper et al. 1990; Königl 1991 and references therein). Depending on the stellar inclination, the bright spots in these rings can rotate behind the limb of the star and produce periodic photometric variations (Kenyon et al. 1994; Ostriker & Shu 1995). The amplitude of the variation depends on the relative luminosity of the spots and the star. Kenyon et al. (1994) find an optical amplitude of 0.75 mag for a spot having roughly 3 times the stellar luminosity.

For simplicity, we model the bright spots in the accretion rings as two diametrically opposed circular spots with radii of 20° at latitudes ±65°. Each spot covers ~6% of a stellar hemisphere (see also Ostriker & Shu 1995). We adopt a spot temperature $T_s = 10{,}000$ K and a stellar temperature $T_* = 4000$ K. Each spot is ~3 times more luminous than a stellar hemisphere at V (0.55 μm). Our model is thus appropriate for continuum + emission TTS in which the UV excess dominates the emission from the stellar photosphere. However, most CTTS have spot luminosities comparable to the stellar luminosity and will have smaller variations in V and P than indicated by our model. In some cases presented below, we assume that the spots are limb darkened and polarized according to the gray approximation of Chandrasekhar (1960, p. 248). This approximation is valid only for very hot spots in which electron scattering is the dominant opacity source; other opacity sources are important for cooler spots with $T_s < 10{,}000$ K.

We assume that a spotted star with radius $R_* = 2\ R_\odot$ is surrounded by a truncated circumstellar disk with an inner radius $R_i = 3\,R_*$ and an outer radius $R_d = 100$ AU. Pre–main-sequence circumstellar disks are usually modeled with a flat disk or a flared disk geometry in which the height of the disk photosphere increases with radial distance (see, e.g., Shakura & Sunyaev 1973; Whitney & Hartmann 1992). However, to facilitate the radiation transfer calculation, we model the disk as a flattened envelope with a dust density

$$\rho(x, y, z) = \frac{\rho_0}{x^2/a^2 + y^2/a^2 + z^2/b^2}, \quad (1)$$

where $b/a = 0.001$. The radial optical depth in the disk midplane is 1000, which determines the value of ρ_0. This parameterization for the circumstellar disk produces continuum polarization levels intermediate between those of the flat and flared disk geometries investigated by Whitney & Hartmann (1992), so our results are representative of the more usual disk geometries. To calculate the dust scattering in our disk, we use the Henyey-Greenstein (1941) phase function and White's (1979) parameters for polarization. The scattering properties of the dust are then determined by the scattering albedo, ω, the asymmetry parameter, g, and the peak linear polarization, P_l. We adopt dust parameters appropriate for the V band with $\omega = 0.5$, $g = 0.56$, and $P_l = 0.51$. Employing this dust scattering and absorption, we calculate the emergent flux and polarization with a Monte Carlo simulation that follows individual photon packets as they are scattered and absorbed within the disk (Whitney & Hartmann 1992; Code & Whitney 1995; Wood et al. 1996a, b).

In this initial investigation, we consider a simple model in which the spots and the star emit as blackbodies. Radiation from these spots will in general be limb darkened and limb polarized. The polarization depends on the angle between the surface normal and the direction of the emergent radiation, with the largest polarization (≈11%) occurring at the stellar limb (Chandrasekhar 1960, p. 248). Since the theoretical levels of limb polarization can be very high, any intrinsic spot polarization will tend to dominate the polarization from scattering within the disk. However, since the angular dependence and intrinsic polarization of the spot radiation is uncertain, we present two cases. In the first, we consider a model in which the spots and star are unpolarized, which determines the polarization produced solely by scattering. In the second, we consider spots that are limb darkened and polarized according to the gray, plane-parallel approximation. This second model estimates the importance of the intrinsic polarization of the spots.

3. RESULTS

Figure 1 shows the V-band photopolarimetric variations arising from the star-spot-disk geometry described above for three inclination angles, 32°, 57°, and 87°. In Figure 2 we show the polarimetric variations plotted in the Q-U plane. In both figures, the left-hand panel indicates results for the unpolarized spot model, and the right-hand panel plots results for polarized spots. The spot is directly visible at light maximum ($\phi = 0°$) and rotates behind the stellar limb at light minimum ($\phi = 180°$). In both cases, the amplitude of the V light curve increases with increasing inclination angle, because more of the spot rotates out of view when the system is viewed edge-on. Our predicted amplitude of $\Delta V \approx 0.25$–1.7 mag is consistent with historical periodic variations of many CTTS (Herbst et al. 1994 and references therein).

For the unpolarized spot model (Fig. 1 [*left*]), the polarization changes by up to 0.7% during the rotation period. As the spot rotates out of view and is occulted by the star, the polarization (ratio of scattered to total flux) increases since it is dominated by scattered radiation and the spot supplies less

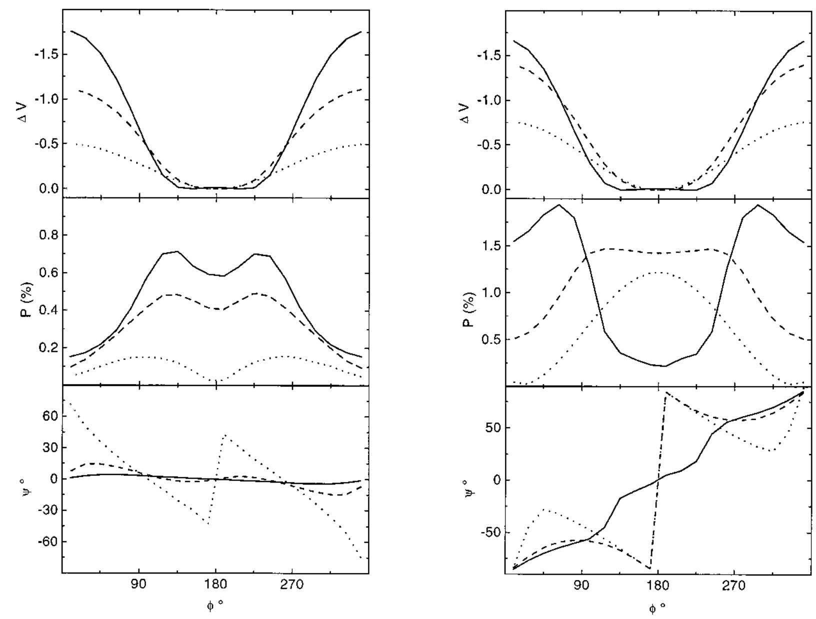

FIG. 1.—Photopolarimetric variations as a function of rotational phase. *Left*: variations of V, percent polarization, P, and position angle, ψ, for unpolarized hot spots illuminating a dusty accretion disk. *Right*: as in the left-hand panel, but for polarized spots. Each panel indicates results for inclination angles, $i = 32°$ (*dotted curves*), 57° (*dashed curves*), and 87° (*solid curves*).

direct (unpolarized) radiation. However, the polarimetric maximum does not occur precisely at photometric minimum since the dust phase function is at a minimum for backscattering (which occurs when the spot is at phase 180°). This produces the small secondary minimum in the polarization variation and explains the double-peaked morphology present at all inclination angles. In the *Q*-*U* plane, the polarization data form loops, which are typical for rotating systems (see, e.g., Brown, McLean, & Emslie 1978), and analysis of such *Q*-*U* ellipses can provide constraints on the system inclination. Note that the *Q*-*U* loops in Figure 2 (*left*) become more elongated with increasing inclination.

For polarized spots (Fig. 1 [*right*]), the polarimetric variations, which are up to 2%, are larger than those of the unpolarized spot model since direct radiation from the visible spot is highly polarized at times during the rotation period when it is positioned on the stellar limb. For inclinations less than the spot radius plus its latitude ($i < 85°$), the spot on the upper hemisphere is always at least partially visible. For an inclination equal to the spot colatitude ($i = 25°$) at phase $\phi = 0°$, the spot appears at the center of the stellar disk and is thus unpolarized. As the star rotates, the spot moves toward the stellar limb, and its polarization level increases, yielding a polarimetric maximum at photometric minimum (see the dotted curve in Fig. 1 [*right*]). At higher inclinations, the spot is already close to the stellar limb at phase $\phi = 0°$, so the polarization at $\phi = 0°$ increases with increasing inclination. For high inclinations ($i > 85°$; solid curve in Fig. 1 [*right*]), the polarization minimum instead occurs at light minimum ($\phi = 180°$) since the direct polarized spot radiation is not visible at this phase (the spot is behind the star). The small residual polarization level is due to scattering off the disk (see Fig. 1 [*left*]). As with the case of unpolarized spots, the shape of the polarization *Q*-*U* loops (Fig. 2 [*right*]) can constrain the inclination.

In general, the magnitude of the photopolarimetric variations depends on several parameters, including the latitude, size, and temperature of the hot spots. As might be expected,

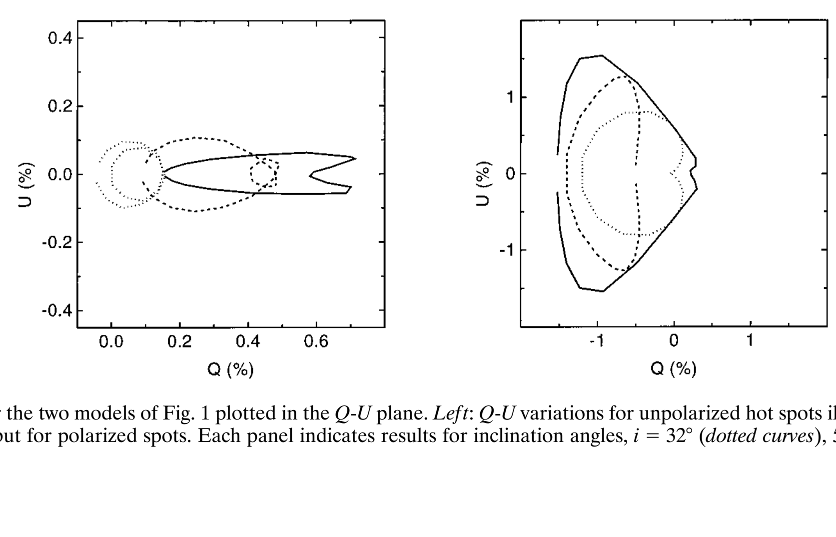

FIG. 2.—Polarimetric data for the two models of Fig. 1 plotted in the *Q*-*U* plane. *Left*: *Q*-*U* variations for unpolarized hot spots illuminating a dusty accretion disk. *Right*: as in the left-hand panel, but for polarized spots. Each panel indicates results for inclination angles, $i = 32°$ (*dotted curves*), 57° (*dashed curves*), and 87° (*solid curves*).

the largest variations occur for spots that completely disappear from view during the rotational cycle and occur for high system inclinations or for low-latitude spots. Low-latitude spots produce an obvious photometric variation and also scatter more light off the disk than spots that lie close to the rotational pole. The behavior in Figure 1 is also more pronounced at shorter wavelengths (e.g., *U* and *B* bands), at which the contrast between the spot and star is highest, while our model produces smaller variations at infrared wavelengths, *JHK*, at which the star emits a larger fraction of the total luminosity.

4. DISCUSSION

Our results indicate that the magnetic accretion model can explain the observed amplitude of the photopolarimetric variations in T Tauri stars reasonably well. The precise details of the accretion geometry—including the inner radius of the disk; the location, size, and temperature of the hot region; and whether this region is a ring or a filled-in spot on the stellar surface—do not change the qualitative behavior of the photopolarimetric variations. As discussed above, we expect the amplitude of the polarization variation, ΔP, to increase with increasing spot luminosity and with decreasing spot latitude, while the relative phase of the polarimetric maximum depends on whether or not the spots are intrinsically polarized. For most cases, the polarization maximum occurs close to photometric minimum, but for polarized spots viewed at a high inclination, the polarimetric maximum is double peaked and occurs near photometric maximum. Although our model predicts strictly periodic photopolarimetric variations, we expect quasi-regular or irregular variations in real CTTS. Hot spots that drift in latitude or longitude on short timescales will produce quasi-periodic variations, while rapid changes in spot size or temperature should produce more irregular photopolarimetric variability. Variations in the accretion rate or the magnetic field strength can cause both types of changes in spot parameters and probably occur in real systems (e.g., Armitage 1995; Clarke et al. 1995).

To test further and confirm the magnetic accretion model, systematic monitoring of the photopolarimetric variations in many CTTS is necessary. These synoptic studies will test whether or not the polarization variations are correlated with the photometric variability in accordance with our model and whether or not the polarization variations are quasi-periodic, matching the rotation periods of CTTS. In addition, these data will provide the photopolarimetric light curves necessary for constraining the system geometry.

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