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POLARIZATION OF FIR EMISSION FROM T TAURI DISKS

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ABSTRACT

Recently far infra-red (FIR) polarization of the 850μm continuum emission from T Tauri disks has been detected. The observed degree of polarization is around 3 %. Since thermal emission from dust grains dominates the spectral energy distribution at the FIR regime, dust grains might be the cause of the polarization. We explore alignment of dust grains by radiative torque in T Tauri disks and provide predictions for polarized emission for disks viewed at different wavelengths and viewing angles. In the presence of magnetic field, these aligned grains produce polarized emission in infrared wavelengths. When we take a Mathis-Rumpl-Nordsieck-type distribution with maximum grain size of 500-1000 μm, the degree of polarization is around 2-3 % level at wavelengths larger than $\sim$100μm. Our study indicates that multifrequency infrared polarimetric studies of protostellar disks can provide good insights into the details of their magnetic structure.

Key words : accretion, accretion disks —circumstellar matter — polarization — stars: pre-main-sequence — dust, extinction

I. INTRODUCTION

Recently, Tamura et al. (1999) first detected polarized emission from T Tauri stars, low mass protostars. They interpreted the polarization (at $\sim$ 3 % level) in terms of thermal emission from aligned dust grains. Magnetic field is an essential component for grain alignment. If grains are aligned with their long axes perpendicular to magnetic field, the resulting grain emission has polarization directed perpendicular to the magnetic field.

The notion that the grains can be aligned in respect to magnetic field can be traced back to the discovery of star-light polarization by Hall (1949) and Hiltner (1949), that arises from interstellar grains. Historically the theory of the grain alignment was developing mostly to explain the interstellar polarization, but grain alignment is a much wider spread phenomenon (see Lazarian 2007 for a review). Among the alignment mechanisms the one related to radiative torques (RTs) looks the most promising. We invoke it for our calculations below.

The RTs make use of interaction of radiation with a grain to spin the grain up. The RT alignment was first discussed by Dolginov (1972) and Dolginov & Mytrophanov (1976). However, quantitative studies were done only in 1990's. In their pioneering work, Draine & Weingartner (1996, 1997) demonstrated the efficiency of the RT alignment for a few arbitrary chosen irregular grains using numerical simulations. This work identified RTs as potentially the major agent for interstellar grain alignment. Cho & Lazarian (2005) demonstrated the rapid increase of radiative torque efficiency and showed that radiative alignment can naturally explain decrease of the degree of polarization near the centers of pre-stellar cores. Large grains are known to be present in protostellar disk environments and this makes the RT alignment promising.

Roughly speaking, the efficiency of grain alignment by RTs depends on two factors - the intensity of radiation and the gaseous drag force. The latter depends on gas pressure. Therefore, the ideal condition for grain alignment by RTs is strong radiation and low gas pressure.

In order to calculate efficiency of grain alignment, we need to know radiation intensity, gas density, and temperature in T Tauri disks. Recently proposed hydrostatic, radiative equilibrium passive disk model (Chiang & Goldreich 1997; Chiang et al. 2001, hereafter C01) fits observed SED from T Tauri stars very well and seems to be one of the most promising models. Here, passive disk means that active accretion effect, which might be very important in the immediate vicinity of the central star, is not included in the model. In this paper we adopt the model in C01.

In this paper, we briefly discuss polarized FIR emission arising from aligned dust grains by radiative torque in T Tauri disks. Detailed calculations and discussions can be found in Cho & Lazarian (2007). In §II, we discuss grain alignment in T Tauri disks. In §III, we give theoretical estimates for degree of polarization. In §IV, we discuss observational implications. We give summary in §V.

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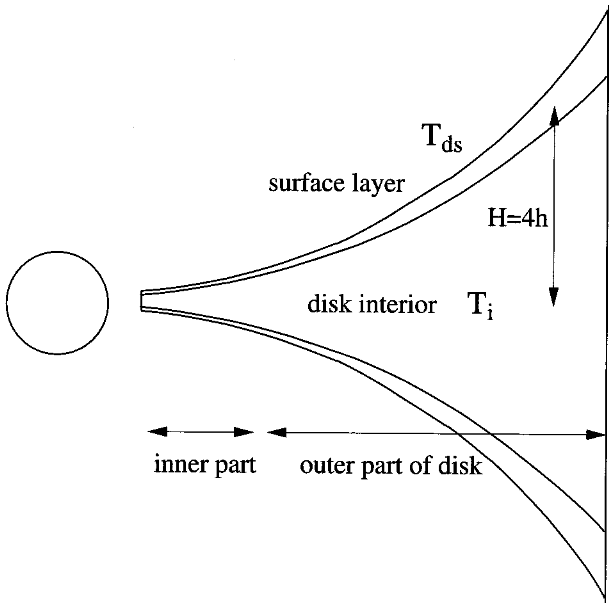

Fig. 1.— A schematic view of the disk model (see C01). The surface layer is hotter and heated by the star light. The disk interior is heated by re-processed light from the surface layers. We assume that the disk height, H, is 4 time the disk scale height, h. From Cho & Lazarian (2007).

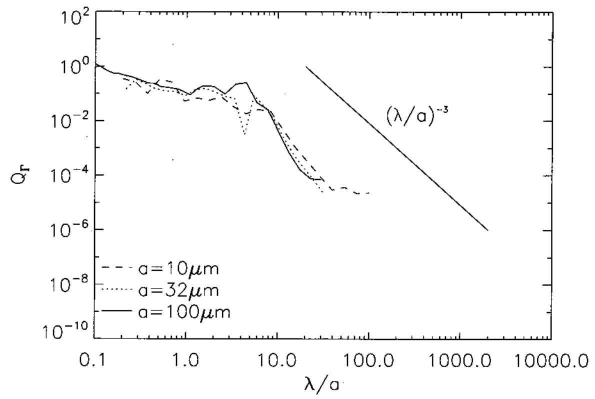

Fig. 2.— Behavior of Torque. Torque is $\sim O(1)$ when $\lambda \sim a$, where a is the grain size. Roughly speaking, torque $\propto (\lambda/a)^{-3}$. The results for large grains. Data from Lazarian & Hoang (2007).

II. GRAIN ALIGNMENT IN PROTOSTELLAR DISKS

(a) The Disk Model Used for This Study

We assume that magnetic field is regular and toroidal (i.e. *azimuthal*). We use a T Tauri disk model in C01. Figure 1 schematically shows the model. The disk is in hydrostatic and radiative equilibrium and shows flaring. They considered a two-layered disk model. Dust grains in the surface layer are heated directly by the radiation from the central star and emit their heat more or less isotropically. Half of the dust thermal emission immediately escapes and the other half enters into disk interior and heats dusts and gas there. They assume that the disk interior is isothermal.

In our calculations, we use a grain model similar to that in C01. We use an MRN-type power-law distribution of grain radii a between a_{min} (=0.01 μm for both disk interior and surface layer) and a_{max} (=1000 μm for disk interior and = 1μm for disk surface layer) with a power index of -3.5: $dN \propto a^{-3.5}da$. As in C01 we assume that grain composition varies with distance from the central star in both disk interior and surface layer. We assume that grains in the surface layer are made of silicate only when the distance r is less than 6 AU, and silicate covered with water ice when $r > 6$AU. We do not use iron grains for the immediate vicinity of the star. We assume that grains in the disk interior are made of silicate when $r < 0.8$AU and ice-silicate for $r > 0.8$AU. The fractional thickness of the water ice mantle, $\Delta a/a$, is set to 0.4 for both disk surface and disk interior. Unlike C01, we use the refractive index of astronomical silicate (Draine & Lee 1984; Draine 1985; Loar & Draine 1993; see also Weingartner & Draine 2001). We take optical constants of pure water ice from a NASA web site (ftp://climate1.gsfc.nasa.gov/wiscombe).

The column density of the disk is $\Sigma_0 r_{AU}^{-3/2}$ with $\Sigma_0 = 1000 g/cm^2$. Here r_{AU} is distance measured in AU. The disk is geometrically flared and the height of the disk surface is set to 4 times the disk scale height h. The disk inner radius is $2R_*$ and the outer radius is 100AU. The central star has radius of $R_* = 2.5R_{Sun}$ and temperature of $T_* = 4000$K. Temperature profile, flaring of disk, and other details of the disk model are described in C01.

(b) Radiative Torque for Large Grains

For most of the ISM problems, dust grains are usually smaller than the wavelengths of interest. However, this is no longer true in T Tauri disks because we are dealing with grains as large as $\sim 1000\mu m$. To understand grain alignment in T Tauri disks we need to know radiative torque for large grains. Figure 2 shows that the radiative torque

$$Q_\Gamma = \begin{cases} \sim O(1) & \text{if } \lambda \sim a \\ \sim (\lambda/a)^{-3} & \text{if } \lambda > a, \end{cases} \tag{1}$$

where a is the grain size and λ the wavelength of the incident radiation. Note that the radiative torque peaks near $\lambda \sim a$ and that its value is of order unity there.

(c) Rotation Rate of Dust Grains by Radiative Torque

Draine & Weingartner (1996) argued that grains can be aligned when they rotates supra-thermally. We also use this simple criterion for grain alignment. Detailed theory of grain alignment can be more complicated (see recent study in Lazarian & Hoang 2007).

After some modifications, equation (67) in Draine & Weingartner (1996) reads

$$\left(\frac{\omega_{rad}}{\omega_T}\right)^2 = 4.72 \times 10^9 \frac{\alpha_1}{\delta^2} \rho_3 a_{-5} \left(\frac{u_{rad}}{n_H kT}\right)^2 \left(\frac{\lambda}{\mu m}\right)^2 [Q_\Gamma]^2 \left(\frac{\tau_{drag}}{\tau_{drag,gas}}\right)^2, \quad (2)$$

where $Q_\Gamma = \mathbf{Q_\Gamma} \cdot \hat{\mathbf{a}}_1$ and $\hat{\mathbf{a}}_1$ is the principal axis with largest moment of inertia, n_H is the hydrogen number density, u_{rad} is the energy density of the radiation field, $\delta \approx 2$, $\alpha_1 \approx 1.745$, $\rho_3 = rho/3gcm^{-3}$, $a_5 = a/10^{-5}cm$, and ω_T is the thermal angular frequency, which is the rate at which the rotational kinetic energy of a grain is equal to $kT/2$. The timescales $\tau_{drag,gas}$ and $\tau_{drag,em}$ are the damping time for gas drag and for electromagnetic emission, respectively, and they satisfy the relation $\tau_{drag}^{-1} = \tau_{drag,em}^{-1} + \tau_{drag,gas}^{-1}$ (see Draine & Weingartner 1996 for details). As we discussed in the previous subsection, Q_Γ is of order of unity when $\lambda \sim a$ and declines as (λ/a) increases. From this observation, we can write

$$\left(\frac{\omega_{rad}}{\omega_T}\right)^2 \approx \left(\frac{\omega_{rad}}{\omega_T}\right)^2_{\lambda\sim a} \left(\frac{Q_{\Gamma,\lambda\sim a}}{Q_{\Gamma,\lambda}}\right)^2 \approx \left(\frac{\omega_{rad}}{\omega_T}\right)^2_{\lambda\sim a} \left(\frac{\lambda}{a}\right)^{-6} \quad (3)$$

for $\lambda > a$, where

$$\left(\frac{\omega_{rad}}{\omega_T}\right)^2_{\lambda\sim a} \approx 4.72 \times 10^9 \frac{\alpha_1}{\delta^2} \rho_3 a_{-5} \left(\frac{u_{rad}}{n_H kT}\right)^2 \left(\frac{\lambda}{\mu m}\right)^2 \left(\frac{\tau_{drag}}{\tau_{drag,gas}}\right)^2, \quad (4)$$

(d) Grain Alignment in Disks

We use Eq. (1), instead of the DDSCAT software package, to obtain radiative torque (Q_Γ) on grain particles in the T Tauri disks. We take a conservative value of Q_Γ at $\lambda \sim a$: $Q_\Gamma \sim 0.1$ at $\lambda \sim a$. Apart from Q_Γ, we also need to know u_{rad} and n_H to get the $(\omega_{rad}/\omega_T)^2_{\lambda\sim a}$ ratio (see Eq. (4)). We directly calculate u_{rad} and n_H using the disk model in C01. We assume that $\tau_{drag} \sim \tau_{drag,gas}$.

We assume that grains are aligned when the ratio $(\omega_{rad}/\omega_T)^2_{\lambda\sim a}$ exceeds 10, which is overly conservative according to a recent study in Hoang & Lazarian (2007). Calculations (see Cho & Lazarian 2007) show that grains near the central star cannot be aligned due to high gas density near the star. Indeed Figure 3 shows the ratio $(\omega_{rad}/\omega_T)^2_{\lambda\sim a}$ exceeds 10 when

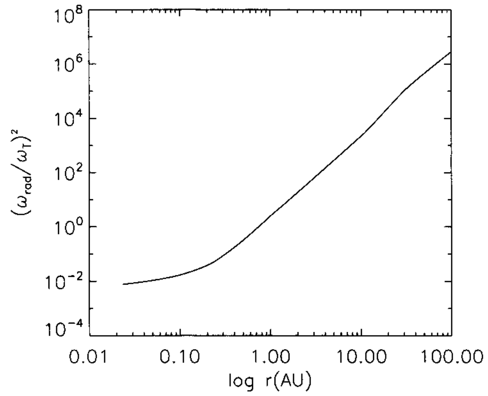

Fig. 3.— Grain alignment in surface layer. The ratio $(\omega_{rad}/\omega_T)^2_{\lambda\sim a}$ exceeds 10 when $r \geq 1$AU, which means that some grains in the surface layer are aligned when $r \geq 1$AU. Results are for $a = 1\mu$m grains. From Cho & Lazarian (2007).

the distance from the central star, r, is large, which means that grains in the surface layer are aligned when r is large. We expect that polarized emission from the surface layer is originated from outer part of the disk. Similar results hold true for disk interior. Calculations show that, at large r, large grains are aligned even deep inside the interior. On the other hand, at small r, only grains near the disk surface are aligned.

III. ESTIMATES FOR DEGREE OF POLARIZATION

(a) Estimates for Spectral Energy Distribution

In this subsection, we calculate the degree of polarization of emitted infrared radiation from a disk with structure and parameters described in C01. In this subsection, we assume that the disk in face-on. The degree of polarization will be zero for a face-on disk when magnetic field is perfectly azimuthal and the disk is cylindrically symmetric. In this section, *we are concerned only with the absolute magnitude of the polarization.*

Figure 4 shows the results for 1.3:1 oblate spheroid. The degree of polarization can be as large as ~5% in FIR/sub-millimeter wavelengths and ~ 10% in mid-IR regimes. The polarized emission at FIR is dominated by the disk interior and that at mid-IR is dominated by the disk surface layer. Note again that, in these calculations, we ignored the direction of polarization and we only take the absolute value of it. Note that, since the degree of polarization of emission from the disk surface layer is very sensitive to the maximum grain size in the surface layer, the results for $\lambda < 100\mu m$ should be very sensitive to the maximum grain size in the surface layer.

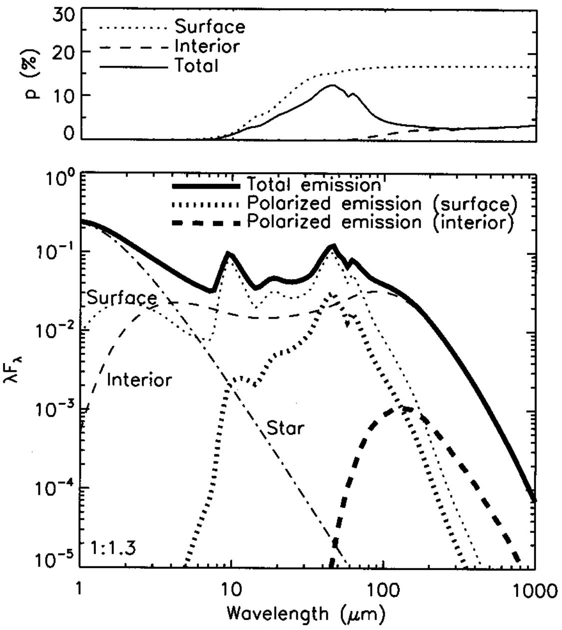

Fig. 4.— Spectral energy distribution. The vertical axis (i.e. λF_λ) is in arbitrary unit. Thick solid line: total (i.e. interior + surface) emission from disk. Thin dotted line: total emission from disk surface. Thick dotted line: polarized emission from disk surface. Thin dashed line: total emission from disk interior. Thick dashed line: polarized emission from disk interior. Note that, in these calculations of polarized emission, we ignored the direction of polarization vectors and we only take the absolute value of them. Results for oblate spheroid grains with axis ratio of 1.3:1. From Cho & Lazarian (2007).

(b) Effects of Disk Inclination

In this subsection we calculate actual degree of polarization that we can observe. Chiang & Goldreich (1999) calculated spectral energy distribution (SED) from inclined disks. We follow a similar method to calculate the the SED of polarized emission.

Figure 5 shows the effects of the disk inclination. We calculate the polarized emission from the disk interior. The viewing angle θ (=the angle of disk inclination) is the angle between the disk symmetry axis and the line of sight. We plot the direction of polarization for 3 different wavelengths and 2 different viewing angles. The lines represent the direction of polarization. Since we assume that magnetic field is azimuthal, the direction of polarization is predominantly radial (see lower panels).

IV. DISCUSSION

Multifrequency observations of protostellar disks have become a booming field recently. They have advanced substantially our knowledge of the disks and allowed theoretical expectations to be tested.

Our study reveals that multifrequency polarimetry is very important for the protostellar disks. The synthetic observations that we provide explicitly show that observations at wavelength less than 100 μm mostly test magnetic fields of the skin layers, while at longer wavelengths test magnetic fields of the bulk of the disk. Therefore polarimetry can, for instance, test theories of accretion, e.g. layered accretion (Gammie 1996). Combining the far-infrared polarimetry with polarimetric measurements at different frequencies may provide additional insight into the magnetic properties of protostellar accretion disks.

Most of the present day polarimetry will be done for not resolved protostellar disks. The size of the T Tauri disks is usually less than $\sim$ 300 AU (see, for example, C01). If we take the distance to proto-stars to be around $\geq 100pc$, then the angular sizes of the disks are usually smaller than $6''$. The angular resolution of SCUBA polarimeter (SCUPOL) is around $14''$ (Greaves et al. 2000) and that of SHARC II polarimeter (SHARP; Novak et al. 2004) at $350\mu m$ is around $9''$. Therefore it is not easy to obtain plots like Figures 5. The angular resolution of the intended SOFIA polarimeter is around $5''$ at $53\mu m$, $9''$ at $88\mu m$, and $22''$ at $215\mu m$. We see that the intended SOFIA polarimeter will be at the edge of resolving structure of close-by disks, while other instruments will not resolve typical T Tauri disk. Therefore for most of the near future observations our predictions in Fig. 4 and 5 are most relevant.

V. SUMMARY

Making use of the recent advances in grain alignment theory we calculated grain alignment by RTs in a magnetized T Tauri disk. Based on this, we calculated polarized emission from the disk. Our results show that

- Polarization arising from aligned grains reveals magnetic fields of the T Tauri disk.
- Disk interior dominates polarized emission in FIR/submillimeter wavelengths.
- Disk surface layer dominates polarized emission in mid-IR wavelengths. The degree of polarization is very sensitive to the maximum size of grain in the disk surface layer.
- Our study of the effect of the disk inclination predicts substantial changes of the degree of polarization with the viewing angle. The coming mid-IR/FIR polarimeters are very promising for studies of magnetic fields in protostellar disks.

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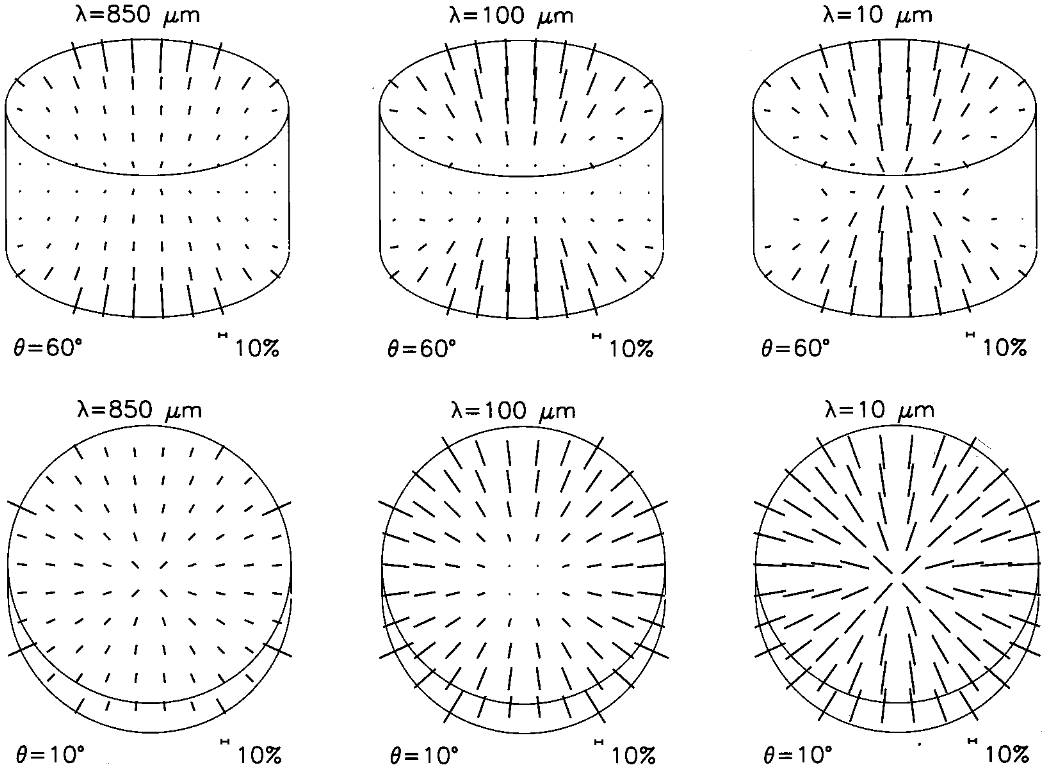

Fig. 5.— Simulated observations. Degree of polarization is calculated for the total radiation (i.e. interior + surface) from the disk. The disk inclination angle θ is the angle between disk symmetry axis and the line of sight. From Cho & Lazarian (2007).

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