POLARIZATION OF THERMAL EMISSION UNDER AN ANISTROPIC RADIATION

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ABSTRACT

Aspherical dust grains in an anisotropic radiation field have different temperatures depending on the cross-sections projected to the radiation. The temperature difference produces polarized thermal emission even without alignment, if the observer looks at the grains from a direction different from the anisotropic radiation. When the dust grains are aligned, the anisotropic radiation makes various affects on the polarization of the thermal emission, depending on the relative angle between the anisotropy and alignment directions. This paper presents examples of the effects and demonstrates the importance of anisotropic radiation field on the polarized thermal emission.

Key words: polarization; interstellar dust; infrared; alignment.

1. INTRODUCTION

Polarization observations in the far-infrared region have been revealed to be a quite efficient means for the investigation of magnetic fields in dense regions and thus for the study of structures in star-forming regions (e.g., Hildebrand 1988, Clemens and Kraemer 1999). There are, however, several factors which could affect the observed polarization and the spectral dependence, such as the different populations of grains with different temperatures, other than the maginetic field and grain alignment (Hildebrand et al. 1999). In this paper, another mechanism, the anisotropy of the incident radiation field, which is believed to occur commonly, is shown also to affect the polarization of thermal emission. The anisotropy of the radiation field may play an important role in the grain alignment (Draine and Weingartner 1996).

If the aspherical grains are immersed in an anisotropic radiation field, the grains with larger cross-sections projected in the direction of anisotropy are supposed to have higher temperatures than those with smaller cross-sections. The former grains emit the radiation polarized in the perpendicular direction to the incident radiation field, while the radiation from the latter grains is polarized in the parallel direction with the radiation field anisotropy, if one observes them from a direction different from the radiation direction. Thus because of the difference in temperature, the resultant thermal emission is polarized perpendicularly to the incident radiation.

Onaka (1995) (hereafter Paper I) has shown that this mechanism produces polarization of a detectable degree ($\sim 1\%$) around 100 μm even without any net alignment and a steep rise of the polarization degree at shorter wavelengths because of the nature of the mechanism. This paper presents the numerical results of several simple cases when aligned dust grains are immersed in an unidirectional radiation field and discusses the effects of anisotropic radiation on the polarized thermal emission.

2. BASIC CONFIGURATION

Figure 1 depicts the geometry adopted in this paper: The radiation field is assumed to be unidirectional and coming from +Z direction; The body axis of greatest inertia of the grain A is tilted from the Z axis by ψ; The angle between the alignment axis and the direction of the radiation is denoted by γ and is assumed to be in the Y-Z plane; The observer is located in the X-Z plane with the angle β from the X axis. In the following, β is set as zero (the observer is on the X axis) for simplicity.

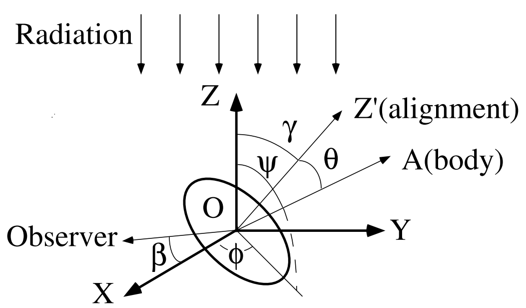

Figure 1. A schematic diagram of the assumed configuration. In the numerical calculations presented in this paper β is set as zero.

If the grains rotate suprathermally, the rotation timescale is very short, typically 10^{-7} to 10^{-9} s (Purcell 1979). The mean duration time of photon absorption in the interstellar radiation field (ISRF) is $1-10$ s for $0.01-0.1$ μm (Purcell 1976). It is much longer than the rotation timescale unless the grains are in the highly strong radiation field. The rotation axis aligns with the body axis A owing to the internal energy exchange, such as anelasticity or the Barnett effect (Purcell 1979). The timescale of change of the direction of rotation axis must be longer than the alignment timescale to make alignment possible. Thus even if the superparamagnetic damping is effective, the timescale of the rotation axis change is no shorter than 10^2 s. Therefore the grain is assumed to have a fixed rotation axis, which coincides with the body axis of greatest inertia, relative to the incident radiation and the temperature of the grain is given by a function of ψ.

The alignment distribution of the dust grains around the alignment axis is assumed to be given by

$$f(\theta)\ d\cos\theta = \frac{0.5\ q}{(\cos^2\theta + q\ \sin^2\theta)^{3/2}}\ d\cos\theta, \quad (1)$$

where q is a parameter of the alignment degree. When no alignment is established, q is equal to unity. For the Davis-Greenstein alignment, the distribution is given by Equation 1 and q is equal to T_g/T_{av}, where T_g is the gas temperature and T_{av} is the weighted mean of gas and dust temperatures (Jones and Spitzer 1967). It can be shown that Equation 1 still holds for the alignment by suprathermal rotation with q being equal to $\exp(2t_c/t_r)$, where t_c and t_r are the time from the last crossover and the magnetic timescale, respectively (Purcell 1979). Figure 2 plots the distributions given by Equation 1 with $q = 1$, 1.2, 1.5, and 2.0. It can be seen that the distribution is quite broad for this range of q and the alignment is far from being perfect.

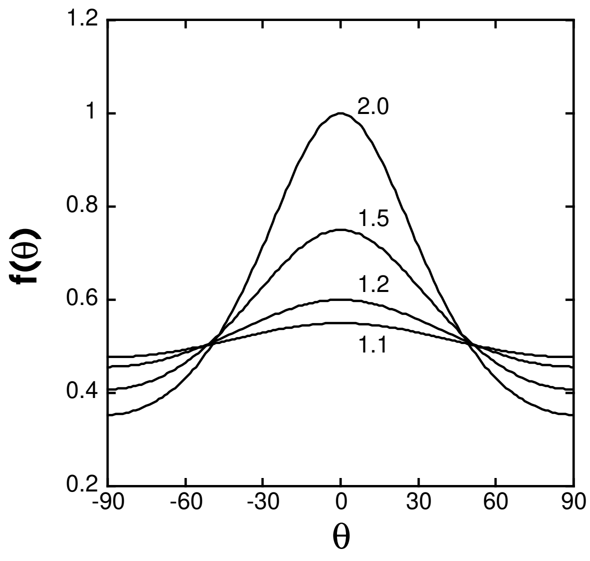

Figure 2. The alignment distribution function $f(\theta)$ given by Equation 1. The numbers indicate the values of alignment parameter q.

In the following calculations, the grains are assumed to be oblate silicate spheroids whose symmetry axis is 0.1 μm and axial ratio is 3. The optical properties are taken from those of astronomical silicate (Draine and Lee 1984) and the incident radiation is given by the ISRF of Mathis et al. (1983). The far-infrared emission is assumed to be optically thin. The absorption cross-sections of spheroid grains are calculated by the method developed by Onaka (1980). Details of the formulation have been given in Paper I.

3. NUMERICAL CALCULATIONS

The temperature of the grain is plotted against cosψ in Figure 3 for the parameters described in the previous section. The difference in temperature is quite small even for the oblate spheroid of axial ratio of 3. Thus the effect is expected to be small in the Rayleigh-Jeans tail of the thermal emission, and it becomes appreciable only for the shorter wavelength range than the emission peak (e.g., Paper I). In the following, three cases of the direction of alignment relative to the radiation direction are presented.

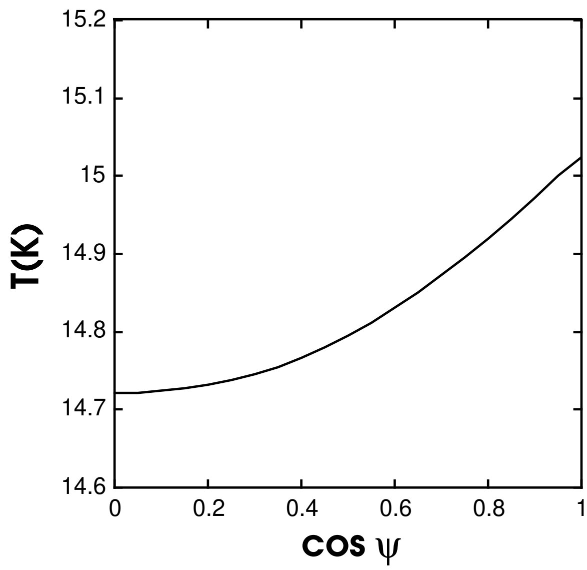

Figure 3. The temperature of oblate silicate spheroid with the axial ratio of 3 and the symmetry axis of 0.1 μm against cosine of the tilt angle ψ.

Figure 4 shows the spectral dependence of the polarization degree (left axis; solid lines) for $\gamma = 0°$ together with the emission spectrum (right axis; solid line labeled as flux). The results of isotropic radiation case are plotted together by dotted lines for comparison. As shown in Paper I, even without alignment ($q = 1$), thermal emission of the dust grains in an anisotropic radiation field is polarized and the polarization degree increases steeply as the wavelength becomes shorter. For the cases when the grains are aligned, the anisotropic radiation field increases the polarization degree appreciably at short wavelengths compared to the isotropic radiation case. The effect of anisotropic radiation field becomes appreciable (more than a few %) particularly for the wavelengths shorter than the thermal emission peak. This can easily be understood from the nature of the mechanism.

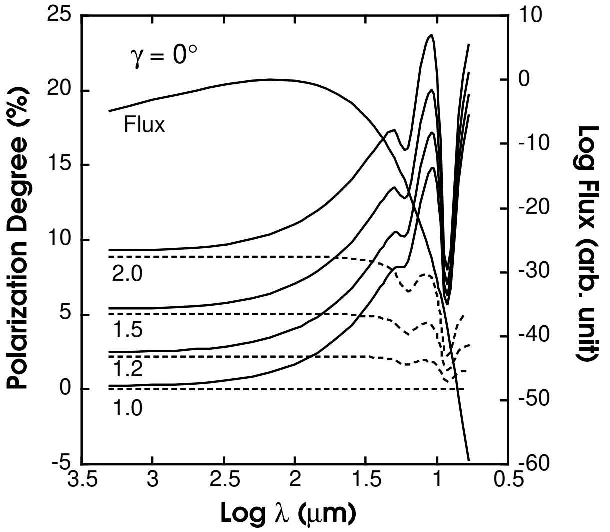

Figure 4. Spectral dependence of the polarization degree (left axis) for the case where the alignment axis is parallel with the radiation direction ($\gamma = 0°$) together with the emission spectrum (right axis in arbitrary units; curve labeled as flux). The dotted lines are the polarization degrees under isotropic radiation field and the solid lines are those under unidirectional radiation field. The numbers indicate the values of alignment parameter q.

When the alignment axis is perpendicular to the incident radiation direction, the polarization degree first decreases for the aligned grains as the wavelength becomes shorter (Figure 5). Then at some wavelength the polarization reversal occurs. In the calculation, the sign of the polarization degree is defined as positive if the emission is polarized in the Y axis. The reversal wavelength depends on the alignment degree, but is expected to be shorter than the emission peak.

If the alignment axis and the radiation direction is tilted by an arbitrary angle, further complicated effects are expected. Figures 6 and 7 show the results for $\gamma = 45°$. The spectral dependence of the polarization degree is similar to that for $\gamma = 0°$, while the polarization angle also changes with the wavelength (Figure 7). As expected the polarization angle is determined by the alignment direction for long wavelengths, but it tends to be perpendicular to the radiation direction as the wavelength becomes shorter.

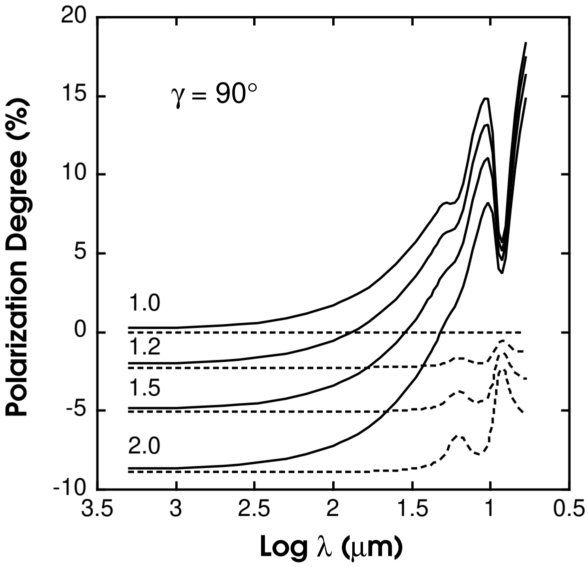

Figure 5. Spectral dependence of polarization degree for the case where the alignment axis is perpendicular to the radiation direction ($\gamma = 90°$). The symbols are the same as in Figure 4.

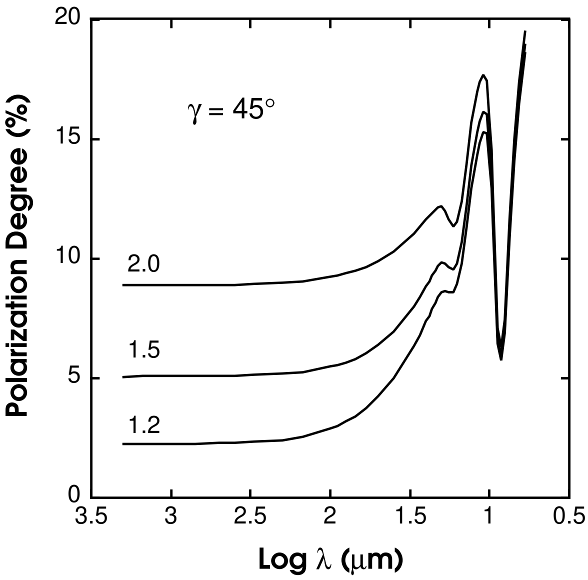

Figure 6. Spectral dependence of polarization degree for $\gamma = 45°$. The numbers indicate the values of alignment parameter q.

4. DISCUSSION AND CONCLUDING REMARKS

The anisotropic radiation field could make several effects on the polarization of the thermal emission from aligned aspherical dust grains. It could either increase or decrease the polarization degree, depending on the relative angle between the alignment axis and the incident radiation direction. It could further produce the spectral dependence of the polarization angle when the alignment axis is not parallel with the radiation direction. When the alignment is perpendicular to the radiation direction, the polarization reversal is expected. The effects become appreciable for short wavelengths in any cases.

Hildebrand et al. (1999) have presented the latest results of far-infrared polarization measurements and shown two particular cases of the spectral dependence of the polarization degree for $60 - 1300$ μm. In one case it increases as the wavelength decreases and in the other case it decreases sharply for short wavelengths. Hildebrand et al. (1999) attributed the ob-

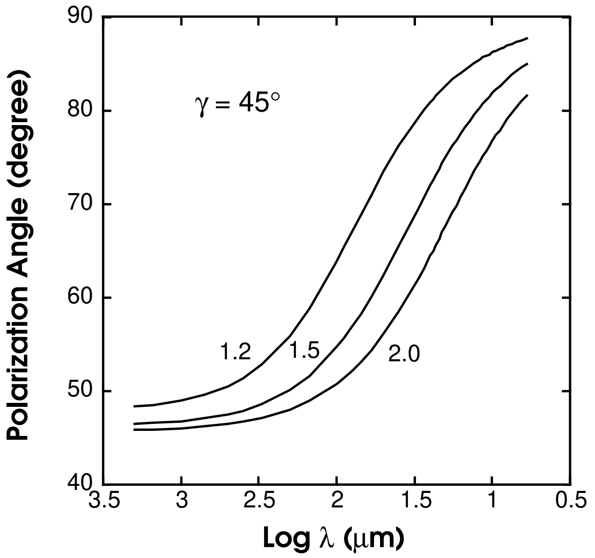

Figure 7. Spectral dependence of polarization angle for $\gamma = 45°$. The numbers indicate the values of alignment parameter q.

served dependence to two populations of grains that differ in their polarization efficiencies and in their temperatures due to the difference in their optical properties.

The mechanism proposed in the present paper also comes from the difference in the temperature of dust grains, but it originates from the anisotropy in the incident radiation field, which is not uncommon in most astronomical objects. Therefore it should not be neglected and could make a significant effect in the polarized thermal emission in some cases. It could either increase or decrease the polarization degree and make positive or negative spectral dependence as have actually been observed, depending on the configuration of the alignment and radiation field. The change in the polarization angle could also be expected by this mechanism.

The present study indicates that the effect on the polarization degree could be up to several percents. The observed polarization is in the same range (Hildebrand et al. 1999) and thus the effect of the anisotropic radiation field must be taken into account in the interpretation, particularly in the polarization shorter than 100 μm. We do not claim that the observed spectral dependence is solely attributed to this mechanism, but it should be making non-negligible contributions in some cases. On the other hand, this effect may be useful in the identification of the heating source for very obscured objects. The effect appears most severely at short wavelengths and the spectral observations of the polarization degree and angle in the thermal emission should be crucial for the investigation of this mechanism.

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