The shocking transit of WASP-12b: modelling the observed early ingress in the near-ultraviolet

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Accepted 2011 June 14. Received 2011 June 7; in original form 2011 May 10

ABSTRACT

Near-ultraviolet (near-UV) observations of WASP-12b have revealed an early ingress compared to the optical transit light curve. This has been interpreted as due to the presence of a magnetospheric bow shock which forms when the relative velocity of the planetary and stellar material is supersonic. We aim to reproduce this observed early ingress by modelling the stellar wind (or coronal plasma) in order to derive the speed and density of the material at the planetary orbital radius. From this, we determine the orientation of the shock and the density of compressed plasma behind it. With this model for the density structure surrounding the planet we perform Monte Carlo radiation transfer simulations of the near-UV transits of WASP-12b with or without bow shock. We find that we can reproduce the transit light curves with a wide range of plasma temperatures, shock geometries and optical depths. Our results support the hypothesis that a bow shock could explain the observed early ingress.

Key words: planets and satellites: magnetic fields – planets and satellites: individual: WASP-12b – planet–star interactions – stars: coronae – stars: winds, outflows.

1 INTRODUCTION

The detection of hot Jupiters, which are found to be orbiting extremely close to their host star with periods of a few days, is continuing to challenge our theories of planet formation and evolution (Watson et al. 2011). Transit surveys such as the Super Wide Angle Search for Planets (SuperWASP) provide great insight into the properties of extrasolar planets and their host star (Seager & Mallén-Ornelas 2003). As the number of detected planets has increased, work has started on characterizing their atmospheres (Croll et al. 2011; Helling et al. 2011; Madhusudhan et al. 2011) including cloud coverage and temperature structure (Vidal-Madjar et al. 2011).

Following on from the identification of the hot Jupiter WASP-12b (Hebb et al. 2009), recent Hubble Space Telescope (HST) observations indicate an early ingress of its near-ultraviolet (near-UV) transit compared to the optical data (Fossati et al. 2010). There have been several attempts to explain such an early ingress by assuming the presence of absorbing material around the planet (Lai, Helling & van den Heuvel 2010; Vidotto, Jardine & Helling 2010). One possible explanation for the presence of an asymmetry is that heavily irradiated gas giants such as WASP-12b can fill and even overflow the planetary Roche lobe (Gu, Lin & Bodenheimer 2003; Ibugi, Burrows & Spiegel 2010; Li et al. 2010) resulting in mass transfer from the planet to the star (Lai et al. 2010).

One further explanation for this observed asymmetry is the presence of a bow shock. Vidotto et al. (2010) have shown that if the relative motion between the planetary and stellar coronal material is supersonic, then a bow shock surrounding the planet’s magnetosphere could form. Such a shock could compress the local plasma to the densities required to reproduce the early ingress observed in the near-UV light curves.

The possibility of detecting and characterizing planetary bow shocks provides a new method to study exoplanetary magnetic fields. If the magnetic field of the star can be determined through, for example, Zeeman–Doppler imaging techniques (Donati & Landstreet 2009), then the early ingress of the near-UV transit can be used to place limits on the exoplanetary magnetic field (Vidotto, Jardine & Helling 2011). The magnetic field is believed to provide a key role in shielding the planetary atmosphere from energetic particles.

In this Letter, we present theoretical light curves for a planet surrounded by a magnetospheric bow shock transiting its host star. Our aim is to test the hypothesis that the early ingress of the near-UV transit light curve can be explained by the presence of such a bow shock.

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Monthly Notices of the Royal Astronomical Society C⃝ 2011 RAS

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2 THE MODEL

If the relative velocity of the planetary and the stellar coronal material is supersonic then a bow shock could form (see Fig. 1). The interaction between planetary material and stellar material compresses the local plasma to produce a region of higher density plasma behind the shock. If the optical depth of the shocked material is high enough then starlight will be absorbed and produce an early ingress in the transit light curve.

The angle between the shock normal and the orbital direction of the planet is given by \( \varphi_0 \). The value of \( \varphi_0 \) is determined by the relative velocity of the planetary and stellar coronal material. Fig. 1 of Vidotto et al. (2010) illustrates the scenarios leading to the various shock orientations. There are two limiting cases: an ‘ahead shock’ (\( \varphi_0 \to 0^\circ \)) forms when the planet is embedded in the stellar corona and a ‘dayside shock’ (\( \varphi_0 \to 90^\circ \)) forms when the radial wind velocity is very much greater than the relative azimuthal velocity of the planet.

Here we use models for the stellar corona and wind (Vidotto et al. 2010, 2011) to obtain a value for the plasma density at the planet. These models assume a typical solar base density of \( n_0 \sim 10^6\, \text{cm}^{-3} \) (Withbroe 1988) and either an isothermal hydrostatic corona or an isothermal thermally driven wind. We assume an adiabatic shock with a maximum compression ratio of 4. For an isothermal coronal plasma density can then be converted into a density of fully ionized magnesium using the relation:

\[
\frac{n_{\text{Mg}}}{n_0} = 4 \times n_{\text{obs}} \times \frac{M_{\text{Mg}}}{n_\text{H}},
\]

where \( n_{\text{Mg}}/n_\text{H} \) is the ratio of magnesium number density to hydrogen number density which is derived from the metallically of the host star (Hebb et al. 2009). For WASP-12, \( n_{\text{Mg}}/n_\text{H} = 6.76 \times 10^{-5} \) (Vidotto et al. 2010). From this density, we can then find bow-shock geometries and orientations that fit the HST observations of Fossati et al. (2010).

To investigate whether the model presented by Vidotto et al. (2010) is able to reproduce the data from the near-UV observations, we use Monte Carlo radiative transfer calculations to produce simulated light curves. The parameters we adopt to match the WASP-12 system are \( M_p = 1.41 M_J \), \( R_p = 1.79 R_J \) (where \( M_J \) and \( R_J \) are the mass and radius of Jupiter), \( M_* = 1.35 M_\odot \) and \( R_* = 1.57 R_\odot \). The host star is a late F type and the planet orbits in the equatorial plane with an impact parameter \( b = 0.36 R_\star \) (Hebb et al. 2009).

The shocked material is considered to be at a distance \( r_M \) from the planet, with a thickness \( \Delta r_M \) and an angular extent \( 2\Delta \varphi \). The maximum distance between the planet and the projected lateral extent of the shock, \( X_M \), can take the following forms:

\[
X_M = \begin{cases} 
  r_M & \text{if } \varphi_0 \leq \Delta \varphi \\
  r_M \cos(\varphi_0 - \Delta \varphi) & \text{if } \varphi_0 > \Delta \varphi.
\end{cases}
\]

2.1 Monte Carlo radiation transfer

Our simulated transit light curves are produced using a 3D Monte Carlo radiation transfer code (Wood & Reynolds 1999). The circumplanetary density structure is prescribed on a 3D spherical polar grid (coordinates \( r, \theta, \varphi \)) and is externally irradiated with Monte Carlo photon packets with a distribution that reproduces the spatial intensity distribution of a limb-darkened star. We assume a spherical planet and a limb-darkening law such that the intensity \( I \) is given by

\[
I(\mu) = I(0) \left[ 1 - \sum_{n=1}^{4} a_n (1 - \mu^{n/2}) \right],
\]

where \( \mu = \cos \theta = (1 - r^2)^{1/2}, 0 \leq r \leq 1 \) is the radial distance into the stellar disc normalized to the stellar radius and \( I(0) \) is the emergent intensity at the centre of the star (Mandel & Agol 2002). The coefficients \( a_n \) are chosen from Claret (2004) to match the \( \mu \)-band limb-darkening of the host star. We assume that the material absorbs or scatters radiation out of the line of sight with no scattering into the line of sight, which is valid for the optical depths required to produce the early-ingress transits. For this Letter, we assume the bow shock is of uniform density and that the material is static, however our models are very general and can incorporate any density structure: analytic, tabulated or from dynamical simulations.

2.2 Analysis of the HST observations

Our goal is to determine the range of shock geometries that can provide both an early-ingress and sufficient optical depth in Mg II to
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3 RESULTS

We find that an acceptable fit can be achieved for many different plasma temperatures. These temperatures determine the sound speed and the wind speed. They therefore fix the values of $\varphi_0$ and also the density of the shocked material (Vidotto et al. 2010).

For certain plasma temperatures, however, we are unable to provide a fit to all the data points simultaneously with reasonable shock parameters. For $T = 1 \times 10^6$ K, the calculated density is too low and the light curve is too shallow. Similarly, for $T = 3.93 \times 10^6$ K, the density is too high and the light curve is too deep. We therefore choose to concentrate on two temperatures between these values, $T = 2 \times 10^6$ and $2.5 \times 10^6$ K. Because the magnetic field geometry is very unconstrained, for each of these temperatures we present a solution where the planet is embedded in the corona and hence the shock is an ‘ahead shock’ with $\varphi_0 = 0^\circ$ and also one where it is immersed in the stellar wind, meaning $\varphi_0$ is dependent on the plasma temperature. As illustrative examples, we choose $\Delta \varphi = 80^\circ$ for models 1A and 2A, and $\Delta \varphi = 40^\circ$ for models 1B and 2B, as these values will ensure the end of the near-UV transit will coincide with the end of the optical light curve whilst still providing us with a large projected shock area. For all cases, we then vary $\Delta r_M$ to find a fit to the observations.

Table 1 shows the parameters adopted for our illustrative cases where a fit to all the data points has been found. Fig. 2 shows the simulated light curves and mid-transit images for our models. From the simulations, it is clear that a range of different shock geometries and orientations are able to provide a fit to the data, suggesting there is some degeneracy in the solutions.
First, we find that $X_M$ is a degenerate quantity. The value of $X_M$ is determined by the values of $r_M$, $\varphi_0$ and $\Delta \varphi$, and therefore different combinations of these values can produce the same lateral projected shock extent projected on the plane of the sky. We have found that $X_M = 5.5R_p$ provides an acceptable fit to the data.

As the temperature of the stellar plasma increases, the wind and static coronal models predict a larger density at the planetary orbital radius. Therefore, the projected area of the shock must decrease to ensure the transit is not too deep and can still fit the data. This area is determined by the angular extent $\Delta \varphi$ and the radial extent $\Delta r_M$. For the cases where $\Delta \varphi = 80^\circ$ (models 1A and 2A), a smaller value of $\Delta r_M$ is required to fit the data compared to the cases where $\Delta \varphi = 40^\circ$ (models 1B and 2B). This is a consequence of the line-of-sight distance through the shock increasing as $\varphi_0$ decreases, allowing more lightstar to be absorbed at the shock front.

The addition of a bow shock breaks the symmetry of the transit lightcurve. This can be seen in the simulated light curves as they are not centred around phase $= 1$, but offset by an amount proportional to $X_M$. Again, if better time-sampled observations could be taken, this offset could be used to provide further insight into the stand-off distance between the shock and the planet.

### 4 DISCUSSION

Our simulations have shown that it is possible to reproduce the HST observations of Fossati et al. (2010) by assuming the presence of a bow shock around the planetary magnetosphere. Using models for the stellar corona and wind (with a solar base density), we have calculated the density of Mg II in the shocked material.

Lai et al. (2010) calculated the column density of Mg II around WASP-12b to be $\geq 1.4 \times 10^{13}$ cm$^{-2}$. For this calculation, they assume an optical depth $\tau = 1$ in the absorption line of Mg II, a velocity $v \approx 100$ km s$^{-1}$ and a characteristic length-scale $S = 3R_p$. From this they found the required number density of Mg II to be

$$n_{\text{MgII}} \geq 400 \text{ cm}^{-3}$$

to reproduce the observed early ingress. Using these assumed values, we have calculated the extinction cross-section of Mg II to be

$$\sigma_{\text{MgII}} = \frac{\tau}{n_{\text{MgII}} S} = 6.5 \times 10^{-14} \text{ cm}^2.$$ \hfill (6)

The maximum optical depth $\tau_{\text{max}}$ can then be calculated using equation (6) by setting $S$ to be the maximum path-length in the line of sight through the shocked material along with the corresponding number density of magnesium, $n_{\text{MgII}}$, (from Table 1) for each of our models. These values are shown in the final column of Table 1.

We have found that it is possible to reproduce the observations with both lower and higher Mg II densities and that the resultant shocked material does not need to be optically thick.

If similar bow-shock structures could be observed in other exo-planetary systems, transit observations could be useful to probe the presence of planetary magnetic fields. Vidotto et al. (2011) proposed a list of candidates that could provide signatures of an early ingress, based on the list of available transiting systems in 2010 September. Should UV observations be obtained for these candidates, we could apply the model developed here to constrain the allowed geometries and orientations for bow shocks.

### ACKNOWLEDGMENTS

JL acknowledges the support of an STFC studentship. CH highlights financial support of the European Community under the FP7 by an ERC starting grant.

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