J. Astrophys. Astr. (2013) **34**, 151–155

Spectro-Polarimetry of Self-Luminous Extrasolar Planets

Sujan Sengupta
Indian Institute of Astrophysics, Koramangala, 2nd Block, Bangalore 560 034, India.
e-mail: sujan@iiap.res.in

Received 27 March 2013; accepted 9 May 2013

Abstract. Planets which are old and close to their parent stars are considered as reflecting planets because their intrinsic temperature is extremely low but they are heated strongly by the impinging stellar radiation and hence radiation of such planets are the reflected star light that is governed by the stellar radiation, orbital distance and albedo of the planet. These planets cannot be resolved from the host stars. The second kind of exoplanets are those which are very young and hence they have high intrinsic temperature. They are far away from their star and so they can be resolved by blocking the star-light. It is now realized that radiation of such planets are linearly polarized due to atmospheric scattering and polarization can determine various physical properties including the mass of such directly detected self-luminous exoplanets. It is suggested that a spectropolarimeter of even low spectral resolution and with a capacity to record linear polarization of 0.5–1% at the thirty-meter telescope would immensely help in understanding the atmosphere, especially the cloud chemistry of the self-luminous and resolvable exoplanets.

Key words. Polarization—scattering, planets and satellite—stars: atmosphere.

1. Introduction

Since the discovery of the first extra-solar planet, 51 Pegasi b (Mayor & Queloz 1995) more than 850 planets outside the solar system have been detected through various astronomical methods. None of the planetary systems detected so far resembles the solar system and many of them have giant gaseous planets orbiting very close to the parent star. The existing detection methods are limited to finding massive giant planets – either very close to their parent stars or young and self-luminous. Therefore new methods are needed to detect and probe comparatively smaller exoplanets. On the other hand, recently a few exoplanets are discovered and imaged directly. These planets are far away from their parent star, with orbital separation a few tens of AU. However, determining the dynamical mass of these planets are not possible at present. Because of the lack of proper understanding on the initial condition, the mass estimated by using evolutionary models is ambiguous (Marley & Sengupta 2011). In this presentation, I discuss how polarimetric observation could serve as a potential method in determining the mass and probing the atmospheric properties of such directly imaged hot and giant exoplanets. The model prediction of polarization has already been successfully applied to brown dwarfs (Sengupta & Krishan 2001; Menard *et al.* 2002; Sengupta 2003; Zapatero Osorio *et al.* 2005; Sengupta & Kwok 2005; Sengupta & Marley 2009, 2010) whose atmosphere is very similar to hot and giant gaseous planets.

2. Model atmospheres

A grid of one-dimensional, plane-parallel, hydrostatic, non-gray, radiative-convective equilibrium atmosphere model is employed that includes about 2200 gas species, about 1700 solids and liquids for compounds of 83 naturally occurring elements and five major condensates as opacity sources (Ackerman & Marley 2001; Marley *et al.* 2002). A log-normal particle size distribution that gives rise to the doubled-peaked size distribution in terrestrial rain clouds is considered. The vector radiative transfer equations that describe the transfer of polarized radiation in a locally plane-parallel atmosphere are self-consistently solved along with the hydrostatic equilibrium equations, radiative equilibrium equations etc. The local polarization calculated at different angular directions is integrated over the rotation-induced oblate disk of the object by using a spherical harmonic expansion method (Sengupta & Marley 2009). The oblateness is estimated by using Darwin–Radau–Chandrasekhar formalisms (Chandrasekhar 1933).

3. Results and discussion

The main results and theoretical prediction are presented in Fig. 1. Since the object is the brightest in I- and J-bands, we presented the results in these two bands. The oblateness increases with the increase in rotational velocity and hence with the decrease in the spin period. The characteristic age of these planets as derived from the age of their parent stars ranges from 10 Myr to 100 Myr. At this age, they should rotate at very near to the breaking value of rotation. Subsequently, the evolution of magnetic field slows down the rotation. The minimum spin rotation period should be similar to that of Jupiter which has an oblateness of 0.064 at 1 bar pressure level. From a medium resolution spectrum obtained by using the Keck telescope, Konopacky *et al.* (2013) recently reported the projected spin rotation velocity of one of the directly imaged exoplanets HR8799c to be 40 km s^{-1}. As the rotation period decreases, the oblateness increases and hence the disc-integrated polarization increases. For a perfectly spherical object, the disc integrated polarization is essentially zero because of the symmetry. Departure from non-sphericity causes net non-zero cancellation of polarization. The rotation-induced oblateness not only depends on the spin period but also on the surface gravity as well as on the density distribution interior of the object. For the density distribution, we have considered the object as a polytrope with index $n = 1$ since it describes the same for Jupiter well. Also, detailed numerical analysis of brown dwarfs indicates that the density distribution of such objects can be described by a polytropic configuration with index ranging between 1 and 1.3. In our model calculations, we have considered the surface gravity corresponding to the age of the object as derived from evolution models.

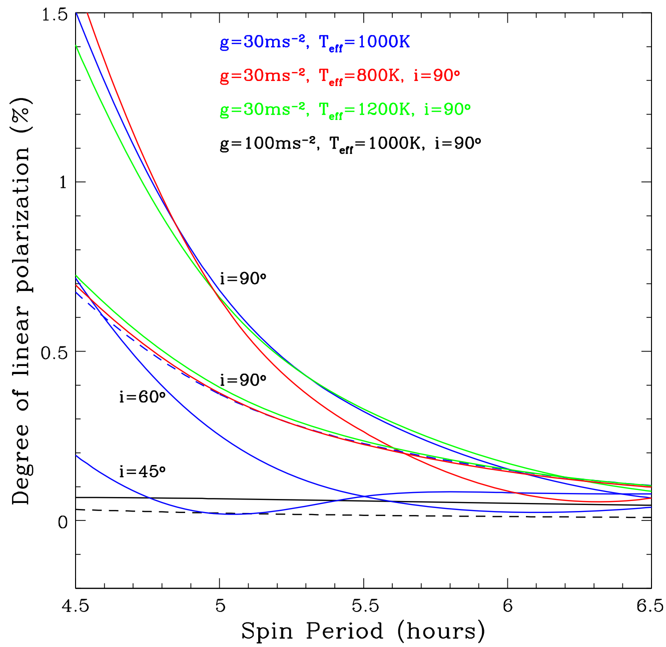

Figure 1. Scattering linear polarization profiles of non-irradiated exoplanets as a function of rotational period. The solid lines represent the percentage degree of linear polarization in the J-band and the dashed lines represent that in the I-band.

Figure 1 shows that detectable amount of linear polarization should arise if the spin period of the object is moderately low. Since, at the very young age, the rotational period should be small, observation of linear polarization would constrain the surface gravity and hence the mass of such objects. No polarization should be detected if the objects have mass higher than 6–8 times solar mass. Therefore, detection of linear polarization would put an upper limit on the mass of such exoplanets.

On the other hand, spectro-polarimetric study of such planets can be possible by large segmented telescope such as the thirty-meter telescope. Figure 2 presents low resolution synthetic polarization spectra of directly imaged exoplanets. While the spectra can be fitted with a wide range of surface gravity of the planet, polarization spectra should be very sensitive to the surface gravity and it should probe the cloud chemisty of the atmosphere of such exoplanets.

The close-in Jupiter-like giant gaseous planets should also have a similar atmospheric condition and so silicate cloud should also be present in the visible atmosphere of such strongly irradiated planets. As a consequence, the reflected light of these planets should also be polarized as suggested by Sengupta & Maiti (2006). However, since these planets are very near to their parent stars, they cannot be resolved. The unpolarized continuum radiation from the star would result into an amount of detectable polarization of the order of the planet to star flux ratio. Such an extremely low ($\sim 10^{-5}$–10^{-6} degree of polarization needs very sophisticated polarimeter. Even if such a polarimeter is available, smaller telescopes can be used

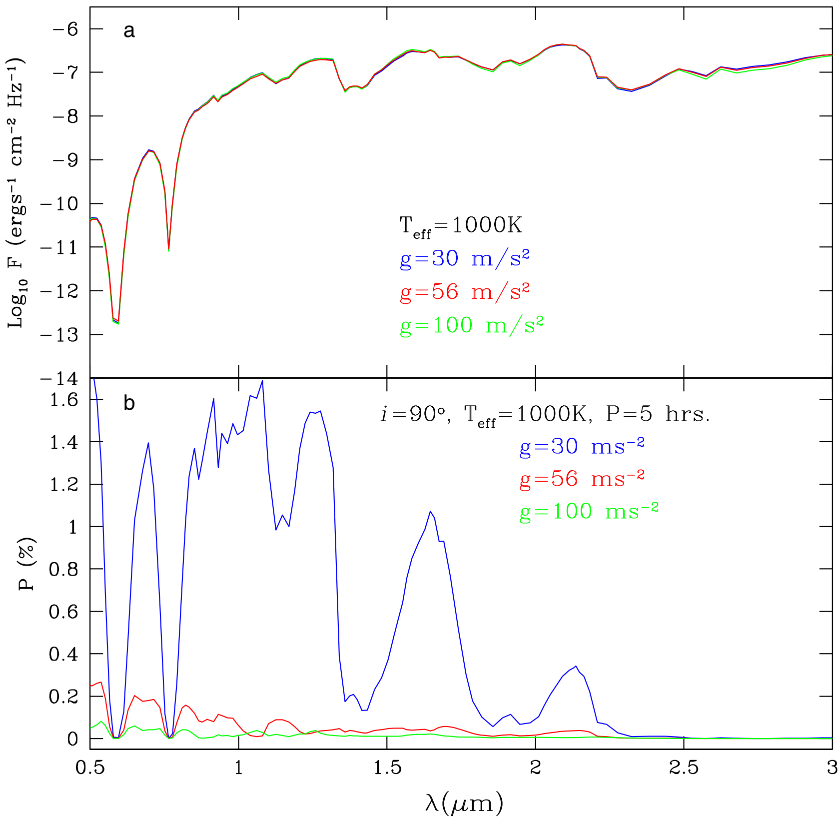

Figure 2. Low resolution synthetic spectra (upper panel) and polarization spectra (lower panel) of hot and young exoplanets for different surface gravity but fixed inclination angle i, effective temperature $T_{\rm eff}$, and spin rotation period P.

to obtain the polarization signal. Therefore, polarimetric study of close-in reflecting exoplanet may not be relevant for the thirty-meter telescope.

4. Conclusions

We have predicted that observable amount of linear polarization would arise in I and J bands of directly imaged, young and hot exoplanets owing to the presence of dust particles in their atmosphere. The degree of polarization would depend on the surface gravity and hence on the mass of the object and hence observation of polarization may constrain the mass of such exoplanets. The polarization spectra should reveal the cloud chemistry in the atmosphere as well as the physical properties of the cloud particles. Imaging and even low resolution spectra of such exoplanets are already obtained by using 10-m class telescope such as the Keck telescope and VLT. A thrity-meter class telescope should be ideal for obtaining polarization spectra of self-luminous planets. It is pointed out that polarimetric study of close-in Jupiter-like gas giant may not be relevant for the thirty-meter telescope because this needs a polarimeter which can detect polarization of the order 10^{-6} and existing smaller telescopes can serve the purpose.

References

Ackerman, A., Marley, M. S. 2001, *AJ*, **556**, 872.
Chandrasekhar, S. 1933, *MNRAS*, **93**, 539.
Chandrasekhar, S. 1960, *Radiative Transfer*, Dover, New York.
Konopacky, Q. M., Barman, T. S., Macintosh, B. A., Marois, C. 2013, eprint arXiv:1303.3280.
Marley, M. S., Sengupta S. 2011, *MNRAS*, **417**, 2874.
Marley, M. S. *et al*. 2002, *AJ*, **568**, 335.
Mayor, M., Queloz, D. 1995, *Nature*, **378**, 355.
Menard, F. *et al*. 2002, *A&A*, **396**, L35.
Sengupta, S. 2003, *ApJL*, **585**, L155.
Sengupta, S., Krishan, V. 2001, *AJL*, **561**, L123.
Sengupta, S., Kwok, S. 2005, *AJ*, **625**, 996.
Sengupta, S., Maiti, M. 2006, *AJ*, **639**, 1147.
Sengupta, S., Marley, M. S. 2009, *AJ*, **707**, 716.
Sengupta, S., Marley, M. S. 2010, *AJL*, **722**, L142.
Zapatero Osorio, M. R. *et al*. 2005, *ApJ*, **621**, 445.