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EXPLAINING THE OBSERVED POLARIZATION FROM BROWN DWARFS BY SINGLE DUST SCATTERING

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ABSTRACT

Recent observation of linear optical polarization from brown dwarfs confirms the dust hypothesis in the atmospheres of brown dwarfs with effective temperature higher than 1400 K. The observed polarization could arise because of dust scattering in the rotation induced oblate photosphere or because of the scattering by nonspherical grains in the spherical atmosphere or by the anisotropic distribution of dust clouds. Assuming single scattering by spherical grains in a slightly oblate photosphere consistent with the projected rotational velocity, the observed optical linear polarization is modeled by taking grains of different sizes located at different pressure height and of different number density. Minimum possible oblateness of the object due to rotation is considered in order to constrain the grain size. It is shown that the observed polarization from the L dwarfs 2MASSW J0036+1821 and DENIS-P J0255−4700 can be well explained by several sets of dust parameters and with the minimum possible oblateness. Models for the observed polarization constrain the maximum size of grains. It is emphasized that future observation of polarization at the blue region will further constrain the grain size.

Subject headings: dust, extinction — polarization — scattering — stars: atmospheres — stars: low-mass, brown dwarfs

1. INTRODUCTION

During the last few years, a large population of L dwarfs covering a range of effective temperature between 2200 and 1400 K has been discovered by several observers (Martin et al. 1997; Kirpatrick et al. 1999). These objects are characterized by the presence of condensates in their atmosphere. Theoretical studies (Allard et al. 2001; Marley & Ackerman 2001) reveal that when the effective temperature of the object is below 1300 K, grains are predominantly formed beyond the visible region of the atmosphere because of complete gravitational settling. At higher effective temperatures, however, grains are present in the visible atmosphere because of incomplete gravitational settling.

Sengupta & Krishan (2001) argued that detectable polarization could arise because of dust scattering in the atmosphere of L dwarfs, where dust grains should be present in the visible region. 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 infrared as well if the particle size is large. The fast rotation of the objects (Basri et al. 2000) imparts to it the shape of an oblate ellipsoid, and the nonsphericity of the object should lead to incomplete cancellation of the polarization of radiation from different areas of the surface. Very recently, detection of linear polarization at 768 nm from a few L dwarfs has been reported (Menard, Delfosse, & Monin 2002) that confirms dust scattering in the atmosphere of these objects.

In the present Letter, I show that single scattering (Mie scattering) by spherical grains in a slightly oblate photosphere can account the observed degree of polarization. Observational data for two L dwarfs 2MASSW J0036+1821 and DENIS-P J0255−4700 are considered from which maximum polarization is detected. It is shown that the detected degree of polarization can be well explained with several sets of dust parameters and the minimum possible oblateness due to rotation. An upper limit on the grain size is discussed on the basis of the analysis of the observed polarization.

2. ESTIMATION OF THE OBLATENESS DUE TO ROTATION

Spectroscopic studies by Basri (1999) and Basri et al. (2000) indicate rapid rotation of brown dwarfs along their axis. A general trend to higher velocities as one looks to objects of lower luminosity is found in this study. The projected angular velocity $v \sin i$ for 2MASSW J0036+1821 and DENIS-P J0255−4700 is determined to be 15.0 km s^{-1} (Schweitzer et al. 2001) and 40 ± 10 km s^{-1} (Basri et al. 2000), respectively, corresponding to an angular velocity of 2.2×10^{-4} and 5.8×10^{-4} s^{-1}, respectively.

The oblateness of a rotating object has been discussed by Chandrasekhar (1933) in the context of polytropic gas configuration and by Hubbard (1984) in the context of solar planets. For slow rotation, the first-order approximation provides the relationship for the oblateness q of a stable polytropic gas configuration under hydrostatic equilibrium with mass M and equatorial radius r_e rotating with an angular velocity ω as

$$q = \frac{2}{3} C \frac{\omega^2 r_e^3}{GM}, \qquad (1)$$

where C is a constant whose value depends on the polytropic index. For the polytropic index $n = 0$, the density is uniform and the configuration is known as a Maclaurin spheroid. In this case, $C = 1.875$. For nonrelativistic completely degenerate gas, $n = 1.5$ and $C = 0.9669$.

The L dwarfs, DENIS-P J0255−4700 and 2MASSW J0036+1821, belong to the spectral types L8 (Kirkpatrick et al. 2000) and L3.5 (Reid et al. 2000), respectively. Therefore, the effective temperature of these two L dwarfs are approximately 1420 and 1870 K, respectively (Stephens et al. 2001). The surface gravity, g, of brown dwarfs varies from 10^5 to 3×10^5 cm s^{-2} (Saumon et al. 1996). Adopting the empirical relationship given in Marley et al. (1996), the mass and radius of the two L dwarfs can be approximated for different values of g. Hence, by using equation (1), the oblateness q of DENIS-P J0255−4700 can be estimated as $q = 0.03$ and 0.008 when $g = 10^5$ and 3×10^5 cm s^{-2}, respectively, for $n = 0$ (Maclaurin spheroid). For $n = 1.5$ (nonrelativistic completely degenerate gas), $q = 0.0154$ and 0.0042 when $g = 10^5$ and 3×10^5 cm s^{-2}, respectively. Similarly, the oblateness of 2MASSW J0036+1821 can be calculated as $q = 0.0043$ and 0.0012 for $n = 0$ and $q = 0.0023$ and 0.0006 for $n = 1.5$ when $g = 10^5$ and 3×10^5 cm s^{-2}, respectively

It is not possible to infer the actual oblateness from direct observation of brown dwarfs. The oblateness decreases as the polytropic index n increases. Since the density distribution in brown dwarfs does not follow polytropic gas law, the exact estimation of the oblateness is not possible. Hubbard (1984) showed that $n = 1$ is appropriate for Jupiter. However, $n > 1.5$ may not be appropriate for brown dwarfs, as it yields much higher pressure. Further, the atmosphere of brown dwarfs extends even up to 0.005 bar pressure level, whereas in the analysis of Hubbard (1984), the oblateness at 1 bar pressure level is considered in order to estimate the polytropic index. Therefore, the values for q with $n = 1.5$ and $g = 3 \times 10^5$ cm s^{-2} can well be considered as the lowest possible values for the oblateness of the two objects discussed here.

3. POLARIZATION FROM OBLATE PHOTOSPHERE BY SINGLE SCATTERING

The dependence of polarization due to single scattering by grains on the oblateness of an object has been discussed by Dolginov, Gnedin, & Silant'ev (1995) and by Simmons (1982). I follow the formalism given by Simmons (1982). For an optically thin medium, the total polarization $p(k)$ can be written as

$$p(k) = |Z(k)| = |Z^*(k)|, \tag{2}$$

where

$$Z(k) = \frac{1}{k^2} \int\int\int \frac{i_1(\theta, k) - i_2(\theta, k)}{2} n(r, \theta, \phi) \exp(2i\phi)\, d\omega\, dr. \tag{3}$$

Here, $k = 2\pi/\lambda$, θ is the scattering angle, $d\omega$ is the element of solid angle, n is the particle number density, and the asterisk denotes the complex conjugate. In addition, i_1 and i_2 are the scattering functions as defined by van de Hulst (1957).

If the density distribution function is reasonably smooth, then we can write

$$n(r, \theta, \phi) = \sum_{l=0}^{\infty} \sum_{m=-l}^{m=l} n_{lm}(r) Y_{lm}(\theta, \phi), \tag{4}$$

where P_l^m is the associated Legendre function of the first kind and the function $Y_{lm}(\theta, \phi)$ is given in Simmons (1982).

Substituting equation (4) for equation (3) and integrating over ϕ, we get

$$p(k) = \frac{2\pi}{k^2} \sum_{l=2}^{\infty} N_{l2} F_{l2}, \tag{5}$$

where

$$F_{lm} = \alpha(l, m) \int_{-1}^{1} \frac{i_1 - i_2}{2} P_l^m(\cos\theta)\, d(\cos\theta) \tag{6}$$

and $\alpha^2(l, m) = (2l + 1)(l - m)!/4\pi(l + m)!$. Considering axisymmetry density distribution with a rotational invariance around some axis (see Simmons 1982) and using the addition theorem of spherical harmonic, N_{lm} can be written as

$$N_{lm} = 2\pi\alpha(l, m) P_l^m(\cos i) \exp(-2i\phi) \int_{R_2}^{R_1} n(r)\, dr \times \int_{-1}^{1} \frac{P_l(\mu) d\mu}{[1 + (A^2 - 1)\mu^2]^{1/2}}, \tag{7}$$

where R_1 and R_2 are the outer and inner equatorial axis lengths, A is the ratio of the length of the equatorial axis to the polar axis, and $\mu = \cos\theta$.

When viewed edge-on, $i = \pi/2$ and $\phi = 0$, and hence N_{lm} is real. We convert $n(r)\, dr$ into $n(P)\, dP$ by using the hydrostatic equation where P is the pressure at different heights of the atmosphere. Therefore, assuming an edge-on viewing angle, we can write by using equation (5) the degree of polarization as

$$p(k) = \frac{4\pi^2}{k^2 g} \int_{P_1}^{P_2} \frac{n(P)\, dP}{\rho(P)} \sum_{l=2}^{\infty} \left\{ \alpha(l, m) P_l^m(0) F_{l2}(k) \times \int_{-1}^{1} \frac{P_l(\mu)}{[1 + (A^2 - 1)\mu^2]^{1/2}}\, d\mu \right\}, \tag{8}$$

where g is the surface gravity assumed to be constant, as the medium is sufficiently thin and $F_{lm}(k)$ is given by equation (6). We calculate the integrals in the above equation numerically. We employed the pressure-density profiles appropriate for the two L dwarfs with $g = 10^5$ and 3×10^5 cm s^{-2}. The opacity data are kindly provided by D. Saumon, and the atmospheric opacity sources are discussed in Saumon et al. (2000). Also, F_{lm} is calculated numerically by first deriving the Mie scattering functions $i_1(\theta)$ and $i_2(\theta)$ for a given particle size distribution and wavelengths. Since polarization due to small as well as large grains has to be investigated, I have included contributions to polarization by multipoles, $l = 2$, 4, and 6.

4. THE DUST PARAMETERS

Extensive theoretical studies have been done (Allard et al. 2001; Ackerman & Marley 2001; Burrows et al. 2001) that enlighten formation, size distribution, and density distribution of dust particulates in the atmosphere of brown dwarfs. However, there is no way to decide the most suitable set of grain parameters out of the vast parameter space. The amount and vertical location of dust should be a function of $T_{\rm eff}$ (Allard et al. 2001), whereas the presence of large grains has been predicted by Ackerman & Marley (2001) and Cooper et al. (2003).

Following Saumon et al. (2000), I have taken a simple vertical density profile of the condensate as

$$n_d = AP, \tag{9}$$

where n_d is the number density of condensed particles, P is the ambient gas pressure, A is a constant, and the cloud layer is bound by $P_1 < P < P_2$. The size distribution of particles is given by

$$f(d) = \frac{d}{d_0} \exp\left[\frac{\ln(d/d_0)}{\ln\sigma}\right]^2, \tag{10}$$

TABLE 1
Grain Parameters for DENIS-P J0255−4700

Number	q	d_0 (μm)	A (cm^{-3} bar^{-1})	P_1 (bar)
1	0.0042	0.2	910.0	0.05
2	0.0042	1.0	82.3	0.05
3	0.0042	2.0	65.0	54.55
4	0.0042	8.0	65.0	78.02

TABLE 2
Grain Parameters for 2MASSW J0036+1821

Number	q	d_0 (μm)	A (cm^{-3} bar^{-1})	P_1 (bar)
1	0.0023	0.2	750.0	0.05
2	0.0006	2.0	895.0	0.05
3	0.0006	8.0	73.3	0.05
4	0.0006	30.0	77.0	75.0

where d is the diameter of the particles and d_0 is the mean diameter. Dust can form far below the visible atmosphere, and there is suggestion that dust may even form in the convective zone (Helling et al. 2001). Spectroscopic analysis indicates that beyond about 70–100 bar pressure level, the atmosphere becomes invisible. Therefore, I set the base of the dust cloud at a pressure level $P_2 = 80$ bar. The real part of the refractive index is taken as 1.65, and the parameter σ is fixed at 1.3. In order to constrain the size of the dust particulates, I have adopted the minimum possible oblateness obtained by adopting $g = 3 \times 10^5$ cm s^{-2} and the polytropic index $n = 1.5$. The representative sets of dust parameters that fit the observed polarization from the two objects are presented in Tables 1 and 2.

5. RESULTS AND DISCUSSION

At present, there is no clear evidence of magnetic field in L dwarfs. As pointed out by Menard et al. (2002), it is very much unlikely that the observed intrinsic linear polarization in the optical arises because of Zeeman splitting of atomic or molecular lines or because of synchrotron emission. Dust scattering remains the most probable cause for the polarization from L dwarfs. There could be more than one way through which the continuum radiation from L dwarfs would be polarized. The simplest case is scattering by spherical grains in a rotationally induced oblate photosphere wherein the disk integrated polarization will not be canceled out. The next possibility is scattering by nonspherical grains in a perfectly spherical or nonspherical photosphere. Other possibilities include random distribution of the condensates and the presence of dust bands. Since the two L dwarfs have relatively high rotational velocity, the photospheric disk cannot be perfectly spherical. On the other hand, a combination of all the possibilities would result in polarization much higher than that observed. Therefore, I investigate the simplest possibility, i.e., dust scattering by spherical grains in an oblate photosphere. This helps to constrain the dust size. The polarization profiles that fit the observed data are presented in Figure 1.

The L dwarf 2MASSW J0036+1821 shows maximum polarization of 0.199% among all the candidates observed by Menard et al. (2000) at 0.768 μm. The degree of polarization observed from DENIS-P J0255−4700 at 0.768 μm is 0.167%. The associated error is 0.028% and 0.04%, respectively. Now, for the same rotational velocity, the oblateness increases with the decrease in surface gravity. As a consequence, the degree of polarization is higher for objects with comparatively lower surface gravity. Further, the integrated dust number density is higher for lower surface gravity, yielding a further increase in polarization. Therefore, keeping the same dust parameters, a lower value of polarization can be obtained by increasing the surface gravity of the object. Hence, with the same dust parameters, the least amount of polarization is produced if the surface gravity is taken to be 3×10^5 cm s^{-2}, as the surface gravity of brown dwarfs varies from 10^5 to 3×10^5 cm s^{-2} (Saumon et al. 1996). This helps to decide the maximum grain size that is allowed by the observed polarization.

Figure 1 shows that the maximum change in the polarization profile occurs when the mean grain diameter is increased from 0.2 to 1 μm. The degree of polarization peaks near the blue if the grain size is very small, whereas it remains almost the same in the optical region if the grain size is large. Therefore, if future observation of the same objects detects higher polarization at blue than at red, then that will imply the presence of small dust grains. The oblateness of 2MASSW J0031+1821 should be larger than the minimum possible value in order to yield the observed polarization by scattering due to small particulates. Obviously, the larger the grain size, the less number of particulates should be present. Thus, the degree of polarization serves to constrain the size of grains present in the atmosphere of brown dwarfs. It is found that if the mean diameter of grains exceeds about 10 μm, then the observed polarization from DENIS-P J0255−4700 cannot be explained by single scattering with spherical dust particulates. However, 2MASSW J0036+1821 can accommodate larger particles, as its minimum possible oblateness is less than that of DENIS-P J0255−4700 owing to low rotational velocity. In reality, the oblateness could be much higher than its minimum possible value because of the nonpolytropic density distribution and less surface gravity of the objects. Therefore, the present investigation indicates that the grain size is unlikely to exceed a few tens of micron. Figure 1 also shows that the degree of polarization changes significantly with the change in the values of

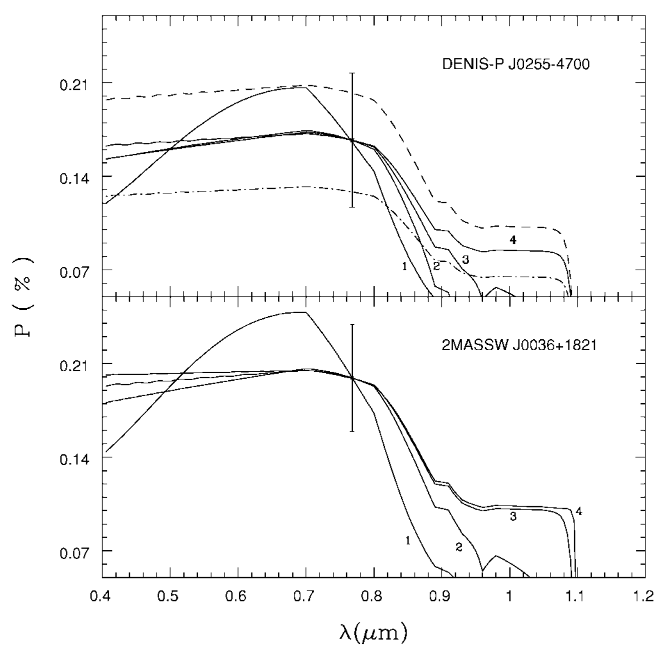

Fig. 1.—Degree of polarization as a function of wavelength for the two L dwarfs. The numbers associated with each curve represent the set of grain parameters given in Tables 1 and 2. The dashed line represents model 4 for DENIS-P J0255−4700 but with $P_1 = 77.6$ bar. The dot-dashed line represents model 4 for the same object but with $A = 50.0$ cm^{-3} bar^{-1}. The observed polarization is at 0.768 μm.

any parameter, e.g., the vertical height or the number density of grains. Therefore, the multiwavelength observation of polarization from the same object will rule out some of the models, providing a better idea of the dust properties and distribution.

In the present investigation, single dust scattering is considered. For the earliest type L dwarfs, single scattering approximation is reasonable, but multiple scattering could be important for the late-type L dwarfs. Multiple scattering usually lowers the degree of polarization substantially (Sengupta & Krishan 2001), because the planes of the scattering events are randomly oriented and average each other's contribution out from the emergent polarization. The degree of polarization in the optical increases slightly if the grain size is increased from 0.1 to 1 μm. Therefore, in order to obtain the observed values of the degree of polarization by multiple dust scattering, not only are very large grains needed, but the number density of grains also must be very high. Since the number density of grains should not exceed the mass of the heavy elements, multiple scattering may not give rise to sufficient amount of polarization unless the oblateness is high. However, the effect of multiple scattering with large grains is worth investigating, as it will provide information on the contribution of molecular absorption as well to the polarization profile.

6. CONCLUSION

Observation of polarization and its theoretical analysis serve as a potential tool to understand the properties of condensates in the atmosphere of brown dwarfs. In addition to that, it provides important information on the geometrical asymmetry of the photosphere. The important message that is conveyed in this Letter is that the observation of polarized radiation can very well constrain the grain size. Modeling of the observed polarization from two L dwarfs indicates that the mean diameter of grains is unlikely to exceed a few tens of microns. Also, the surface gravity of the objects plays a crucial role in determining the degree of polarization. Lower surface gravity yields higher asymmetry in the photospheric disk as well as a higher number of dust particulates. Both help in increasing the degree of polarization significantly. Therefore, if the surface gravity of brown dwarfs is less, large grains cannot be accommodated in the atmosphere. The oblateness of the object is constrained by the observed rotational velocity. Single dust scattering is consistent with the available knowledge on the oblateness and grain size of brown dwarfs. Since multiple scattering yields much less polarization, larger grain size with greater number density and greater oblateness are needed to account the observed polarization. Observation of variable polarization should indicate randomly distributed dust cloud. Further observation of polarization at different wavelengths will provide significant information on the grain properties in the atmosphere of brown dwarfs.

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