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Probing Planetary Magnetic Fields During Transits

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Abstract

Recently, Fossati et al. observed that the near-UV transit light curve of the close-in giant planet WASP-12b shows an early ingress as compared to its optical transit. Such observations were interpreted as due to the presence of asymmetries in the exosphere of the planet. In particular, we suggest that this asymmetry could be explained by the presence of a shock formed around the planet's magnetosphere. Bow shocks are formed as a result of the interaction of the planet with the coronal material of the host star, similar to the one formed around the Earth's magnetosphere. According to our model, shock detection through transit observations can be a useful tool to probe and constrain exoplanetary magnetic field. In the case of WASP-12b, we derive an upper limit for the magnetic field of $\sim$ 24 G. In addition, we predict that observable shocks should be a common feature in other transiting systems. Promising candidates are: WASP-19b, WASP-4b, WASP-18b, CoRoT-7b, HAT-P-7b, CoRoT-1b, TrES-3 and WASP-5b.

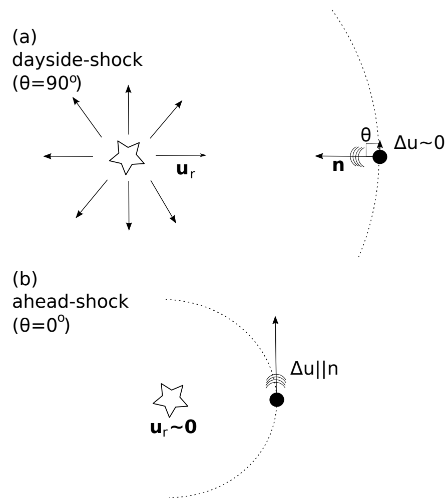

Figure 1: Sketch of shock limits: (a) dayside-shock ($\theta = 90°$), (b) ahead-shock ($\theta = 0°$). Arrows radially leaving the star depict the stellar wind, dashed semi-circles represent the orbital path, θ is the deflection angle between $\mathbf{n} = \mathbf{\Delta u} - \mathbf{u}_r$ and the relative azimuthal velocity of the planet $\Delta \mathbf{u}$. Adapted from [5].

1 The Shock Model

A bow shock around a planet is formed when the relative motion between the planet and the stellar corona/wind is supersonic. The shock configuration depends on the direction of the flux of particles that arrives at the planet. We illustrate two different limits of the shock configuration in Fig. 1, where θ is the deflection angle between the azimuthal direction of the planetary motion and $\mathbf{n}$ is a vector that defines the outward direction of the shock. As seen from the planet, $-\mathbf{n}$ is the velocity of the impacting material.

The first shock limit, a "dayside-shock", occurs when the dominant flux of particles impacting on the planet arises from the (radial) wind of its host star. For instance, the impact of the supersonic solar wind forms a bow shock at the dayside of Earth's magnetosphere (i.e., at the side that faces the Sun). This condition is illustrated in Fig. 1a and is met when $u_r > c_s$, where u_r and c_s are the local radial stellar wind velocity and sound speed, respectively.

A second shock limit, an "ahead-shock" (Fig. 1b), occurs when the dominant flux of particles impacting on the planet arises from the relative azimuthal velocity between the planetary orbital motion and the ambient plasma. This condition is especially important when the planet orbits at a close distance to the star, and therefore, possesses a high Keplerian velocity u_K. In this case, the velocity of the particles that the planet 'sees' is supersonic if $\Delta u = |u_K - u_\varphi| > c_s$, where u_φ is the azimuthal velocity of the stellar corona.

WASP-12b's Magnetic Field

WASP-12b orbits its host star (mass $M_* = 1.35\ M_\odot$, radius $R_* = 1.57\ R_\odot$) at an orbital radius of $a =$

$3.15\ R_*$ [3]. Due to its close proximity to the star, the flux of coronal particles impacting on the planet comes mainly from the azimuthal direction, as the planet moves at a Keplerian orbital velocity of $u_K = (GM_*/a)^{1/2} \sim 230$ km s^{-1} around the star. Therefore, stellar coronal material is compressed ahead of the planetary orbital motion, possibly forming a bow shock ahead of the planet. We believe this material is able to absorb enough stellar radiation, causing the early-ingress observed in the near-UV light curve.

By measuring the phase difference between the beginnings of the near-UV and optical transits, [4] derived the stand-off distance from the shock to the centre of the planet: $r_M \simeq 4.2\ R_p$. We take this distance to be the extent of the planetary magnetosphere. Pressure balance between the coronal total pressure and the planet total pressure requires that, at r_M,

$$\rho_c \Delta u^2 + \frac{[B_c(a)]^2}{8\pi} + p_c = \frac{[B_p(r_M)]^2}{8\pi} + p_p, \quad (1)$$

where ρ_c, p_c and $B_c(a)$ are the local coronal mass density, thermal pressure, and magnetic field intensity, and p_p and $B_p(r_M)$ are the planet thermal pressure and magnetic field intensity at r_M. Neglecting the kinetic term and the thermal pressures in Eq. (1), we have that $B_c(a) \simeq B_p(r_M)$ (see [5]). Assuming that stellar and planetary magnetic fields are dipolar, we have

$$B_p = B_* \left(\frac{R_*/a}{R_p/r_M} \right)^3, \quad (2)$$

where B_* and B_p are the magnetic field intensities at the stellar and planetary surfaces, respectively. Using the upper limit of $B_* < 10$ G provided by [2], our model predicts $B_p < 24$ G for WASP-12b.

Magnetic Fields in Other Exoplanets

To extend the previous model to other transiting systems, near-UV data must be acquired. Here, we classify known transiting systems according to their potential for producing shocks that could cause observable light curve asymmetries (see more details in [6]). We use data from the compilation in http://exoplanet.eu (Sept/2010) and the sky-projected stellar rotation velocities $v_{\rm rot} \sin(i)$ from [7], assuming that $\sin(i) \simeq 1$.

Once the conditions for shock formation are met, for it to be detected, it must compress the local plasma to a density high enough to cause an observable level of optical depth. For a hydrostatic, isothermal corona, the local density at a is

$$\frac{n}{n_0} = \exp\left\{ \frac{u_K^2}{c_s^2}\left[1 - \frac{a}{R_*}\right] + \frac{v_{\rm rot}^2}{c_s^2}\left[\frac{a}{R_*} - 1\right]\right\}, \quad (3)$$

where n_0 is the density at the base of the corona. Assuming $c_s = |u_K - v_{\rm rot} a/R_*|$ (the maximum value that could still allow shock formation), we can obtain a minimum density required for shock formation. Fig. 2 shows this critical density as a function of a for a range of planets, assuming that all stars have a base coronal density equal to that of the Sun (10^8 cm^{-3}). We estimate that a lower limit of $n_{\rm min} \simeq 10^4$ cm^{-3} could still provide detection (dashed line). We note that a reasonable number of planets lie above a detection threshold, suggesting that a detectable shock might be a common feature surrounding transiting planets. The most promising candidates to present shocks are: WASP-19b, WASP-4b, WASP-18b, CoRoT-7b, HAT-P-7b, CoRoT-1b, TrES-3, and WASP-5b.

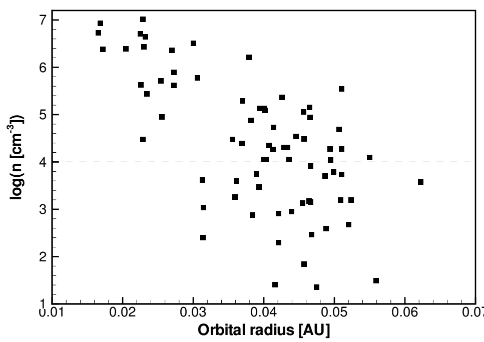

Figure 2: Predicted coronal density at the orbit of each planet, assuming that the stellar magnetic field is strong enough to confine the coronal gas out to the orbit of the planet. The dashed line represents a lower limit for detection of bow shocks. A detectable shock might be a common feature surrounding transiting planets. Figure adapted from [6]

References

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