Cloudy Atmosphere of the Extra-solar Planet HD189733b : 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 of 10^{-4}, more than an order of magnitude higher than all theoretical predictions. Rayleigh scattering off H_2 and He may although 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 sub-micron size dust grains in the upper visible atmosphere which supports the observational finding of an almost feature-less 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 $16^o \pm 6$ which interestingly coincides with the observationally inferred location of the peak hemisphere-integrated brightness.

Subject headings: polarization – scattering – planetary systems – 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 detectable amount of linear polarization from L dwarfs because of the presence of condensates in the

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visible atmosphere. Subsequently, linear polarization attributed to dust scattering (Sengupta 2003; Sengupta & Kwok 2005) has been detected in several brown dwarfs (Menard, Delfosse & Monin 2002; Zapatero Osorio, Caballero & Bejar 2005) whose atmospheres resemble those of irradiated extrasolar planets, the 'Hot Jupiters'. The use of polarimetry in detecting and understanding the physical properties of extra-solar planets, especially the close-in-planets or the so called roaster such as the first discovered extra-solar planet 51 Peg b (Mayor & Queloz 1995), is emphasized by Seager, Whitney & Sasselov (2000); Saar & Seager (2003); 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 Jupiter' HD 189733b (Bouchy et al. 2005). If the observation is correct, then it should have several important implications to 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 one order of magnitude higher than that predicted by current theroetical models (Showman et al. 2008; Burrows et al. 2007; Barman, Hauschildt & Allard 2001). In order to model and interpreate 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 polariation 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 sub-micron 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 section 3. The results are discussed in the fourth section and specific conclusions are made in the last section.

2. Theroetical Model

The state of polarization of light is described by the Stoke 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 centres 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 simplify the model calculations. Since the dust density is presumed to be low and scattering by atoms and molecules does not contribute to polarization significantly, 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 section 3). If present, multiple scattering can reduce the degree of polarization by a few orders of magnitude (Sengupta & Krishan 2001) because the planes of the scattering events are randomly oriented and average each other's contribution out from the final polarization. The model, described in details 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 :

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

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

where $k = 2\pi/\lambda$, λ being the wavelength, i is the orbital inclination angle and Λ is the orbital phase angle. The harmonic co-efficients are given by

$$\begin{pmatrix} p_m \\ q_m \end{pmatrix} = \frac{2\pi}{k^2} \sum_{l=M}^{\infty} F_{l2}(k) G_m^l(i) \begin{pmatrix} \eta_{lm} \\ \xi_{lm} \end{pmatrix}, m = 0, 1, 2, 3, \cdots \tag{3}$$

$$\begin{pmatrix} u_m \\ v_m \end{pmatrix} = \frac{2\pi}{k^2} \sum_{l=M}^{\infty} F_{l2}(k) H_m^l(i) \begin{pmatrix} -\xi_{lm} \\ \eta_{lm} \end{pmatrix}, m = 0, 1, 2, 3, \cdots \tag{4}$$

$M = max(2, m)$ and $G_m^l(i)$, $H_m^l(i)$ are given in Simmons (1983). η_{lm} and ξ_{lm} are related with the density distribution in the co-rotating frame and are given by

$$\begin{pmatrix} \eta_{lm} \\ \xi_{lm} \end{pmatrix} = \left[\frac{(2l + 1)(l - m)}{4\pi(l + m)} \right]^{1/2} \int n'(r, \theta, \phi) P_l^m(\cos \theta_i) \begin{pmatrix} \cos m\phi \\ sinm\phi \end{pmatrix} \sin \theta d\theta d\phi dr. \tag{5}$$

where $n'(r, \theta, \phi)$ is the number density of scatterer in the co-rotating frame, θ_i is the viewing angle and P_l^m is the associated Legendre function of the first kind. $F_{l2}(k)$ is related to the scattering function and is given in Simmons (1983); Sengupta & Maiti (2006). The effect of the optical properties, the shape and size of dust grains are incoporated through this function. In the present work we consider spherical dust particles as scatterer.

I assume an ellipsoidal distribution of scatterers illuminated by an unpolarized and point-like light source such that

$$\eta_{lm} = 2\pi \left[\frac{(2l+1)(l-m)}{4\pi(l+m)} \right]^{1/2} P_l^m(0) \int_{R_2}^{R_1} n(r)dr \int_{-1}^{1} \frac{P_l(\mu)d\mu}{[1 + (A^2 - 1)\mu^2]^{1/2}}, \tag{6}$$

where R_1 and R_2 are the outer and the inner equatorial axis 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 $\mu = \cos\theta$. Multi-poles up to l=5 and up to fifth harmonic, i.e., m=0,1,2,3,4,5 are taken.

If the light source is assumed to be point-like, 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's 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 inclinatioin $i = 90^o$ so that $\xi_{lm} = 0$ in equation 5. However, the distribution and physical properties of scatterers depend on the thermal structure of the planetary atmosphere which is dependent on the orbital separation and on the amount of the stellar flux. The observable Q and U are obtained by rotating the scattering reference plane by an angle Ω, 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 $f = 2C\Omega^2 R_e^3/(3GM)$, where M is the total mass, R_e is the equatorial radius and Ω 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 HD209458b and estimated its oblateness to be about 0.00285 whereas the polytropic approximation yields a value of 0.00296. Considering 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 $1.15R_J$, surface gravity 1995.0 cms^{-2} and 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 $n(P) = 3q_c\rho\mu_d/(4\pi r^3\mu\rho_d)$ where ρ is the mass density of the surrounding gas, r is the cloud particle radius, ρ_d is the mass density of the dust condensates, μ and μ_d are the mean molecular weight of atmospheric gas and condensates respectively. The condensate mixing number ratio (q_c) is given as $q_c = q_{below}P_{c,l}/P$ for heterogeneously condensing clouds where q_{below} is the fraction of condensible vapor just below the cloud base, $P_{c,l}$ 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 it is the case for L dwarfs of similar effective temperature (Helling, Woitke & Thi 2008). The values of μ_d, ρ_d and q_{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 $P_n = 0.3$ (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 $P_{c,l}$ 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.

4.   Results and Discussions

As mentioned in section 1, Berdyugina et al. (2008) obtained a fit of the observed polarimetric data by assumeing a perfectly reflecting Lambert sphere with the radius as large as 1.5-1.7 R_J. While a Lambert sphere does not yield any polarization, the argument in favour 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) interpreated 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. 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 sub-micron particles in the upper atmosphere of HD 189733b. Burrows, Ibgui & Hubeny (2008) have found that a high star-to-planet flux ratio in the blue is possible due to Rayleigh scattering off H_2 and He. This although 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 infered from transit observation.

Absorption in the stellar Lyman α 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 interpreated 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, fails to get theoretical support (Hubbard et al. 2007) and lead to controversy (Ben Jaffel 2007). Recently, Holmstrom et al. (2008) have provided a viable alternative interpretation of the measured transit-associated Lyman alpha absorption as the interaction between the exosphere 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 re-binned 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 $U/Q = 0.63 \pm 0.3$. Hence, for a small value of U in the scattering reference

plane, the longitude of the ascending node Ω can be estimated to be $16^o \pm 6$. Coincidentally, the observation of HD189733b over half an orbital period indicates (Knutson et al. 2007) the peak hemisphere-integrated brightness to occur $16^o \pm 6$ before opposition. Similar type of observation along with the polarimetry data for other planets may decide if there is any correlation. Taking the inclination angle $i = 85^o.76$ as determined by transit method (Winn et al. 2007), I obtain the best fit by setting $\Omega = 20^o$ and the modal grain diameter $d_0 = 0.8\mu m$. The theoretical model alongwith the observed data is presented in figure 1. Since the inclination angle of the planet is nearly 90°, polarization is zero at the transit ($\Lambda = 180^o$) and at the secondary eclipse ($\Lambda = 0^o$). These are the positions when the planet's night and day sides are turned towards the observer. The polarization peaks near $\Lambda = 90^o$ because polarization of light that is singly scattered is the largest for a scattering angle $\pi - \Lambda = 90^o$ and in a sufficiently thin medium, single scattering is favoured over multiple scattering. In a non-circular orbit, the peak polarization shifts towards the longitude of pericentre ω (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 $\omega = 89^o$ which is consistent with the time delay of the secondary eclipse (Knutson et al. 2007). However, more stringent 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 $90^o + i$. At small values of x 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 $(1 + \cos 2i)/2 \cos i$ and hence Fourier transformation of more accurately measured polarization data may provide the inclination angle of any extrasolar planet, transits as well as non-transits.

Unlike the case of Brown Dwarfs which needs nonspherical photosphere to make incomplete cancellation of polarization when integrated over the disk, a perfectly spherical planet can yield non-zero 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 distrotion of the planetary disk introduces additional asymmetry which increases the amount of polarization. For a non-spherical planetary disk, the shape of the planet could also affect the time variation of the polarization. However, as estimated in section 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 comapred 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 non-spherical 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 $1 - \sigma$ errors in the data makes 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. Rayleigh scattering of H_2 and He may although 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 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 sub-micron 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 sub-micron size grains in the visible atmosphere of the planet.

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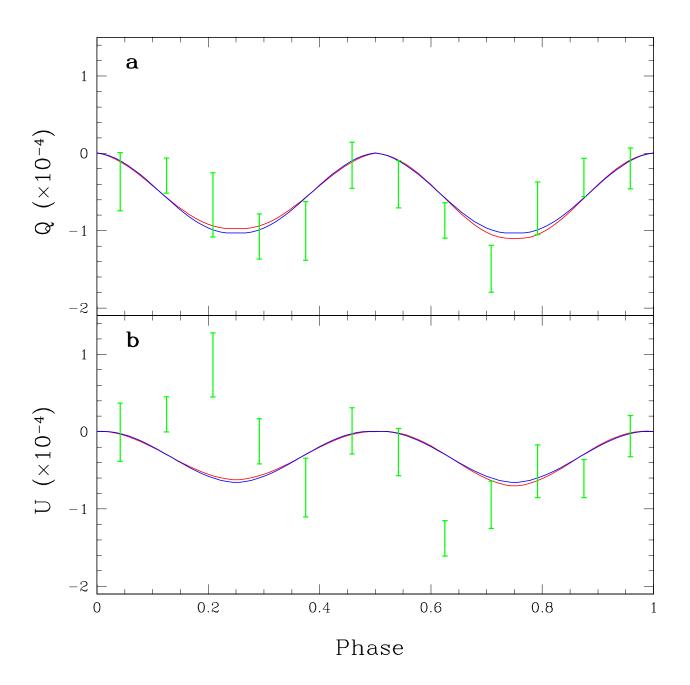
Fig. 1.— Best-fit models of the observed linear polarization at B-band of HD 189733b. The polarization of HD 189733b expressed as the normalized and disk integrated Stokes Q (panel a) and U (panel b) for circular orbit (blue) and for elliptical orbit (red) with eccentricity 0.06 and the longitude of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