Correlation between Interstellar Polarization and Dust Temperature:
Is the Alignment of Grains by Radiative Torques Ubiquitous?

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Abstract

We have investigated the efficiency of interstellar polarization, \( p_\lambda / A_\lambda \), where \( p_\lambda \) is the fractional linear polarization and \( A_\lambda \) is the extinction, in 14 lines of sight as a function of the wavelength, \( \lambda \). We used the data of lines of sight to the Pleiades cluster obtained with the low-dispersion spectropolarimeter HBS as well as those in literature. It has been found that the polarization efficiency, \( p_\lambda / A_\lambda \), is proportional to \( \exp(-\beta/\lambda) \) in wavelength, \( \lambda \approx 0.4-0.8 \mu m \), where \( \beta \) is a parameter that varies from 0.5 to 1.2. We find that \( \beta \) is negatively correlated with the dust temperature deduced from infrared data by Schlegel et al. (1998, ApJ, 500, 525), suggesting that the polarization efficiency is higher in short wavelengths for higher temperature. According to the alignment theory by radiative torques (RATs), if the radiation is stronger, RATs will make small grains align better, and the polarization efficiency will increase at short wavelengths. Our finding of the correlation between \( \beta \) and the temperature is consistent with what is expected with the alignment mechanism by RATs.

Key words: alignment mechanism — ISM: dust, extinction — polarization

1. Introduction

Observed linear polarization in the light from distant stars, i.e., often called “interstellar polarization”, is interpreted as a phenomenon of dichroic extinction, and shows that interstellar grains are optically anisotropic and aligned, although the mechanism of the alignment is still being debated (Lazarian 2007, for a recent review). The alignment of grains had been explained based on paramagnetic relaxation of thermally spinning grains that obtain angular momentum by collisions with gas particles (Davis & Greenstein 1951, hereafter DG). However, the DG mechanism is not efficient, and it cannot explain the interstellar polarization quantitatively. For more efficient alignment, Purcell (1979) assumed a spin-up of grains by the ejection of molecular hydrogen from the grain surface (the “pinwheel mechanism”), though there still remain problems regarding quantitative explanations (Lazarian & Draine 1999; Roberge & Lazarian 1999).

Dolginov and Mitrofanov (1976) first pointed out that irregularly shaped grains that have “helicity” can spin up by radiative torques (hereafter RATs). More recently, Draine and Weingartner (1996) showed that RATs are very effective to align grains. Since magnetic moments within rotating grains are induced by the Barnett effect, the grains precess around the magnetic field, and the direction of alignment is usually parallel to the interstellar magnetic field (e.g., Draine & Weingartner 1997; Lazarian & Hoang 2007), i.e., the same direction as that by the DG mechanism. The alignment by RATs can be more efficient if grains have superparamagnetic inclusions (Lazarian & Hoang 2008), or if the pinwheel mechanism is working with RATs (Hoang & Lazarian 2009).

The efficiency of the RATs alignment varies with the strength and spectral energy distribution of the radiation field, and thus the size of aligned grains should vary accordingly (Draine & Weingartner 1996; Cho & Lazarian 2007). Observationally, the maximum wavelength, \( \lambda_{\text{max}} \), of polarization in dark clouds was shown to be correlated with the extinction, \( A_V \), in the \( V \)-band (Whittet et al. 2001; Andersson & Potter 2007). Andersson and Potter (2010) showed that grain alignment is enhanced by stellar radiation in the vicinity of a young star, HD 97300, in the Chamaeleon I cloud. For stars in the Taurus dark cloud, Whittet et al. (2008) showed that the polarization efficiency, \( p_A / 2k \), in the \( K \)-band, where \( 2k \) is optical depth, decreases smoothly with \( A_V \) beyond the region where the ice mantle feature was detected. This suggests that the alignment efficiency is not directly related to the state of grain surface, as is expected by the “pinwheel” alignment. Those observations suggest that the RATs alignment works in dark clouds and star-forming regions. However, it is still not clear whether RATs alignment works or not in more diffuse clouds.

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The Pleiades cluster is associated with diffuse reflection nebula, where the grain alignment may be enhanced by strong stellar radiation if the alignment by RATs works. This motivated us to observe polarization in the lines of sight to stars in the Pleiades cluster with the low-dispersion spectropolarimeter HBS (Kawabata et al. 1999). In this Letter, using our polarimetric data and those available from literature, we investigate correlations between the polarization quantities and the dust temperature, because such correlations may be expected from the RATs alignment theory.

2. Observations and Data Reduction

We observed 8 stars in the Pleiades cluster with the low-dispersion spectropolarimeter HBS (Kawabata et al. 1999) attached to the 1.88 m telescope in Okayama Astrophysical Observatory, from 2008 October 30 to November 13, and from 2009 January 13 to 19. HBS has a superachromatic half-wave plate and a quartz Wollaston prism, and it can measure linear polarization over a wide range of the optical region, from 0.4 to 0.8 μm. We used a slit of 0.2 mm width, yielding a wavelength resolution of ~0.006 μm. After binning, we obtained spectropolarimetric data with a resolution of 0.02 μm, and also synthesized V-band data. A unit of the observing sequence consists of successive integrations at 0°, 22°5, 45°, and 67°5 position angles of the half-wave plate. The exposure time per object was from 1800 to 17600 s, depending on the brightness of the object, and also on the weather conditions.

The instrumental polarization was evaluated with nonpolarized standard stars, i.e., HD 432, HD 21447, HD 95418, HD 198149, and HD 210027 in 2008, and HD 21447, HD 20630, HD 95418, HD 114710, and HD 142373 in 2009 (Kawabata et al. 1999 and references therein). The standard deviations of the fractional Stokes parameters for those standard stars were 0.02%–0.07% in the synthesized V-band. Since these values are larger than those expected from photon noise, i.e., 0.01%–0.03% for each measurement, they can be interpreted as instrumental stability in polarization measurements. The photon noise for program stars was also small, ~0.01%. We thus consider that the accuracy in our polarimetry is mainly limited by the instrumental stability, and estimated the error for the fractional polarization, $p_V$, to be 0.04%, which is a mean value of the standard deviations for nonpolarized standard stars.

The position angle, $\theta_V$, of linear polarization in the V-band was calibrated with polarized standard stars, i.e., HD 7927, HD 43384, and HD 204827, in both observational runs. Since HD 43384 shows a small temporal variation in polarization (Hsu & Breger 1982; Matsumura et al. 1998), we considered it to be a secondary standard, though no significant deviations were found from the tabulated value of $\theta_V = 170°$ in the literature. We thus calibrated $\theta_V$ with an accuracy of ~0.5°.

From observations of nonpolarized standard stars through a Glen-Taylor prism, we estimated the instrumental depolarization to be 0.95–0.99, depending on the wavelength, and used it for calibration. The position angle, $\lambda_V$, in the wavelength region $\lambda = 0.4$–0.8 μm was calibrated with reference to $\theta_V$, with the same observation.

3. Results and Discussion

3.1. Fractional Polarization and Position Angle

The observed fractional polarization, $p_\lambda$, and the position angle, $\theta_\lambda$, are shown in figure 1, except for HD 23985 and HD 24118, which show low polarization of $\lesssim 0.1%$. We assume an empirical formula for $p_\lambda$ by Serkowski et al. (1975):

$$p_\lambda = p_{\max}\exp[-K\ln^2(\lambda/\lambda_{\max})],$$

where $p_{\max}$ is the maximum polarization, $K$ is a parameter that determines the width of the curve, and $\lambda_{\max}$ is the wavelength at $p = p_{\max}$. Those derived values of $p_{\max}$, $\lambda_{\max}$, and $K$ are tabulated in table 1. Figure 1a shows that $p_\lambda$ is well expressed with equation (1). The position angle, $\theta_\lambda$, is almost constant, though $\theta_\lambda$ of 19 Tau varies with $\lambda$ at short wavelengths of $1/\lambda \gtrsim 2.3 \mu m^{-1}$ (figure 1b).

Since the scattered light is often strongly polarized, it may affect the polarimetric results of nebulous objects, if it is not subtracted properly, and/or if the objects are surrounded by an optically thick cloud, e.g., young stellar objects, such as R Mon (Matsumura et al. 1999). However, the brightness of nebulousness around the stars in the Pleiades is not intensive compared with the stellar light, typically ~20 mag arcsec$^{-2}$ in the $B$ or $V$-band. We thus expect that the effect of the nebulousness is

![Figure 1](https://academic.oup.com/pasj/article-abstract/63/5/L43/2898183/DC2V)
We thus use another quantity less affected by the variation of the size of the total, i.e., aligned and nonaligned, grains. (1986), but it is 140° in Markkanen (1977) and in Breger (1986), but it is 140° ± 4° in our observation (table 1). We thus exclude 19 Tau in the following discussion.

3.2. Polarization Efficiency

The $A_V$-dependence of $\lambda_{\text{max}}$ in dark clouds suggests that the alignment of grains is induced by RATs (see section 1). However, Andersson and Potter (2007) noticed that the extrapolated value of $\lambda_{\text{max}}$ at $A_V = 0$ in each cloud is correlated with the mean value of the ratio of the total to selective extinction, $R_V$, where $R_V = A_V/E_{V-B}$ and $E_{V-B}$ is the color excess for $B - V$. Since $R_V$ characterizes the extinction, this correlation means that $\lambda_{\text{max}}$ depends not only on the alignment, but also on the size of the total, i.e., aligned and nonaligned, grains. We thus use another quantity less affected by the variation of the grain size.

Compared with $\lambda_{\text{max}}$, the polarization efficiency, $p_{\lambda}/A_\lambda$, should be less dependent on the variation of the grain size, because such a variation will be canceled in $p_{\lambda}/A_\lambda$. We thus explore the observed properties of $p_{\lambda}/A_\lambda$, expecting to obtain information on the alignment. It should be noted, however, that Yoschchinikov and Das (2008) and Das et al. (2010) showed that $p_{\lambda}/A_\lambda$ depends on the grain size, shape, material, and other parameters. It would be possible to examine the properties of $p_{\lambda}/A_\lambda$ in more detail by using light-scattering calculations (e.g., Matsumura & Seki 1991, 1996; Matsumura & Bastien 2009), but it is beyond the scope of this Letter.

To evaluate the extinction, $A_\lambda$, we have used two methods:

**Method 1**: Based on the assumption that the $\lambda$-dependence of $A_\lambda$ is determined by $R_V$ and scaled by $A_V$ (Cardelli et al. 1989), we evaluated $A_\lambda$ by interpolating the data of $A_\lambda/E_{V-B}$ for $R_V = 2.1$–5.5 tabulated in Fitzpatrick (2004). The values of $A_V$ and $R_V$ were calculated by the formula $A_V = 1.1 E_{V-K}$ and $R_V = 1.1 E_{V-K}/E_{B-V}$ (Whittet & van Breda 1980), respectively, where $E_{V-K}$ is the color excess for $V - K$. We used $B$ and $V$ magnitudes in the Simbad database, while for the $K$ band, we transformed the $K_S$ magnitude in the Two Micron All Sky Survey (2MASS) into the $K$ magnitude in the system of Koornneef (1983) with a formula by Carpenter (2001). We refer to FitzGerald (1970) and Koornneef (1983) for the intrinsic colors of $B - V$ and $V - K$, respectively.

Since the errors of $R_V$ derived with Method 1 are large for some stars (table 1), we also used another method, as described below (Method 2). The error of $K_S$ for 27 Tau was particularly large, ~0.3 mag, we could not obtain reliable results, and excluded 27 Tau in the following discussion.

**Method 2**: We assumed that the extinction properties are not variable within the Pleiades cluster, and applied the extinction curve for HD 23512 to other stars, scaling it by the value of $A_V$ deduced with Method 1. The extinction curve for HD 23152 was reduced by Fitzpatrick and Massa (2007), and is the most reliable among the Pleiades stars.

We explored not only the Pleiades stars, but also the stars for which polarization and extinction data are available from the literature. We used the polarimetric data of various stars by Weitenbeck (1999, 2004). The data of HD 29647 (Whittet et al. 2001) and HD 38087 (Serkowski et al. 1975) were used in addition to those from Weitenbeck (1999). Extinction data for those stars are cited from Fitzpatrick and Massa (2007). Also used were data for high-latitude clouds MBM 30 and MBM 20 (LDN 1642) by Seki and Matsumura (1996).

Figure 2 shows the $\lambda$-dependence of $p_{\lambda}/A_\lambda$, which was derived with Method 1. The values of $\ln(p_{\lambda}/A_\lambda)$ decrease linearly with the inverse wavelength, $1/\lambda$, though slight deviations from the linear relation are found. We thus made a linear fitting in $\lambda = 0.4$–0.8 $\mu$m with the equation

$$\ln(p_{\lambda}/A_\lambda) = \ln\alpha - \beta(1/\lambda - 1/0.55 \mu m).$$

where $\lambda$ is in $\mu$m, and $\alpha$ and $\beta$ are parameters; all are tabulated in tables 1 and 2.
3.3. Polarization Efficiency and Dust Temperature

To discuss the correlations between the polarization properties and the dust temperature, we used the temperature, $T_{\text{dust}}$, by Schlegel et al. (1998). They deduced $T_{\text{dust}}$ from COBE and IRAS data, on the assumption of $\lambda^{-2}$ emissivity of grains in the infrared. Their data are homogeneous all over the sky, and are thus suitable for our study that contains not only the lines of sight to Pleiades stars, but also those to other objects.

Between $\lambda_{\text{max}}$ and $T_{\text{dust}}$, we find a weak correlation in figure 3a, and the correlation coefficient, $r$, is $-0.30$. The correlations between $\beta$ and $T_{\text{dust}}$ are much better, i.e., $r = -0.54$ (Method 1, figure 3b) and $r = -0.57$ (Method 2, figure 3c). It is remarkable that the relative positions of HD 210121 and HD 38087 are different between in figure 3a and in figures 3b and 3c. This is caused by the different values of $R_F$, i.e., $R_F$ of HD 210121 is smaller ($= 2.0$, Fitzpatrick &...
Massa 2007), and that of HD 38087 is larger (= 5.8, Fitzpatrick & Massa 2007) than other objects ($R_V \sim 3$).

We finally discuss the above-mentioned correlations on the basis of the RATs alignment theory. Using their equation (5) in Cho and Lazarian (2007) and equation (67) in Draine and Weingartner (1996), with typical values for physical quantities in interstellar space tabulated in table 2 of Lazarian and Hoang (2007), we can express the smallest size $a_{lower}$ of aligned grains as

$$
(a_{lower}/1 \mu m) = 0.089 \times (T_{dust}/18 K)^{-2},
$$

where we assume that the efficiency, $Q_T$, for RATs is 0.1, and that the emissivity of grains is $\propto \lambda^{-2}$.

Concerning the size distribution of aligned grains, Mathis (1986) showed that the observed polarization, $p_\lambda$, can be reproduced if the fraction $\{1 - \exp\left[-(a/a')^3\right]\}$ of grains with radius $a$ are aligned, where $a'$ is a parameter for the typical size of smallest aligned grains. Mathis (1986) then obtained the equation

$$
(a'/1 \mu m) = 0.327 \times (\lambda_{max}/1 \mu m)^{2.17}.
$$

If we assume $a' = a_{lower}$ (or $a' = 2a_{lower}$), we can relate $\lambda_{max}$ and $T_{dust}$ with equations (3) and (4), and draw the short dashed (or long dashed) line in figure 3a.

For the relation between $\beta$ and $\lambda_{max}$, we obtain

$$
(\beta/1 \mu m) = 1.79 \times (\lambda_{max}/1 \mu m)^{3.9},
$$

with using equation (1) and extinction curve for $R_V = 3.1$ (Fitzpatrick 2004). We then write $\beta$ as a function of $T_{dust}$, and draw short and long dashed lines for $a' = a_{lower}$ and $a' = 2a_{lower}$, respectively, in figures 3b and 3c.

Those lines in figure 3 seem to follow the observations well, i.e., the correlation between $\lambda_{max}$ and $T_{dust}$, and that between $\beta$ and $T_{dust}$ can be explained by the RATs alignment theory. Since those data contain regions of various temperature, i.e., the Taurus dark cloud, reflection nebulae, etc., our results suggest that the alignment by RATs is ubiquitous in interstellar space.

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References

Andersson, B-G, & Potter, S. B. 2007, ApJ, 665, 369
Andersson, B-G, & Potter, S. B. 2010, ApJ, 720, 1045
Breger, M. 1986, ApJ, 309, 311
Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, ApJ, 345, 245
Carpenter, J. M. 2001, AJ, 121, 2851
Cho, J., & Lazarian, A. 2007, ApJ, 669, 1085
Crawford, D. L., & Perry, C. L. 1976, AJ, 81, 419
Das, H. K., Voshchinnikov, N. V., & Il’in, V. B. 2010, MNRAS, 404, 265
Davis, L., Jr., & Greenstein, J. L. 1951, ApJ, 114, 206 (DG)
Dolginov, A. Z., & Mitrofanov, I. G. 1976, Ap&SS, 43, 291
Draine, B. T., & Weingartner, J. C. 1996, ApJ, 470, 551
Draine, B. T., & Weingartner, J. C. 1997, ApJ, 480, 633
FitzGerald, M. P. 1970, A&A, 4, 234
Fitzpatrick, E. L. 2004, ASP Conf. Ser., 309, 33
Fitzpatrick, E. L., & Massa, D. 2007, ApJS, 170, 39
Fitzpatrick, E. L., & Massa, D. 2007, ApJ, 663, 320
Hoang, T., & Lazarian, A. 2009, ApJ, 695, 1457
Hsu, J.-C., & Breger, M. 1982, ApJ, 262, 732
Kawabata, K. S., et al. 1999, PASP, 111, 898
Koornneef, J. 1983, A&A, 128, 84
Lazarian, A. 2007, J. Quant. Spectrosc. Radiat. Transfer, 106, 225
Lazarian, A., & Draine, B. T. 1999, ApJ, 516, L37
Lazarian, A., & Hoang, T. 2007, MNRAS, 378, 910
Lazarian, A., & Hoang, T. 2008, ApJ, 676, L25
Markkanen, T. 1977, A&A, 56, 83
Mathis, J. S. 1986, ApJ, 308, 281
Matsumura, M., & Bastien, P. 2009, ApJ, 697, 807
Matsumura, M., & Seki, M. 1991, Ap&SS, 176, 283
Matsumura, M., & Seki, M. 1996, ApJ, 456, 557
Matsumura, M., Seki, M., & Kawabata, K. S. 1998, in Proc. Pulsating Stars: Recent Developments in Theory and Observation, ed. M. Takeuchi & D. D. Sasselov (Tokyo: Universal Academy Press) 107
Matsumura, M., Seki, M., & Kawabata, K. S. 1999, AJ, 117, 429
Purcell, E. M. 1979, ApJ, 231, 404
Roberge, W. G., & Lazarian, A. 1999, MNRAS, 305, 615
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Seki, M., & Matsumura, M. 1996, ASP Conf. Ser., 97, 168
Serkowski, K., Mathewson, D. S., & Ford, V. L. 1975, ApJ, 196, 261
Voshchinnikov, N. V., & Das, H. K. 2008, J. Quant. Spectrosc. Radiat. Transfer, 109, 1527
Weitenbeck, A. J. 1999, Acta Astron., 49, 59
Weitenbeck, A. J. 2004, Acta Astron., 54, 87
Whittet, D. C. B., Gerakines, P. A., Hough, J. H., & Shenoy, S. S. 2001, ApJ, 547, 872
Whittet, D. C. B., Hough, J. H., Lazarian, A., & Hoang, T. 2008, ApJ, 674, 304
Whittet, D. C. B., & van Breda, I. G. 1980, MNRAS, 192, 467

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