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Detection of Pegasides: a ground-based approach and preliminary observations

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Abstract. Discriminating exo-planetary photons from stellar photons with a ground-based instrument is a physically interesting and challenging issue. We propose an observational technique based upon both spectral and polarimetric coding to discriminate the exo-planetary photons. We also discuss a preliminary observation run performed with the spectrograph "CARELEC" on the 193 *cm* telescope at the Observatoire de Haute provence (OHP).

Keywords. techniques: photometric, spectroscopic.

1. The principle

Several physical phenomena are responsible of the light reflection by the atmosphere of a Pegaside. Among them, the well known Rayleigh scattering may play a non negligible role, especially if the fraction of solid particles in the atmosphere is low enough. Under this hypothesis, the star's light scattered by the planet (called "planetary photons" in this article) should be at least partially polarized, with a maximum of polarization at quadratures (see Figure 1). In this article, we shall assume this hypothesis to be valid.

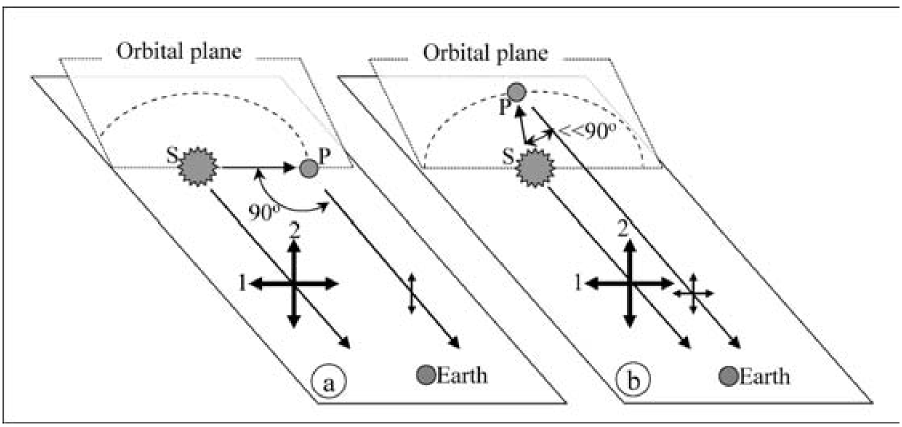

Figure 1. The polarization of the planetary photons, if only Rayleigh scattering occurs. **(a)** At quadrature, the planetary photons are polarized (ideally 100% if only Rayleigh diffusion occurs). The stellar photons are not. Thus, the composite light (star+planet) in polarization "2" contains more planetary photons than the light in polarization "1". **(b)** At or near opposition, the planetary photons are not (or few) polarized, and the composite light (star+planet) in polarization "1" and "2" contains equal amount of planetary photons.

We thus propose to use both the orbital motion induced Doppler shift *and* this possible partial polarization of planetary photons, to distinguish them from the unpolarized stellar photons. If successful, this method could provide for relevant physical and orbital information yet unavailable, such as the on-sky orientation of the nodal line, and the orbital inclination.

The principle of the method is to use a telescope with a spectro-polarimetric device, whose polarization direction can be freely oriented on the sky. This instrument is to provide for pairs of spectra in two orthogonal linear polarization states denoted $A(\theta)$ and $B(\theta)$, where θ is the angle between the polarization direction A and the local north direction.

For bright Pegasides such as υ *And* or τ *Boo*, the orbital motion is well known, and it is in principle possible to determine the epochs for optimal spectro-polarimetric efficiency. This corresponds to a trade-off between the positions of maximum polarization (the quadratures) and the positions of maximum brightness (the oppositions). However, the orientation of the nodal line on the sky is unknown. Thus, several pairs of spectra, with different on-sky orientations have to be taken. A typical sequence of orientations could be: $\theta = 0^o$ and 90^o, then $\theta = 30^o$ and 120^o, then $\theta = 60^o$ and 150^o.

These spectra have to be expressed as functions of the logarithm of the wavelength, for a reason explained in Figure 2. Indeed, the composite spectra in both polarization states involve essentially the spectrum of the stellar light (Figure 2-a), plus a very low amplitude Doppler-shifted replica due to the planetary scattered photons (Figure 2-b). In terms of the wavelength, the Doppler shift is *not* wavelength-independent, whereas it is in logarithmic coordinates (Figure 2-c). From both spectra in $log\lambda$ coordinates, a reference Dirac mask is computed from a selection of the most powerful absorption lines (Figure 2-d).

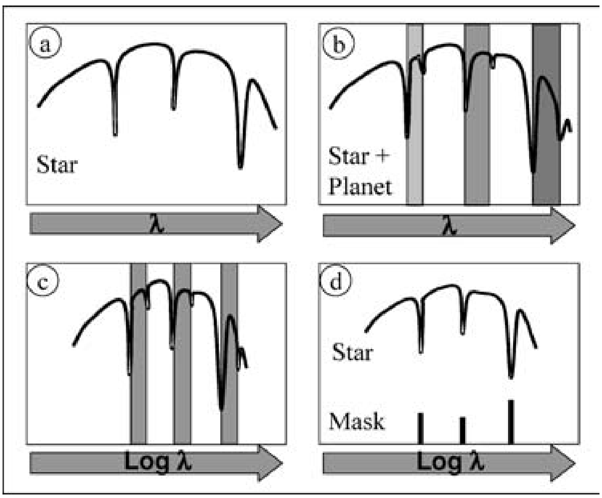

Figure 2. The sketched spectrum of a star and a Pegaside. **(a)** The spectrum of the star alone. **(b)** The spectrum of the star + planet Doppler-shifted. **(c)** The same in $log(\lambda)$ coordinate, so as to make the Doppler shift constant. **(d)** The spectrum of the star and the correlation Dirac mask.

For each on-sky orientation angle θ, The reduction procedure involves the following steps (assuming standard spectral and photometric calibrations have been done):

- Extract the four carefully calibrated spectra $A_\theta(\lambda)$, $B_\theta(\lambda)$, $A_{\theta+90^o}(\lambda)$ and $B_{\theta+90^o}(\lambda)$.
- Compensate for the instrumental photometric difference between the two

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polarization channels by computing the two averages $A_\theta(\lambda) + B_{\theta+90^o}(\lambda)$ and $B_\theta(\lambda) + A_{\theta+90^o}(\lambda)$. Indeed, rotating the whole instrument of 90^o around its axis is equivalent to permutate the two polarization channels.

- Express the resulting functions in terms of $\log\lambda$ instead of λ.
- Compute the two correlation functions of the two compensated and log-scaled spectra $a(\log\lambda)$ and $b(\log\lambda)$ with the common reference Dirac mask.
- Compute their difference $\Delta(\log\lambda)$. The stellar signature should vanish, and the planetary signature should emerge out of the noise, with the expected Doppler shift (see Figure 3).

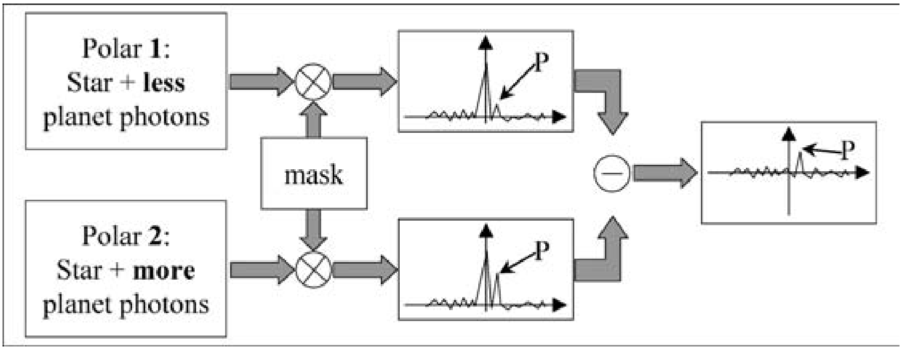

Figure 3. How the planetary signal should appear. The spectra in two complementary polarization states are convoluted with the same Dirac mask. Both correlation functions are dominated by the stellar photons (small Doppler shift). The small planetary Doppler shifted pike is present with different amplitude in both signals. When subtracting one to the other, the stellar features should cancel, and the planetary signature should remain, hopefully emerging out of the residual noise.

2. Preliminary observations at OHP

One of the best candidates for a spectro-polarimetric detection is certainly τ *Boo* (HD120136), a $F6IV$ star at $15.6\,pc$, with $M_v = 4.50$. This star is well known to have a Jupiter-like planet orbiting in 3.3128 days at a distance of $0.0462\,AU$ (see Butler *et al.*(1997), Cameron *et al.*(1999) and Charbonneau *et al.*(1999) for example).

For a first preliminary spectro-polarimetric observation of τ *Boo*, we have chosen the spectrograph CARELEC on the $193\,cm$ telescope at the Observatoire de Haute Provence (OHP). On this instrument, the bonette can be rotated over 360^o on the sky, but no polarimetric capabilities are available.

Thus, we had to introduce additional optics in front of the slit of the spectrograph, so as to separate the two complementary linear polarizations. This additional optics is a $1\,cm$ thick calcite ($CaCO_3$) crystal, with a cylindrical diverging lens (see Figure 4). The crystal splits the input beam into two polarized beams. The lens spreads the light of each polarized beam along the slit, so as to produce elliptic rather than circular focal spots. This avoids too rapid a saturation of the CCD pixels, which would result in several short exposures, with a lot of time-consuming readout cycles. With this optics added, each CCD image displays simultaneously two complementary polarized spectra (see Figure 5). The spectral domain under consideration was $[385\,nm\ ,\ 480\,nm]$.

A very careful post-processing pipeline has been designed and implemented to reject all systematic instrumental biases below the photon noise.

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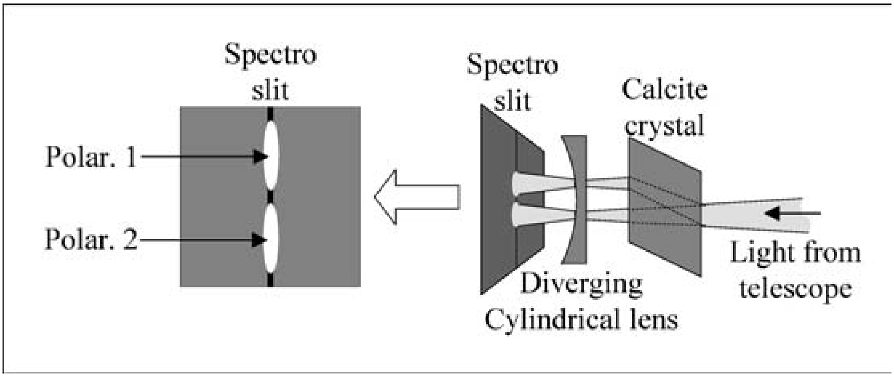

Figure 4. The additional optics to split polarizations and spread the focal spots along the spectrograph slit. A calcite crystal ($CaC0_3$) transforms the convergent beam from the telescope into two convergent beams, one with polarization 1, the other with polarization 2. The cylindrical diverging lens spreads the two spots in the direction of the spectrograph slit.

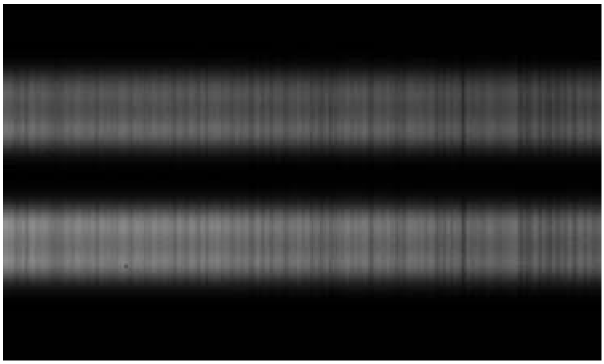

Figure 5. An example of polarized spectra taken with CARELEC+crystal+lens.

3. Conclusion

The preliminary observation run on the modified CARELEC spectrograph at OHP did not yield an effective detection of planetary photons for τ *Boo*. Indeed, the *rms* residual noise on the difference of correlation functions corresponds to a magnitude difference of 8.2, which is definitely not sufficient for any planetary photon discrimination. One of the limiting features is the overall photometric efficiency of the whole instrumental chain (atmosphere, telescope, calcite crystal + lens, spectrograph and camera), which remained below 1 %, that is, far below our most pessimistic assumptions.

Further observations should be performed on more recently designed spectrographs with built-in polarimetric capabilities (no added calcite crystal), such as NARVAL (TBL, Observatoire du Pic du Midi) or ESPADON (CFHT). On such instruments, the planetary signature should emerge within a few hours of exposure time.

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