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LETTER TO THE EDITOR

# Exoplanet transmission spectroscopy: accounting for the eccentricity and the longitude of periastron

## Superwinds in the upper atmosphere of HD 209458b?

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**ABSTRACT**

*Context.* A planet transiting in front of the disk of its parent star offers the opportunity to study the compositional properties of its atmosphere by means of the analysis of the stellar light that is filtered by the planetary atmospheric layers. Several studies have so far placed useful constraints on planetary atmospheric properties with this technique, and for the case of HD 209458b even the radial velocity of the planet during the transit event has been reconstructed. This opens up a new range of possibilities.
*Aims.* In this contribution we highlight the importance to account for the orbital eccentricity and the longitude of periastron of the planetary orbit to accurately interpret the measured planetary radial velocity during the transit.
*Methods.* We calculate the radial velocity of a transiting planet in an eccentric orbit.
*Results.* Given the higher orbital speed of planets with respect to their stellar companions, even small eccentricities can result in detectable blue or redshift radial velocity offsets during the transit with respect to the systemic velocity, the exact value of which also depends on the longitude of the periastron of the planetary orbit. For a hot-jupiter planet, an eccentricity of only $e = 0.01$ can produce a radial velocity offset on the order of the km $s^{-1}$.
*Conclusions.* We propose an alternative interpretation of the recently claimed radial velocity blueshift ($\sim$2 km $s^{-1}$) of the planetary spectral lines of HD 209458b, which implies that the orbit of this system is not exactly circular. In this case, the longitude of the periastron of the stellar orbit is most likely confined in the first quadrant (and that of the planet in the third quadrant). We highlight that transmission spectroscopy allows us not only to study the compositional properties of planetary atmospheres, but also to refine planetary orbital parameters, and that any conclusion regarding the presence of windflows on planetary surfaces coming from transmission spectroscopy measurements requires precisely known orbital parameters from RV.

**Key words.** techniques: spectroscopic – planets and satellites: atmospheres – planets and satellites: individual: HD 209458b – planetary systems

### 1. Introduction

The first proof of the existence of an exoplanetary atmosphere was given by Charbonneau et al. (2002), once they succeeded in the detection of sodium absorption in the transmission spectrum of the exoplanet HD 209458b. This result was obtained using the Space Telescope Imaging Spectrograph (STIS) on board of the *Hubble* Space Telescope (HST). In the following years several other attempts were made to detect absorption features from exoplanet atmospheres using also ground-based observatories but, until recently, they were able to place only upper limits (Moutou et al. 2001; Snellen 2004; Narita et al. 2005). Sodium detection from the ground was first achieved for HD 189733b by Redfield et al. (2008) and later confirmed in HD 209458b by Snellen et al. (2008), who found Na levels that matched HST the values found by Sing et al. (2008). Additionally Sing et al. (2011), using ground-based narrowband spectrophotometric measurements at the GTC, detected potassium absorption in XO-2b, while Wood et al. (2010) detected sodium absorption in WASP-17b by means of transmission spectroscopy at the VLT. Recently Snellen et al. (2010), presented further ground-based detection of CO absorption lines in the atmosphere of HD 209458b. Their refined analysis allowed them to isolate for the first time the Doppler shift of the planetary spectral lines during the transit, which allowed them a direct determination of the masses of both the star and the planet in the same manner as done for double lined eclipsing binaries. In the course of their analysis, Snellen et al. (2010) also noticed that the CO planetary absoption lines appeared blueshifted with respect to the systemic velocity of the host star, which they attributed to superwinds on the planetary surface, that flow from the day side to the night side of the planet and cross both its equatorial and polar regions. However, the planetary orbit of HD 209458b was assumed to be perfectly circular. The aim of this contribution is to analyze the consequences of a non-null planetary orbital eccentricity on transmission spectroscopy measurements. Even if a residual small orbital eccentricity is present, the velocity of the planet during the transit can be expected to be offset with respect to the systemic velocity, and that by a significant amount, given the large orbital speed of the planet, as demonstrated in Sect. 2. In Sect. 3 we discuss the particular case of HD 209458b. Finally we summarize in Sect. 4 our results and conclude.

## 2. Transmission spectroscopy of an eccentric transiting planet

We assume a two-body system composed of a planet and its host star. The radial velocity RV of the planet with respect to the barycenter of the system is given by (e.g. Hilditch 2001)

$$\mathrm{RV} = \frac{(2\pi)^{1/3}}{P^{1/3}} \frac{(G)^{1/3} m_{\mathrm{s}} \sin(i)}{\sqrt{1-e^2}\left(m_{\mathrm{s}}+m_{\mathrm{p}}\right)^{2/3}} \left(\cos(\omega+f)+e\cos\omega\right), \tag{1}$$

where $f$ is the true anomaly, $e$ is the eccentricity of the orbit, and $i$ is the inclination with respect to the plane of the sky, $m_{\mathrm{s}}$ and $m_{\mathrm{p}}$ are the masses of the star and of the planet, $\omega$ is the longitude of the periastron of the planetary orbit, $P$ is the orbital period, and $G$ the gravitational constant. Isolating the terms that depend on the eccentricity and the longitude of the periastron, and grouping all others in the constant $\tilde{K}$, we obtain:

$$\mathrm{RV} = \tilde{K}\,\frac{\cos(\omega+f)+e\cos\omega}{\sqrt{1-e^2}}\cdot \tag{2}$$

Once the planet crosses the line of sight of the observer, the term that depends on the true anomaly is exactly null. Then the radial velocity of the planet in that moment ($\mathrm{RV}_0$), with respect to the barycentric radial velocity, is given by

$$\mathrm{RV}_0 = \tilde{K}\,\frac{e\cos\omega}{\sqrt{1-e^2}}\cdot \tag{3}$$

This velocity is null only if the eccentricity is null or if the longitude of the periastron equals 90° (or 270°). Assuming $m_{\mathrm{s}} = 1\ M_{\odot}$, $m_{\mathrm{p}} = 1\ M_{\mathrm{jup}}$, $i = 90°$, $P = 3$ days and $e = 0.01$, we can derive the following upper limit for $\mathrm{RV}_0$, given that $|\cos\omega| \le 1$

$$|\mathrm{RV}_0| \le 1.48\ \mathrm{km\,s^{-1}}. \tag{4}$$

This result is entirely determined by the orbital speed of the planet, which exceeds that of its stellar companion, given its much smaller mass. Because transmission spectroscopy allows us to sample only a small portion of the planetary orbit close to the mid-transit point, all measurements acquired during the transit would appear to be offset with respect to the systemic velocity as represented in Fig. 1. Then, considering the case of a hot-jupiter, even a low eccentricity can produce a radial velocity offset on the order of the $\mathrm{km\,s^{-1}}$ (depending also on the value of the longitude of the periastron). This offset can be either blueshifted or redshifted. If the eccentricity of the system is completely neglected, assuming that the orbit is exactly circular, this radial velocity offset may be interpreted as having a different physical origin.

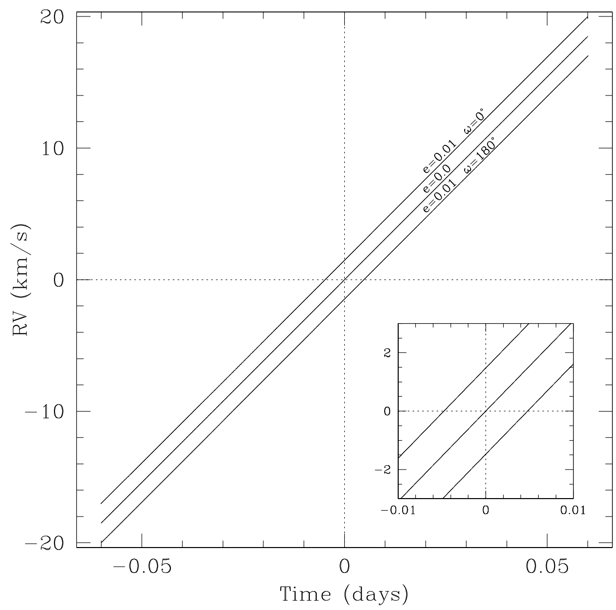


**Fig. 1.** Continuous lines represent the planetary radial velocity during the transit for different values of the eccentricity ($e$) and the longitude of periastron ($\omega$). In this figure we assumed $m_{\mathrm{s}} = 1\ M_{\odot}$, $m_{\mathrm{p}} = 1\ M_{\mathrm{jup}}$, $i = 90°$, $P = 3$ days. The dotted lines indicate the mid-transit point and the systemic velocity. The box in the *lower right* corner is a magnified view close to the mid-transit point.

## 3. The case of HD 209458b

As reported in the introduction, transmission spectroscopy was applied to HD 209458b by several authors in the past, which placed useful constraints on the abundances of different elements in its atmosphere. Recently Snellen et al. (2010) presented a refined procedure, by means of which the orbital motion of the planet during the transit was unveiled for the first time through the analysis of the Doppler effect of CO absorption lines. The signal they detected appeared blueshifted with respect to the systemic velocity of the host star by around 2 $\mathrm{km\,s^{-1}}$, and the uncertainty estimated by the authors was 1 $\mathrm{km\,s^{-1}}$. The authors then interpreted this blueshifted signal as evidence that superwinds are flowing on the surface of the planet, from the dayside to the nightside, and crossing both the equator and the poles.

This conclusion was drawn on the basis of the assumption that the orbit of HD 209458b is perfectly circular. High-precision radial velocities allow one to conclude that the eccentricity of this system is consistent with zero within the uncertainties (Laughlin et al. 2005). In particular, Laughlin et al. (2005) pointed out that: *"even when the orbit underpinning a data set is circular, e computed from an ensemble of bootstrap trials will have a characteristic nonzero value"*.

Nevertheless, considering the uncertainties, a residual low eccentricity cannot be ruled out a priori (Kipping 2008), and in the last years, this was indeed a matter of an animated debate.

Winn et al. (2005), who analyzed high-precision radial velocities of the host-star, photometry and timing of the secondary eclipse, obtained for the eccentricity and longitude of periastron of the star ($\omega_{\mathrm{s}}$) the values $e = 0.0147 \pm 0.0053$ and $\omega_{\mathrm{s}} = 84° \pm 11°$. If these mean values are inserted in Eq. (3), we obtain an expected blueshifted signal equal to $\mathrm{RV}_0 = 0.21\ \mathrm{km\,s^{-1}}$. However, considering the 90% upper confidence limits ($e\cos\omega = 0.0049$) reported by Winn et al. (2005), we derive that $\mathrm{RV}_0$ could be as high as $\mathrm{RV}_0 = 0.68/\sqrt{1-e^2}\ \mathrm{km\,s^{-1}}$. Similarly, Deming et al. (2005) derived that the secondary eclipse occurs at the midpoint between transits within 21 min (3-$\sigma$). This translates into an upper limit for the expected radial velocity offset equal to $\mathrm{RV}_0 = 0.91/\sqrt{1-e^2}\ \mathrm{km\,s^{-1}}$. These estimates appear still consistent with the observed blushifted signal, considering the uncertainties of the observations.

Then at present, given the high sensitivity of the mechanism presented here on the orbital eccentricity and given the uncertainty of the measurements, it is questionable if other mechanisms like superwinds should be invoked to account for the observations. As explained by Deming et al. (2005), even a dynamically significant eccentricity ($e \sim 0.03$) could still agree

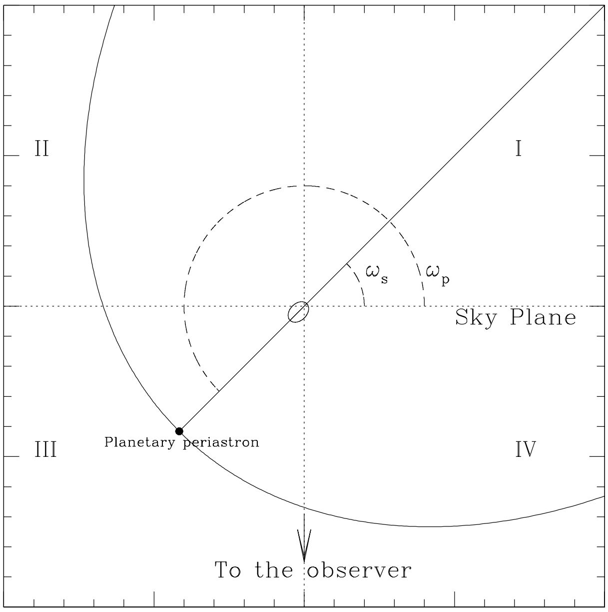


**Fig. 2.** Schematic representation of the orbit of the planet (large ellipse) and the orbit of the star (small ellipse), with the definition of the quadrants and of the longitude of periastron of the star ($\omega_s$) and of the planet ($\omega_p$). The dotted horizontal line indicates the plane of the sky, whereas the dotted vertical line indicates the position of the observer (arrow).

with their 3-$\sigma$ limit, despite requiring a fairly good alignment of the apsidal line with the line of sight $|\omega - \pi/2| < 12°$.

If it were entirely attributed to the eccentricity, the observed blueshift would imply that the longitude of the periastron of the planet ($\omega_p$) should lie either in the second or in the third quadrant, and consequently that of the star ($\omega_s = \omega_p + 180°$) either in the fourth or in the first quadrant respectively (see Fig. 2). Despite the large uncertainty, Winn et al. (2005) report $\omega_s = 84° \pm 11°$ (1-$\sigma$). Taken together, the above considerations reinforce the idea that the longitude of periastron of the star should lie most likely in the first quadrant (and that of the planet in the third).

## 4. Conclusions

Thanks to the high orbital speed of planets with respect to their stellar companions, transmission spectroscopy allows us not only to constrain the properties of the atmosphere of a transiting planet, but also offers an alternative means to refine its orbital parameters. For the eccentric planet Gj436b ($P = 2.6438986$ days, $e = 0.15$, $\omega_s = 351°$) we expect a redshifted radial velocity offset equal to 11.68 km s$^{-1}$. For the particular case of HD 209458b, nominally almost half of the blueshifted signal reported by Snellen et al. (2010) could be explained by assuming that the orbital eccentricity of the system is not exactly null (just at the percent level) considering the limits imposed by transit timing of the secondary eclipse given by Deming et al. (2005). However, given the uncertainty of the measurements of Snellen et al. (2010), our estimates appear still consistent with the observations. Once attributed to the eccentricity, the blueshifted signal together with radial velocity measurements of the host star allow us to confine the longitude of the periastron of the star in the first quadrant (and one of the planet in the third quadrant).

Finally, it should be also noted that any conclusion regarding the presence of windflows on planetary surfaces coming from transmission spectroscopy measurements requires precise known orbital parameters from RV.

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