PROBING DUST IN THE ATMOSPHERE OF BROWN DWARFS THROUGH POLARIZATION

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ABSTRACT

The theoretical analysis and observational evidence indicate that a brown dwarf with an effective temperature greater than 1300 K would have a dust cloud in its atmosphere. In this Letter, we show that dust scattering should yield polarized continuum radiation from the relatively warm brown dwarfs and that the polarized flux profile could be a potential diagnostic tool for the physical properties of dust grains. The degree of polarization that is due to multiple scattering will be more in the optical region if the particle size is small, while significant polarization should be detected in the infrared region if the particle size is large. It is pointed out that the departure from sphericity in the shape of the object due to rapid rotation and due to the tidal effect by the companion in a binary system ensures that the disk-integrated polarization is nonzero.

Subject headings: polarization — radiative transfer — scattering — stars: atmospheres —
stars: low-mass, brown dwarfs

1. INTRODUCTION

The synthetic continuum spectra of the brown dwarf Gliese 229B has been obtained by several authors. Marley et al. (1996), Griffith, Yelle, & Marley (1998), and Saumon et al. (2000) obtained an overall good fit of the observed spectra of Gl 229B over a wide range of wavelengths and attributed the very rapid decline of the observed continuum flux in the optical region to the dust particulates in its atmosphere. On the other hand, Tinney et al. (1998), Kirkpatrick et al. (1999), Tsuji, Ohnaka, & Aoki (1999), and Burrows, Marley, & Sharp (2000) argued that the pressure-broadened red wing of the K I 0.77 μm doublet and the Na I D 0.5891, 0.5897 μm lines could account for the observed features of the continuum flux shortward of 1.1 μm (for a recent review, see Burrows et al. 2001). The first optical spectrum of the T dwarf SDSS 1624+0029 favors the latter explanation (Liebert et al. 2000), and at present there is enough evidence to show that dust particulates cannot exist in the visible atmospheres of comparatively cool T dwarfs such as Gl 229B. However, dust can be present at the visible height of the atmosphere of warmer brown dwarfs and L dwarfs with effective temperatures greater than 1300 K.

Very recently, Allard et al. (2001) presented a detailed theoretical investigation on the effects of dust in the atmospheres of brown dwarfs by considering two limiting cases: (1) the inefficient gravitational settling of dust grains and (2) the efficient gravitational settling of dust grains. In the former case the dust is distributed according to the chemical equilibrium predictions and provides the maximum impact on the atmosphere, while in the latter case the dust forms and depletes refractory elements from the gas, yielding a minimal effect on the brown dwarf atmosphere. When the effective temperature of the object is below 1300 K, the complete gravitational settling of dust grains should occur, whereas gravitational settling cannot occur when the effective temperature is above 1800 K. In the intermediate case ($T_{\mathrm{eff}} = 1400$ K), an optically thick dust cloud forms in the visible atmosphere (Marley & Ackerman 2001).

In this Letter, we show that significant polarization can arise because of dust scattering in the atmosphere of relatively warmer brown dwarfs where dust grains have not been settled completely. In the presence of dust particulates of small size, the continuum flux in the near-optical region could be polarized significantly, while nonzero polarization can occur in the in-

frared if the particle size is large. Hence, the observation of polarized radiation from brown dwarfs could be a potential probe for the properties of dust grains.

2. NONSPHERICITY OF RAPIDLY ROTATING BROWN DWARFS AND INTRINSIC POLARIZATION BY DUST SCATTERING

The polarization of radiation that is due to scattering in stellar atmospheres or envelopes has been considered by many authors. Numerous polarimetric data and their interpretations have been presented by Gehrels (1974). Since a noticeable deviation from sphericity is to be expected from rapidly rotating stars, much attention has been paid to calculations of the intrinsic polarization of Be stars. The degree of polarization varying from 0.1% in the visible region to 2% in the far-infrared has been observed in Be stars by Rucinski (1970), Collins (1970, 1972), Harrington & Collins (1968), and Haisch & Cassinelli (1976). Extensive observational data for the polarization from cool stars are given by Serkowski (1966, 1970). It has been established by many observations that the intrinsic polarization of radiation is a common behavior for most young stars (see, e.g., Menard & Bastien 1992, Yudin & Evans 1998, Yudin 2000, and references therein).

The observation of nonzero polarization from unresolved objects indicates the nonsphericity of the stars. The nonsphericity of an object, which leads to an incomplete cancellation of the polarization of radiation from different areas of the surface, may result from several causes. The rotation of a stellar object imparts to it the shape of an oblate ellipsoid. This is evident in the outer solar planets as well. The eccentricities of Jupiter, Saturn, and Uranus are 0.35, 0.43, and 0.21, respectively, at a 1 bar pressure level. The tidal interaction with the companion in a binary system imposes an ellipsoidal shape that is extended toward the companion.

Spectroscopic studies by Basri (1999) indicate the rapid rotation of brown dwarfs along their axes. A general trend toward higher velocities as one looks to objects of lower luminosity is found in this study. The brown dwarf Kelu 1 is found to be the fastest rotator, having a projected angular velocity $v \sin i$ as high as 80 km s^{-1} corresponding to an angular velocity of 1.16×10^{-3} s^{-1}. The surface gravity of a brown dwarf varies from 10^5 to 3×10^5 cm s^{-2}, implying a mass range from 36

to 73 $M_{\rm J}$ (Marley et al. 1996). As a consequence, a fast-rotating brown dwarf will have a significant departure from sphericity.

The maximum possible oblateness of a stable rotating fluid body having a polytropic equation of state with different indices has been derived by Chandrasekhar (1933). The relation between the eccentricity e and the rotational velocity ω for a rigidly rotating body (Maclaurine spheroid) with uniform density is given by

$$\omega = \left\{ 2\pi G \rho \left[\frac{(1-e^2)^{1/2}}{e^3} (3 - 2e^2) \sin^{-1} e - \frac{3}{e^2} (1 - e^2) \right] \right\}^{1/2},$$

(1)

where ρ is the density of the fluid. Here the eccentricity is defined as $e = (1 - r_p^2/r_e^2)^{1/2}$, where r_p and r_e are the polar and equatorial radius, respectively. The eccentricity e and the oblateness q are related by the expression $e^2 = 1 - (1 - q)^2$.

Adopting the empirical relationship given in Marley et al. (1996) for the mass and radius of a brown dwarf, the mean density of a brown dwarf with $g = 10^5$ cm s^{-2} and $T_{\rm eff} = 1500$ K would be 51 g cm^{-3}. For $\omega = 1.16 \times 10^{-3}$ s^{-1}, the above formula yields $e = 0.48$. However, in reality, the density is not uniform, and the above formula yields a slightly higher value of e compared with the same for a nonuniform density distribution, which can be verified by applying to the case of Jupiter, Saturn, and Uranus. Nevertheless, the rapid rotation of brown dwarfs would certainly impose a deviation from sphericity in its shape, and hence the disk-integrated polarization will not be canceled out.

The dependence of the polarization that is due to a single scattering by grains on the oblateness of an object has been discussed by Dolginov, Gnedin, & Silant'ev (1995) and by Simmons (1982). Following Simmons (1982), the analytical expression (a first-order approximation) for the degree of polarization due to single scattering from a spheroid with uniform density can be written as

$$p = \lambda^2 (R_1 - R_2) n_0 K_2 \left(\frac{5}{96\pi} \right)^{1/2} P_2^2 \cos (i) \exp (-2i\phi) F_{22},$$

(2)

where F_{22} depends on the scattering phase function, R_1 and R_2 are the outer and inner equatorial axis lengths, respectively, n_0 is the particle number density, P_2^2 is the associated Legendre polynomial of order 2, and λ is the wavelength. The expression for K_2 depends on the density distribution and hence on the eccentricity of the spheroid. The values of F_{22} for different values of $x = 2\pi a/\lambda$, with a being the radius of the scattering particle, as well as the expression for K_2 are given in Simmons (1982). The first-order approximation is valid when $x \leq 2$. We have calculated the degree of polarization as a function of eccentricity e by considering Mie scattering. Figure 1 presents the degree of polarization as a function of eccentricity viewed edge-on, i.e., when $i = \pi/2$ and $\phi = 0$.

Figure 1 shows that the qualitative feature of polarization does not change with the change in the eccentricity. This is found by Simmons (1982) as well. Polarization increases with the increase in the eccentricity. For $x \geq 2$, the change in the degree of polarization is small. For all the values of x, the variation in polarization is not too high when e varies from 0.2 to 0.4. In our calculation, we have taken $n_0 a^2 = 100$. The choice is arbitrary since the main purpose of Figure 1 is to
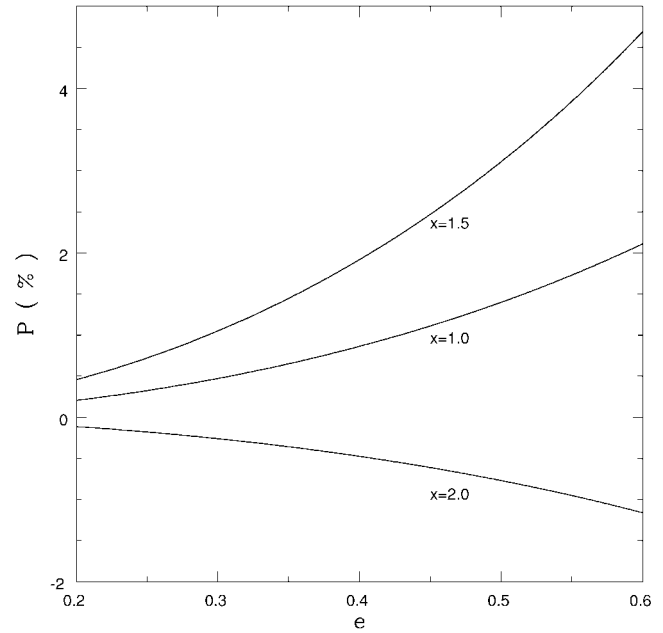

Fig. 1.—Degree of polarization as a function of eccentricity for different values of $x = 2\pi a/\lambda$. Single scattering on a spherical grain in an oblate spheroid with uniform density is considered.

show the effect of eccentricity on the degree of polarization. In the realistic case, the density must be nonuniform, and the polarization would occur because of multiple scattering. Therefore, one has to solve the equations for the transfer of polarized radiation with the incorporation of the Mie theory of scattering.

3. TRANSFER EQUATIONS FOR POLARIZED RADIATION

The Stokes parameters representing a linearly polarized beam are given by $I = I_l + I_r$ and $Q = I_l - I_r$, where I_l and I_r represent two mutually orthogonal states of linear polarization. The degree of polarization is given by $p = Q/I$.

For a plane-parallel atmosphere, the equation of transfer can be written as (Chandrasekhar 1960)

$$\mu \frac{d\boldsymbol{I}(\tau, \mu)}{d\tau} = \boldsymbol{I}(\tau, \mu) - \frac{\omega_0}{2} \int_{-1}^{1} \boldsymbol{P}(\mu, \mu') \boldsymbol{I}(\tau, \mu') d\mu', \quad (3)$$

where

$$\boldsymbol{I}(\tau, \mu) = \begin{bmatrix} I_l(\tau, \mu) \\ I_r(\tau, \mu) \end{bmatrix},$$

μ is the cosine of the angle made by the ray to the normal, τ is the optical depth, ω_0 is the albedo for single scattering, and $\boldsymbol{P}(\mu, \mu')$ is the azimuth-independent phase matrix.

4. THE ATMOSPHERE MODEL

The values of the effective temperature $T_{\rm eff}$ and the surface gravity g of a brown dwarf are constrained by the bolometric luminosity and the evolutionary sequence of the object (Saumon et al. 1996). In the present Letter, we have adopted a model atmosphere with $T_{\rm eff} = 1500$ K, $\log g = 5.0$, and [M/H] $= -0.3$ (K band). The temperature-pressure profile for a model with $\log g = 5.0$ and $T_{\rm eff} = 1030$ K has kindly been provided by M. Marley (1999, private communication), and the opacity data have be provided by D. Saumon. Using an

iterative process for temperature correction, we have obtained the temperature profile for $T_{\rm eff} = 1500$ K. In this process, we have used the temperature profile for $T_{\rm eff} = 1030$ K as the initial temperature profile. We have ignored any change in the density profile with the increase in the temperature. We have incorporated the dust opacity by using the Mie theory of scattering. Following Griffith et al. (1998) and Marley & Ackerman (2001), we have considered a lognormal spherical particle size distribution. The mean radius of the silicate grain (the real part of the refractive index 1.65) has been considered as 0.1 and 1.0 μm. Although it is difficult to infer the grain sizes by direct observation, the atmospheres of the outer solar planets indicate that the mean radius of the grains is expected to be as high as 10–100 μm (Marley & Ackerman 2001). However, in the present investigation, we have considered smaller particles since the effect of particle size on the degree of polarization can well be visualized without going for a larger particle size.

5. RESULTS AND DISCUSSION

We solve the transfer equations for the polarized radiation by using discretization method. The numerical procedure is described in detail by Sengupta (1993).

In the absence of a magnetic field, a radiation field could be polarized only by scattering. The extent of scattering is determined by the albedo ω_0, and the angular distribution of the scattered photon is governed by the phase function. The albedo for single scattering is defined as $\omega_0 = (\sigma_{\rm R} + \sigma_{\rm M})/\chi_\nu$, where $\sigma_{\rm R}$ and $\sigma_{\rm M}$ are the cross sections for the Rayleigh and the Mie scattering, respectively, and χ_ν is the total extinction coefficient. While the Rayleigh phase function is symmetric in the sense that the amount of backward and forward scattering are the same, the Mie phase function is asymmetric. The larger the size of the dust particulate, the greater the effect of the Mie scattering.

When there are dust clouds at or above the photosphere, the albedo is high. Conversely, when clouds are absent, the albedo in a mostly absorbing atmosphere is low (Burrows et al. 2001). As a consequence, in the atmosphere of a cool brown dwarf such as Gl 229B, the contribution of scattering is negligible, and so there will be no polarization. If the mean particle size is small, say, 0.1 μm, the albedo beyond the near-infrared is zero since the Mie scattering cross section goes over to that of the Rayleigh and since the scattering cross section of various molecules present in the atmosphere is negligibly small or zero. Therefore, scattering polarization can arise only up to the optical and near-infrared region where the contribution of the scattering cross section to the total extinction coefficient is significant. It should be mentioned that grains of small size cannot contribute significantly to the opacities in the near-infrared where water bands still dominate the spectra of brown dwarfs from the J band to the K band. On the other hand, if we consider a larger particle size, then scattering will contribute to the far-infrared region as well.

The degree of polarization due to multiple scattering is presented in Figure 2. Here we notice that the degree of polarization is almost zero at 1.34 μm and onward when the mean particle size is 0.1 μm. Shortward of 1.3 μm, the degree of polarization increases. This is because scattering is negligible at wavelengths greater than 1.3 μm. As the wavelength decreases, the effect of dust scattering increases. As a consequence, the radiation field gets polarized because of scattering, and the degree of polarization increases with the decrease in the wavelength. The degree of polarization always remains negative.
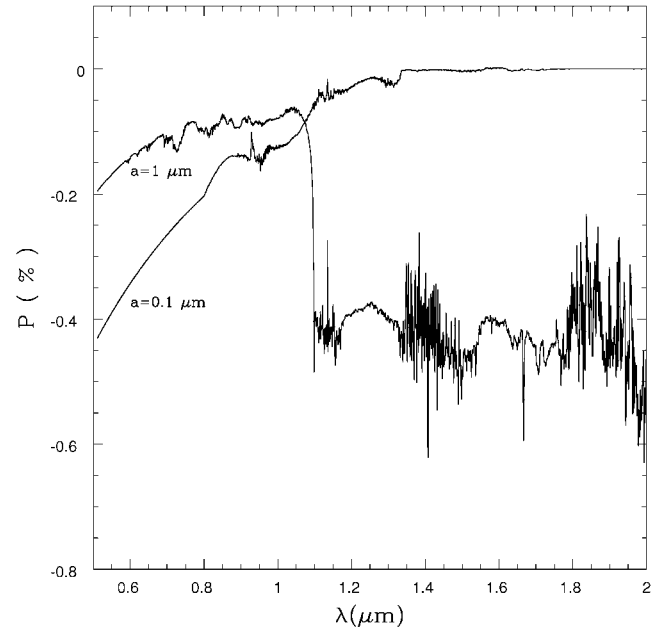

Fig. 2.—Degree of polarization by multiple scattering

If we consider dust particles with a larger mean radius, say, 1 μm, then most of the flux gets blocked in the optical region. As a result, the degree of polarization decreases significantly in the optical region. However, when the size of the particle is comparable to the wavelength, the degree of polarization increases significantly. Figure 2 shows that the degree of polarization decreases in the optical region if the particle size is comparatively large. In the infrared and far-infrared, the degree of polarization increases if the grain size is increased. It is worth mentioning that multiple scattering decreases the degree of polarization as compared with that of single scattering.

6. CONCLUSION

The important message that is conveyed in this Letter is that the continuum radiation from the atmosphere of relatively warm brown dwarfs, where the dust particulates are not gravitationally settled, should be polarized; this polarized radiation could provide a lot of information on the properties of dust particulates. Since no polarization will occur in the absence of dust grains, the observation of polarized radiation will also help in deciding if a particular brown dwarf contains dust in its atmosphere. Rapid rotation would impose nonsphericity in the shape of brown dwarfs. As a result, a net nonzero polarization integrated over the stellar disk should be obtained. The results strongly suggest that the polarimetric observations possess a great diagnostic potential for the understanding of the properties of dust particulates. Furthermore, if no polarization is observed from any particular brown dwarf, then that will indicate the absence of dust in its atmosphere.

REFERENCES

Allard, F., Hauschildt, P. H., Alexander, D. R., Tamanai, A., & Schweitzer, A. 2001, ApJ, 556, 357
Basri, G. 1999, BAAS, 194, 82.08
Burrows, A., Hubbard, W. B., Lunine, J. I., & Liebert, J. 2001, preprint
Burrows, A., Marley, M. S., & Sharp, C. 2000, ApJ, 531, 438
Chandrasekhar, S. 1933, MNRAS, 93, 390
———. 1960, Radiative Transfer (New York: Dover)
Collins, G. W., II. 1970, ApJ, 159, 583
———. 1972, ApJ, 175, 147
Dolginov, A. Z., Gnedin, Yu. N., & Silant'ev, N. A. 1995, Propagation and Polarization of Radiation in Cosmic Media (Basel: Gordon & Breach)
Gehrels, T., ed. 1974, Planets, Stars, and Nebulae Studied with Photopolarimetry (Tucson: Univ. Arizona Press)
Griffith, C. A., Yelle, R. A., & Marley, M. S. 1998, Science, 282, 2063
Haisch, B. M., & Cassinelli, J. P. 1976, ApJ, 208, 253
Harrington, J. P., & Collins, G. W., II. 1968, ApJ, 151, 1051
Kirkpatrick, J. D., Allard, F., Bida, T., Zuckerman, B., Becklin, E. E., Chabrier, G., & Baraffe, I. 1999, ApJ, 519, 834

Liebert, J., Reid, I. N., Burrows, A., Burgasser, A. J., Kirkpatrick, J. D., & Gizis, E. 2000, ApJ, 533, L155
Marley, M. S., & Ackerman, A. S. 2001, preprint (astro-ph/0103269)
Marley, M., Saumon, D., Guillot, T., Freedman, R., Hubbard, W. B., Burrows, A., & Lunine, J. I. 1996, Science, 272, 1919
Menard, F., & Bastien, P. 1992, AJ, 103, 564
Rucinski, S. M. 1970, Acta Astron., 20, 1
Saumon, D., Geballe, T. R., Leggett, S. K., Marley, M. S., Freedman, R. S., Lodders, K., Fegley, B., Jr., & Sengupta, S. K. 2000, ApJ, 541, 374
Saumon, D., Hubbard, W. D., Burrows, A., Guillot, T., Lunine, J. I., & Chabrier, G. 1996, ApJ, 460, 993
Sengupta, S. 1993, MNRAS, 265, 513
Serkowski, K. 1966, ApJ, 144, 857
———. 1970, ApJ, 160, 1107
Simmons, J. F. L. 1982, MNRAS, 200, 91
Tinney, C. G., Delfosse, X., Forveille, T., & Allard, F. 1998, A&A, 338, 1066
Tsuji, T., Ohnaka, K., & Aoki, W. 1999, ApJ, 520, L119
Yudin, R. V. 2000, A&AS, 144, 285
Yudin, R. V., & Evans, A. 1998, A&AS, 131, 401