Transit Polarimetry of Exoplanetary System HD 189733

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Abstract. We present and discuss a polarimetric effect caused by a planet transiting the stellar disk thus breaking the symmetry of the light distribution and resulting in linear polarization of the partially eclipsed star. Estimates of this effect for transiting planets have been made only recently. In particular, we demonstrate that the maximum polarization during transits depends strongly on the centre-to-limb variation of the linear polarization of the host star. However, observational and theoretical studies of the limb polarization have largely concentrated on the Sun. Here we solve the radiative transfer problem for polarized light and calculate the centre-to-limb polarization for one of the brightest transiting planet host HD 189733 taking into account various opacities. Using that we simulate the transit effect and estimate the variations of the flux and the linear polarization for HD 189733 during the event. As the spots on the stellar disk also break the limb polarization symmetry we simulate the flux and polarization variation due to the spots on the stellar disk.

1. Introduction

HD 189733 is currently the brightest ($m_V = 7.67 mag$) star known to harbour a transiting exoplanet (Bouchy et al. 2005). This, along with the short period (2.2 days) and large ratio of planet-to-star radii ($R_{pl}/R_\star \approx 0.15$), makes it very suitable for different types of observations including polarimetry (Berdyugina et al. 2008, 2011). In this paper we model the polarimetric effect that occurs during the planetary transit in front of the stellar disk. The planetary transit breaks the symmetry of the distribution of light coming from the stellar disk which results in the net linear polarization. This effect was simulated first by Carciofi & Magalhães (2005) for artificial exoplanetary systems who revealed that the accuracy of

modern polarimeters of 1×10^{-6} is enough to detect it. Later, Kostogryz et al. (2011) and Frantseva et al. (2012) calculated the planetary transit effect for HD 189733 with Monte Carlo simulations taking into account two different types of center-to-limb variations of linear polarization (CLVP) of the host star as initial approximations such as the CLVP for pure scattering atmosphere (Chandrasekhar 1950) and the solar CLVP (Trujillo Bueno & Shchukina 2009). They showed that result of such simulation strongly depends on CLVP of the stellar disk.

So far, the efforts to study the CLVP are concentrated only for the Sun (e.g. Stenflo (2005), etc...) while there is no information about the CLVP for cooler dwarf stars. In this paper, we present our calculations of the CLVI and CLVP which are obtained by solving the radiative transfer equations for polarized light taking into account various opacities. Using results of these calculations, we simulate polarization resulting from the planetary transit and stellar spots in HD 189733. In Section 2, we describe our method of calculation of the CLVI and CLVP for HD 189733 and in Section 3 we show results of our transit polarization simulations. Section 4 presents discussion of our results.

2.   Stellar center-to-limb variation of intensity and linear polarization

We solve the radiative transfer equations for polarized radiation iteratively assuming no magnetic field and considering a plane-parallel model atmosphere (see Kostogryz & Berdyugina (2014)).

As the stellar model atmosphere of HD 189733 we use the PHOENIX model (Hauschildt et al. 1999) with effective temperature $T_{\text{eff}} = 5000 K$ and gravity $\log g = 4.5$. Scattering and absorption continuum opacities are calculated using the SLOC code (Berdyugina 1991) at the wavelength of 4500Å. We take into account the following contributors:

- scattering opacity: Thomson scattering on free electrons and Rayleigh scattering on HI, HeI, H_2, CO, H_2O, and other molecules,

- absorption opacity: free-free and bound-free transitions in $H^-, HI, HeI, He^-, H_2^-, H_2^+$, and metal photoionization.

With these contributors, the calculated CLVI and CLVP in the continuum spectrum of HD 189733 are presented in Fig. .1. In addition, we consider the solar CLVI and CLVP (Kostogryz & Berdyugina 2014) and the CLVs calculated by Chandrasekhar (1950) for pure scattering atmosphere.

As is seen in Fig..1, the continuum polarization for HD 189733 is slightly larger than for the Sun, while it is significantly smaller than the polarization calculated in Chandrasekhar (1950) for pure scattering atmosphere. We conclude that neither Chandrasekhar's calculation nor the solar CLVP can reproduce correctly the CLV of the polarization for the K dwarf star HD 189733.

3.   Polarization of the transiting system

Using Monte Carlo simulations following Carciofi & Magalhães (2005) and Kostogryz et al. (2011) and taking into account the CLVI and CLVP calculated for HD 189733 as described
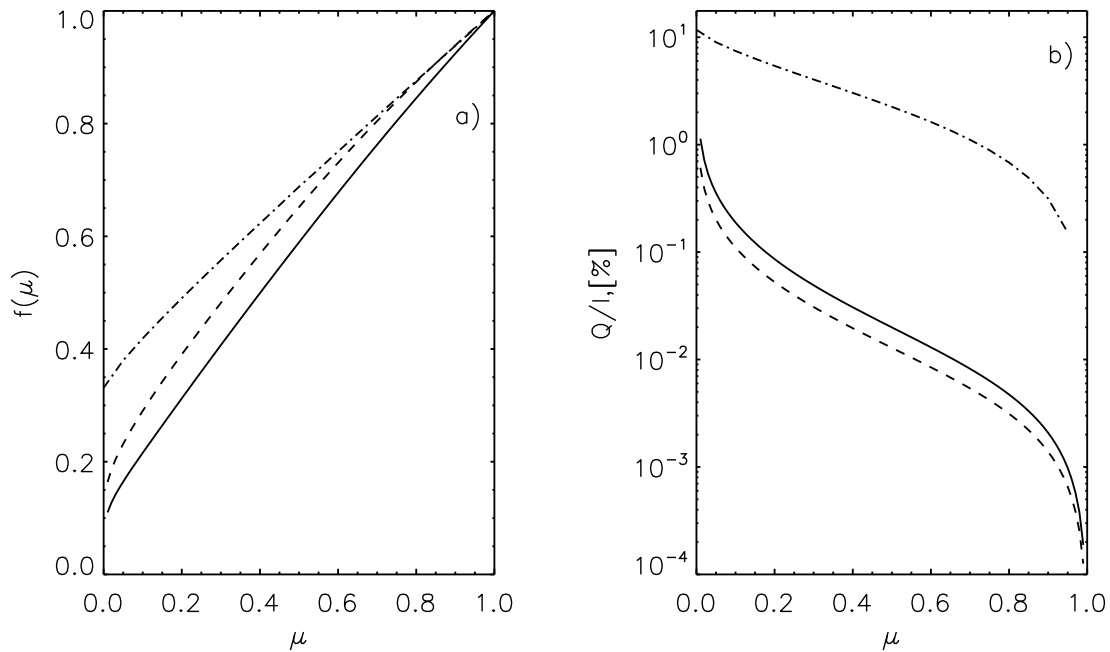
Figure .1: Center-to-limb variations of (a) the intensity and (b) the continuum polarization in log scale for HD 189733 (solid line), for the Sun (dashed line) and for a pure scattering atmosphere (dash dotted line) at $4500\mathring{A}$.

in Section 2, we obtain the variation of the flux, the normalized Stokes q and u parameters and the polarization degree during the planetary transit (Fig. .2, first column). The flux and polarization curves are sensitive to orbit inclination angle and ratio of planet-to-star radii. The flux provides the planet-to-star radii ratio and the inclination angle, while polarimetry provides also the information in which South or North hemisphere the planet transits the star. The value and the sign of Stokes q and u describe the position of the planet on the stellar disk projected onto the sky plane. As is seen in Fig. .2 (first column) the variation of the polarization degree is symmetric and the maxima are slightly larger than 4×10^{-6} at 4500 Å.

Another effect that breaks the symmetry of the host star disk and results in linear polarization is the presence of spots on the stellar disk. As was shown by Winn et al. (2005), HD 189733 is an active star and spots can cover up to 1% of the total stellar surface. In our simulation we set different parameters of spots such as temperature $(3500K - 4000K)$, sizes (up to 1% of the stellar surface) and locations (chosen randomly in the range of latitudes of ± 20 deg to ± 60 deg). The CLVI and CLVP for spots are calculated for Phoenix model atmosphere with adopted effective temperatures and gravities. Thus, we calculate the flux and polarization variations contributing from stellar activity which are shown in Fig. .2 (second and third columns). In both columns for times before and after the planet transit, we obtain a flux decrease and a polarization increase caused only by spots present on the stellar disk. The variation of the polarization provides information about the position of

starspots. Since the polarization of the star is the largest at the limb, Fig. .2 (second column) shows simulation for the extreme case of the biggest possible spot at the limb for HD 189733. In this case, the polarization due to the spot is the largest polarization degree $\approx 2 \times 10^{-6}$. Berdyugina et al. (2011) assumed the same extreme starspot parameters and estimated the maximum polarization from spot up to 3×10^{-6} which is in very good agreement with our simulations.

The third column of the Fig. .2 shows the same parameters as the other two columns but for another distribution of starspots. In this case we distribute 8 spots more or less homogeneously over the stellar disk between the latitudes ± 20 deg to ± 60 deg with the total area covered by spots of about 1% of the stellar disk. It is seen, that the cases of the spotless star and the star with the distributed spots lead to very similar signals in all panels which mostly differ by vertical offsets of 0.5×10^{-6} which corresponds to the signal from the spots. We would like to draw your attention that in Fig..2 (third column) at t=1.7h the planet covers one of the spots which leads to little bumps in all the curves below.
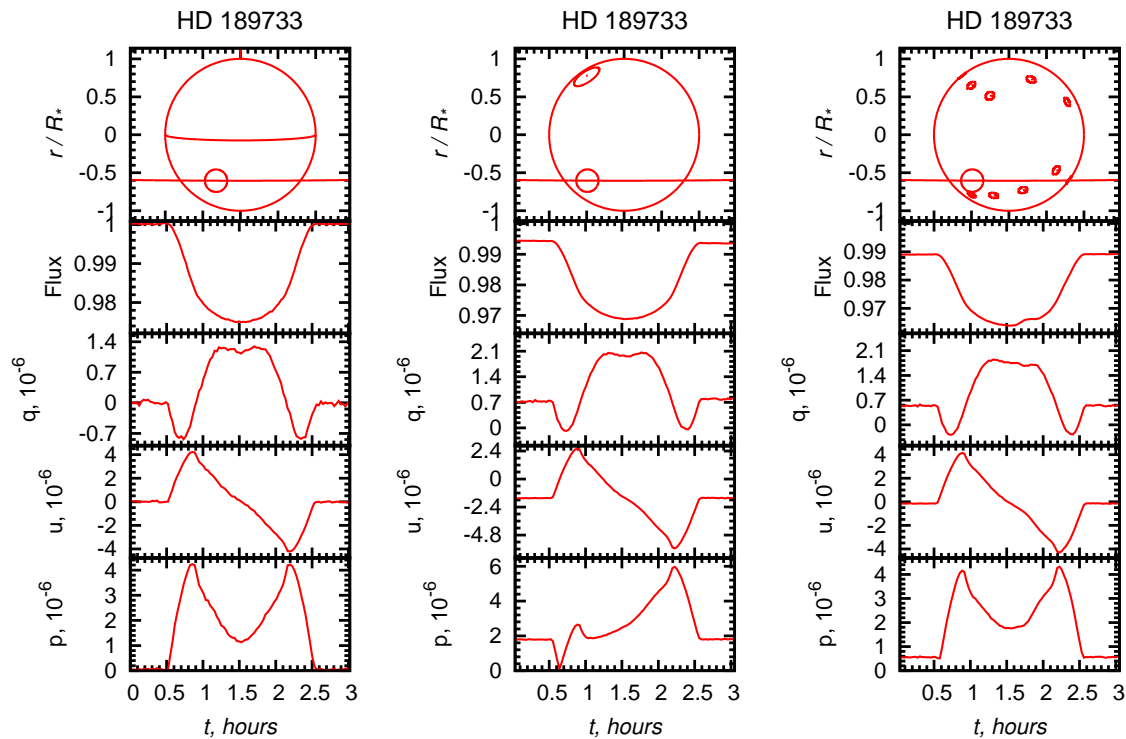

Figure .2: Simulations for the HD 189733 system. Each column top to bottom contains panels transit(starspot) geometry, the flux and the polarization variations (normalized Stokes parameters q, u, and polarization degree p) during the planet transit. The first column describes only the planetary transit, while the next two columns show the variation of intensity and polarization during the planetary transit at the presence of spots on the stellar disk.

4. Summary

In this paper, we calculate the center-to-limb variations of the intensity and linear polarization in stellar continuous for HD 189733. Similar to limb darkening measurements in transit photometry, we show that it is possible to measure the center-to-limb variations of the linear polarization by means of transit polarimetry. Transit polarimetry provides information about the ratio of planet-to-star radii, orbit inclination and the transit hemisphere. In addition, it constrains the sizes and positions of starspots on the stellar disk, while transit photometry cannot, unless the planet covers a spot during its transit.

Using Monte Carlo simulations we also obtain the linear polarization for the transiting exoplanetary system HD 189733 with the found maximum equal to 4.4×10^{-6} at 4500Å. In order to measure this effect for HD 189733 we need a very sensitive polarimeter.

We show that the maximum polarization effect due to starspots is still less than 2×10^{-6} for a single spot seen at the stellar limb and even smaller for a more homogeneous distribution of spots over the surface. Thus, the influence of the spots on the total polarization for HD 189733 is too small to be measurable. It requires many planetary transit observations in order to achieve better statistics and polarimetric accuracy.

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