CLOUDY ATMOSPHERE OF THE EXTRASOLAR PLANET HD 189733b: A POSSIBLE EXPLANATION OF THE DETECTED B-BAND POLARIZATION

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ABSTRACT

The peak amplitude of linear polarization detected recently from an extrasolar hot giant planet, HD 189733b, is a few \( \times 10^{-4} \), more than an order of magnitude higher than all theoretical predictions. Although Rayleigh scattering off H\(_2\) and He may give rise to a planet-star flux ratio of the order of \( 10^{-4} \) in the blue band, it cannot account for the high polarization unless the planet has an unusually extended atmosphere. Therefore, it is suggested that the high polarization should be attributed to the presence of a thin cloud of submicron size dust grains in the upper visible atmosphere which supports the observational finding of an almost featureless transmission spectrum in the optical with no indication of the expected alkaline absorption features. It is found that the polarimetry observation allows for a small eccentricity of the orbit that is predicted from the time delay of the secondary eclipse of the planet. The estimated longitude of the ascending node is \( 16^\circ \pm 6^\circ \) which interestingly coincides with the observationally inferred location of the peak hemisphere-integrated brightness.

Subject headings: planetary systems — polarization — scattering — stars: individual (HD 189733)

1. INTRODUCTION

Polarization has always been an efficient tool to probe the physical properties in the environment of various astrophysical objects. Sengupta & Krishan (2001) predicted a detectable amount of linear polarization from L dwarfs because of the presence of condensates in the visible atmosphere. Subsequently, linear polarization attributed to dust scattering (Sengupta 2003; Sengupta & Kwok 2005) has been detected in several brown dwarfs (Menard et al. 2002; Zapatero Osorio et al. 2005) whose atmospheres resemble those of irradiated extrasolar planets, the “hot Jupiters.” The use of polarimetry in detecting and understanding the physical properties of extrasolar planets, especially the close-in planets or the so-called roaster such as the first discovered extrasolar planet 51 Peg b (Mayor & Queloz 1995), is emphasized by Seager et al. (2000), Saar & Seager (2003), and Sengupta & Maiti (2006).

Recently, Berdyugina et al. (2008) have reported detection of linear polarization in the blue band from one of the well-studied hot Jupiters, HD 189733b (Bouchy et al. 2005). If the observation is correct, then it should have several important implications for our understanding of the physical processes of the planetary atmosphere. The observed peak amplitude of polarization is about \( 10^{-4} \) implying the B-band flux ratio of the planet and the star to be more than 1 order of magnitude higher than that predicted by current theoretical models (Showman et al. 2008; Burrows et al. 2007; Barman et al. 2001). In order to model and interpret the observed polarization, Berdyugina et al. (2008) have assumed the planet as a Lambert sphere of perfectly reflecting surface. A Lambert sphere follows Lambert’s law of diffuse reflection. On this law the diffusely reflected light is isotropic in the outward hemisphere and is natural, independently of the state of polarization and the angle of incident light (Chandrasekhar 1960, p. 147). That a Lambert sphere of perfectly reflecting surface yields zero polarization is also shown by Stam et al. (2006). Consequently, the model fit and the inference by Berdyugina et al. (2008) that the observed polarization implies that the planet has an abnormally large scattering radius of 1.5–1.7 \( R_J \) is unphysical.

In the present Letter, I show that single scattering of photons by submicron size grains in a thin layer of silicate cloud in the upper atmosphere of HD 189733b may explain the observed polarization. I discuss the polarization model in the next section. The cloud model adopted is discussed in § 3. The results are discussed in § 4 and specific conclusions are made in § 5.

2. THEORETICAL MODEL

The state of polarization of light is described by the Stokes parameters, \( i, q, u, \) and \( v \). The parameter \( i \) is the total scalar specific intensity of radiation. It is the complete flux of radiant energy inside the unit intervals of frequency, time, solid angle, and area perpendicular to the flux. This flux includes all radiation independently on polarization. Polarization is described by the parameters \( q, u, v \). These parameters are proportional to the scalar specific intensity and have the same dimension. For linear polarization, \( v = 0 \). On the other hand, in a plane-parallel scattering medium, \( u \) is zero (Chandrasekhar 1960). The amount of polarization is defined by the ratio of the polarized intensities and the total intensity. For an unresolved extrasolar planet, the total intensity is the sum of the total reflected intensity and the unpolarized stellar intensity. Here, I define the polarization as the normalized Stokes parameters \( Q \) and \( U \) in a scattering reference plane through the centers of the star, the planet, and the observer. The reference plane can be transformed to another one by using the Mueller rotation matrix (Chandrasekhar 1960). Since the reflected intensity is negligible as compared to the stellar intensity, my normalization is with respect to the stellar intensity only. The Stokes parameters are integrated over the planetary disk. I assume single scattering which simplifies the model calculations. Since the dust density is presumed to be low and scattering by atoms and molecules does not contribute to polarization significantly, the single-scattering approximation is reasonable for the region where the optical depth \( \tau < 1 \). In the present model, we incorporate a sufficiently thin cloud layer located between 0.2 and 0.1 bar of pressure level (see § 3). If present, multiple scattering can reduce the degree of polarization by a few orders of magnitude (Sengupta & Krishan 2001) because the planes

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of the scattering events are randomly oriented and average each other’s contribution out from the final polarization. The model, described in detail in Sengupta & Maiti (2006), is based on the formalism given in Simmons (1983). In a circular orbit, the normalized Stokes parameter $Q$ and $U$ are given as a harmonic series:

$$Q(k, i, \Lambda) = \sum_{m=0}^{\infty} [p_m(k, i) \cos m\Lambda + q_m(k, i) \sin m\Lambda], \quad (1)$$

$$U(k, i, \Lambda) = \sum_{m=0}^{\infty} [u_m(k, i) \cos m\Lambda + v_m(k, i) \sin m\Lambda], \quad (2)$$

where $k = 2\pi/\lambda$, $\lambda$ being the wavelength, $i$ the orbital inclination angle, and $\Lambda$ the orbital phase angle. The harmonic coefficients are given by

$$p_m = \frac{2\pi}{k^2} \sum_{l=m}^{\infty} F_2(k)G_m(l)(\eta_{lm}), \quad m = 0, 1, 2, 3, \ldots , \quad (3)$$

$$u_m = \frac{2\pi}{k^2} \sum_{l=m}^{\infty} F_2(k)H_m(l)(-\xi_{lm}), \quad m = 0, 1, 2, 3, \ldots , \quad (4)$$

$M = \max (2, m)$ and $G_m(l), H_m(l)$ are given in Simmons (1983). Here $\eta_{lm}$ and $\xi_{lm}$ are related with the density distribution in the corotating frame and are given by

$$\eta_{lm} = \left[\frac{(2l+1)(l-m)}{4\pi(l+m)}\right]^{1/2}$$

$$\times \int n=n(r, \theta, \phi)P^m(\cos \theta) \left(\cos \frac{m\phi}{\sin \frac{m\phi}{\sin \frac{m\phi}}\sin \theta d\theta d\phi dr, \quad (5)$$

where $n(r, \theta, \phi)$ is the number density of scatterer in the corotating frame, $\theta$ is the viewing angle, and $P^m$ is the associated Legendre function of the first kind. $F_2(k)$ is related to the scattering function and is given in Simmons (1983) and Sengupta & Maiti (2006). The effect of the optical properties and the shape and size of dust grains are incorporated through this function. In the present work we consider spherical dust particles as scatterers.

I assume an ellipsoidal distribution of scatterers illuminated by an unpolarized and pointlike light source such that

$$\eta_{lm} = \frac{2\pi}{4\pi(l+m)}$$

$$\times \int P^m(0) \int_{R_1}^{R_3} n(r) dr \int_{12}^{1} \frac{P(\mu)d\mu}{[1 + (A^2 - 1)\mu^2]^{1/2}}, \quad (6)$$

where $R_1$ and $R_2$ are the outer and the inner equatorial length of the oblate planetary atmosphere, $A$ is the ratio of the length of the equatorial axis to the polar axis such that the oblateness $f = 1 - 1/A$, and $\mu = \cos \theta$. Multipoles up to $l = 5$ and up to the fifth harmonic, i.e., $m = 0, 1, 2, 3, 4, 5$, are taken.

If the light source is assumed to be pointlike, the incident specific intensity from the star becomes distance independent. Hence, the amount of polarization or the normalized Stokes parameters $Q$ and $U$ becomes distance independent and I calculate them directly assuming spherical scatterers. It is worth mentioning here that the model does not calculate the reflected flux from the planet but it estimates the amount of polarization from the unresolved system as seen edge-on at an inclination $i = 90^\circ$ so that $\xi_{lm} = 0$ in equation (5). However, the distribution and physical properties of scatterers depends on the orbital separation and on the amount of the stellar flux. The observables $Q$ and $U$ are obtained by rotating the scattering reference plane by an angle $\Omega$, the longitude of the ascending node of the planet.

For a slow rotator, the relationship for the oblateness $f$ of a stable polytropic gas configuration under hydrostatic equilibrium is given by Chandrasekhar (1933) as

$$f = 2C_0^2 R_0^4/(3GM),$$

where $M$ is the total mass, $R_0$ is the equatorial radius, and $\Omega$ is the angular velocity of the object. $C$ is a constant whose value depends on the polytropic index. For a polytropic index of $n = 1.0$, $C = 1.1399$, which is appropriate for Jupiter (Hubbard 1984). Barnes & Fortney (2003) modeled the planet HD 209458b and estimated its oblateness to be about 0.00285 whereas the polytropic approximation yields a value of 0.00296. Considering that HD 189733b is tidally locked with its parent star, we estimate its spin-induced oblateness to be about 0.003 by taking the orbital period of 2.218 days (Bouchy et al. 2005; Bakos et al. 2006; Winn et al. 2007), radius 1.15 $R_0$, surface gravity 1995.0 cm s$^{-2}$, and by assuming a polytropic equation of state with the polytropic index $n = 1$ for the density distribution of the entire planet.

3. DUST DISTRIBUTION AND LOCATION

The dust distribution in the atmosphere is calculated based on the one-dimensional cloud model of Cooper et al. (2003). The number density of cloud particles is given by

$$n(P) = 3\rho_0 \mu_0/(4\pi r^3 \mu_0^2)$$

where $\rho$ is the mass density of the surrounding gas, $r$ is the cloud particle radius, $\rho_0$ is the mass density of the dust condensates, and $\mu$ and $\mu_0$ are the mean molecular weight of atmospheric gas and condensates, respectively. The condensate mixing number ratio ($q_\alpha$) is given as $q_\alpha = q_{\text{below}} P_\text{below}/P$ for heterogeneously condensing clouds where $q_{\text{below}}$ is the fraction of condensable vapor just below the cloud base, $P_\text{below}$ is the pressure at the condensation point, and $P$ is the gas pressure in the atmosphere. Given the equilibrium temperature of HD 189733b, condensates, if formed, should be dominated by silicates in the form of forsterite or silicate oxide as is the case for L dwarfs of similar effective temperature (Helling et al. 2008). The values of $\mu_\alpha$, $P_\text{above}$, and $q_{\text{below}}$ for forsterite are taken from Cooper et al. (2003). I have adopted the dust-free temperature-pressure profile of HD 189733b with the day-night heat distribution parameter $P_\text{above} = 0.3$ (Burrows et al. 2007). This is kindly provided by Adam Burrows (private communication). The location of the cloud base for different atmospheric models and different chemical species is determined by the intersection of the T-P profile of the atmosphere model and the condensation curve $P_\text{below}$, as prescribed in Cooper et al. (2003). Taking the condensation curve for forsterite as given in Sudarsky et al. (2003) we determine the base of the cloud from the T-P profiles of HD 189733b to be at 0.2 bar of pressure height. I consider the deck of the cloud at 0.1 bar pressure level. This makes the cloud sufficiently thin so that single scattering by dust grains is favored.
and disk-integrated Stokes HD 189733b. The polarization of HD 189733b expressed as the normalized fit of the observed polarimetric data by assuming a perfectly albedo. However, the conclusion for TrES-3 may not be applicable to other planets, and in particular to HD 189733b. In fact, Pont et al. (2008) have reported an almost featureless transmission spectrum between 550 and 1050 nm with no indication of the expected alkaline absorption features which suggests the presence of a haze of submicron particles in the upper atmosphere of HD 189733b. Analysis of the transit spectrum by Lecavelier des Etangs et al. (2008) also favors the presence of condensates with submicron-size grains in the atmosphere of HD 189733b. Burrows et al. (2008) have found that a high star-to-planet flux ratio in the blue is possible due to Rayleigh scattering off H₂ and He. Although this explains a high geometric albedo implied by the observed polarization, it cannot explain the peak amplitude of the polarization itself unless the scattering radius is much larger than that inferred from transit observation.

Absorption in the stellar Lyα line observed during the transit of the extrasolar planet HD 209458b by Vidal Madjar et al. (2003) revealed high-velocity atomic hydrogen at great distances from the planet. This is interpreted by Vidal Madjar et al. (2004) as hydrogen atoms escaping from an extended atmosphere of the planet that is possibly undergoing hydrodynamic blow-off. This interpretation, however, has failed to get theoretical support (Hubbard et al. 2007) and has led to controversy (Ben Jaffel 2007; also see Vidal-Madjar et al. 2008). Recently, Holmstrom et al. (2008) have provided a viable alternative interpretation of the measured transit-associated Lyα absorption as the interaction between the esosphere of HD 209458b and the stellar wind. These authors suggest a slow and hot stellar wind near the planet at the time of observation. This interpretation is consistent with the energetic neutral atoms around solar system planets that is observed to form from charge exchange between solar wind protons and neutral hydrogen from the planetary exospheres. Under such situation and in the absence of any signature obtained by any other method, it would highly be premature to consider an extended exosphere of HD 189733b in order to explain the observed polarimetric data.

The rebinned polarization data shows negative value of Q at all phase angles. Because of the large error bars in U, I choose the value of U corresponding to the maximum value of Q and find that $\frac{U}{Q} = 0.63 \pm 0.3$. Hence, for a small value of U in the scattering reference plane, the longitude of the ascending node $\Omega$ can be estimated to be $16^\circ \pm 6^\circ$. Coincidentally, the observation of HD 189733b over half an orbital period indicates (Knutson et al. 2007) the peak hemisphere-integrated brightness occurs $16^\circ \pm 6^\circ$ before opposition. A similar type of observation along with the polarimetry data for other planets may decide if there is any correlation. Taking the inclination angle $i = 85.76^\circ$ as determined by the transit method (Winn et al. 2007), I obtain the best fit by setting $\Omega = 20^\circ$ and the modal grain diameter $d_g = 0.8 \mu m$. The theoretical model along with the observed data is presented in Figure 1. Since the inclination angle of the planet is nearly 90°, polarization is zero at the transit ($\Delta = 180^\circ$) and at the secondary eclipse ($\Delta = 0^\circ$). These are the positions when the planet’s night and day sides are turned toward the observer. The polarization peaks near $\Delta = 90^\circ$ because polarization of light that is singly scattered is the largest for a scattering angle $\pi - \Delta = 90^\circ$ and in a sufficiently thin medium, single scattering is favored over multiple scattering. In a noncircular orbit, the peak polarization shifts toward the longitude of pericenter $\omega$ (Sengupta & Maiti 2006). The observed data for Q allows an eccentricity as high as $e = 0.06$ so that $e \cos \omega = 0.001$ for $\omega = 89^\circ$ which is consistent with the time delay of the secondary eclipse (Knutson et al. 2007). However, a more strin-

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**Fig. 1.**—Best-fit models of the observed linear polarization at B band of HD 189733b. The polarization of HD 189733b expressed as the normalized and disk-integrated Stokes $Q$ (a) and $U$ (b) for circular orbit (blue) and for elliptical orbit (red) with eccentricity 0.06 and the longitude of pericenter at 89°. The observed data, rebinned for equal phase intervals, are presented by error bars (green). $Q$ and $U$ are on the scale of $10^{-4}$.

**4. RESULTS AND DISCUSSIONS**

As mentioned in § 1, Berdyugina et al. (2008) obtained a fit of the observed polarimetric data by assuming a perfectly reflecting Lambert sphere with the radius as large as 1.5–1.7 $R_p$. While a Lambert sphere does not yield any polarization, the argument in favor of an unusually large Rayleigh scattering exosphere is somewhat premature at this stage. Taking the scattering radius to be the same as the optical radius measured through transit photometry, the geometric albedo as implied by the polarization is larger than $2/3$ which is the geometric albedo of a Lambert sphere of perfectly reflecting surface. This may not be impossible as some solar system objects have geometric albedo exceeding unity due to strong back-scattering. However, Berdyugina et al. (2008) interpreted the polarization by considering smaller albedo but an abnormally large planetary radius. Recent observation of the exoplanet TrES-3 by Winn et al. (2008) does not support such interpretation. These authors find upper limits on the planet’s geometric albedo in the i, z, and R bands as 0.30, 0.62, and 1.07, respectively. Thus they rule out the presence of highly reflective clouds in the atmosphere of TrES-3. It is worth mentioning that the geometric albedo and the degree of polarization are two distinct physical quantities. The geometric albedo is calculated from the ratio of the incident starlight to the sum of the isotropic and anisotropic components of the emergent radiation from the planet. On the other hand, the degree of polarization from an unresolved planet is the ratio of the emergent anisotropic radiation from the planet to the star light. While albedo is always non-zero, polarization could be zero if there is no anisotropy in the emergent planetary radiation. Therefore, the photometric study by Winn et al. (2008) implies that the degree of polarization of TrES-3 should be very small although it can have high albedo. However, the conclusion for TrES-3 may not be applicable to other planets, and in particular to HD 189733b.
gent limit is needed for $e \sin \omega$ in order to constrain the eccentricity (Winn et al. 2007). Contrary to the claim (Berdyugina et al. 2008) that the orbital inclination angle greater than 90° can be detected through polarization, I do not find any change in the polarization profile if the inclination is taken to be 90° + $i$. At small values of $x = 2\pi r / \lambda$ and the oblateness, the higher harmonic coefficients of the Stokes parameters are expected to be negligible as compared to the second one for Mie scattering. The ratio of the second harmonic coefficients is equal to $(1 + \cos 2\pi r / \lambda) / 2 \cos i$ and hence Fourier transformation of more accurately measured polarization data may provide the inclination angle of any extrasolar planet, transits as well as nontransits.

Unlike the case of brown dwarfs which need nonspherical photosphere to make incomplete cancellation of polarization when integrated over the disk, a perfectly spherical planet can yield nonzero polarization because the illumination of the planetary surface by the starlight does not cover the entire disk except when the planetary phase angle is 0° or 180°. The rotation-induced oblateness or tidal distortion of the planetary disk introduces additional asymmetry which increases the amount of polarization. For a nonspherical planetary disk, the shape of the planet could also affect the time variation of the polarization. However, as estimated in § 2, the rotation-induced oblateness of the tidally locked planet HD 189733b is too small to yield any significant effect on the polarization profile as compared to the case of a perfectly spherical geometry. In fact, the estimated oblateness of the planet increases the polarization by about twice its value calculated by considering spherical geometry. Therefore, the observed high peak amplitude of polarization cannot be achieved by considering only the nonspherical photosphere. Consequently, the presence of dust in the photosphere of the planet becomes essential in order to explain the observed polarization. Finally, it remains to be verified if the inclusion of forsterite-dominated thin cloud can give rise to a flux ratio of about $10^{-4}$ in the blue band.

5. CONCLUSION

The relatively high peak amplitude of the detected polarization and the large 1 σ errors in the data make the reported polarization tentative and it remains to be confirmed by further polarimetric observations with more accuracy. Until then, any interpretation of the observation is only speculative. However, if confirmed, the reported polarization would indicate the presence of highly reflecting species in the uppermost atmosphere of HD 189733b that makes the B-band albedo much higher than the present theoretical estimation. Although Rayleigh scattering of H and He may make the flux ratio of the planet and the star to reach the required order of magnitude ($10^{-4}$), it is unlikely that Rayleigh scattering would give rise to a sufficient amount of polarization unless an unusually large radius of the planet is assumed. On the other hand, recent observation (Pont et al. 2008) of an almost featureless transmission spectrum between 550 and 1050 nm with no indication of the expected alkaline absorption features suggests the presence of a haze of submicron particles in the upper atmosphere of HD 189733b. The important message conveyed by the present work is that the detected high amount of polarization from HD 189733b, if correct, strongly supports the presence of a thin cloud layer with submicron size grains in the visible atmosphere of the planet.

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