Transit Timing in the UV: Taking Advantage of Limb brightening

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ABSTRACT

Subject headings: extrasolar planets: transit timing — stellar chromospheres

1. Introduction

Of the exoplanets so far discovered, more than 60 are known to transit their host star. These planets, with their favorable orbital alignment, allow for calculation of planetary radii, stellar radii and average density. Very accurate timing of the transit may reveal even more information about the planet. So called transit timing variation (TTV) measurements (cite something here ??) can reveal deviations from Keplerian elliptical motion due to the tug of another planet or even a satellite.

Conventional transit timing is usuall (or always?) done with optical telescopes. (cite some transit measurement groups?) The light curve of these transits is smooth and therefore the exact time at which egress begins or ingress ends is difficult to pin down exactly (pin down the statistics of this?). Part of the reason for the curves smoothness is the limb darkening of the star: due to the temperature stucture of the star, which decreases in temperature with radius, shallower radial components in the line of sight will appear darker. At the limb, where the shallowest radial component is seen, the photosphere is (??? K), whereas a straight line of sight goes to a deeper radial component and is (K).

In this paper, we outline a method of observing that has the opposite effect: stars are limb brightnened for some wavelengths. In particular, any optically thin chromospheric emission line will be brighter at the limb than in the center. Just as with a planetary nebula, like the Ring Nebula, the limb of a shell of gas is brighter at the edges. This is because the column density at the limb is much larger at the limb than in the center. This is different from the effect of limb darkening, which has to do with the temperature structure of the star. Coincidentally, the chromosphere is slightly temperature inverted so the same effect that causes limb brightening for optical emission can cause limb brightening for optically thick chromospheric lines.

Assef et al. (2009) point out that limb brightening could be very useful for detection of transits of giant planets. One advantage to photometry in limb brightened wavelenghts is that transits are deeper overall than for both limb brightened and uniform disk emission. This is because the planet cover a larger amount of the emission. **?** approximate the limb brightened star as a uniform ring of emission and therefore the amount of light the planet blocks is simply the fraction of the ring covered instead of the fraction of areas. With their approximation, the maximum depth of the transit=(R_p/R_*) instead of the $(R_p/R_*)^2$ as expected for a uniform disk.

A better approximation for the transit depth is to compare the area of the projected planet shadow on the star to the total area of the curved stellar surface. If the scale-height of the chromosphere, h, is much smaller than the size of the planet and star, R_p, R_*, then we can treat the chromosphere as a geometrically thin hemisphere of emission. This limit has the problem that at the edge of the shell, the surface brightness will be infinite; this is an example classic fold-caustic. However, when one integrates the surface brightness over area, the total flux is finite, and thus this still proves to be a useful approximation.

However, rather than integrating over surface brightness to compute the transit depth, the depth of transit is simply the area of the hemisphere that is blocked by the planet, A_t, divided by the total area of the hemisphere, $2\pi R_*^2$.

We can estimate the maximum depth of transit as follows from Figure 1. When the planet touches the edge of the star (second contact), as shown from an edge-on viewpoint in this figure, then the length of the arc of the long axis of the shadow is $R_*\theta$. Now, the diameter of the planet is given by $2R_p \approx R_*(1-\cos\theta) \approx \frac{1}{2}R_*\theta^2$, where the latter approxmiation is valid for $\theta \ll 1$. Solving for θ, we find $\theta = 2\sqrt{R_p/R_*}$, so to be valid we require $R_p/R_* \ll 1/4$. Now, we can approximate the shadow as an ellipse which will have a minor axis of R_p and a major axis of $R_*\theta$, so we can approximate the area of the shadow as

$A_t = \pi\sqrt{R_p R_*} R_p$. Thus, the maximum depth of transit is given by

$$\frac{A_t}{\pi R_*^2} = \frac{1}{2}\left(\frac{R_p}{R_*}\right)^{3/2}. \tag{1}$$

Note that this is a different scaling than that given in Assef et al. (2009) who did not consider the fold-caustic nature of a chromospheric transits.

This has the remarkable consequence that the depth of a chromospheric transit does not decline as much with the radius of the planet as a transit of a uniform disk. A chromospheric transit has a maximum depth that is $\frac{1}{2}\left(\frac{R_*}{R_p}\right)^{1/2}$ times deeper than the maximum transit depth of a uniform disk; thus smaller planets have an advantage to be observed at chromospheric wavelengths, as emphasized by Assef et al. (2009).

could be useful for giant planets, but the scaling is different from their approximation of (R_p/R_*).

-Transit Timing Variations

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Find the presence of other planets/moons and inclinations (Agol et al. 2005). For example, using the Fast Inversion Method (Nesvorný & Beaugé 2010)

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-Limb Brightening

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How we can take advantage of optically thin chromospheric lines

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- We present a more detailed calculation in §2.2 -

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2. Limb Brightening

2.1. Limb Brightened Lines

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Optically thin lines are the most limb-brightnened -

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For M Stars in the Near UV, we'd be looking at -

- FeII, SiII lines from 2300 Å to 2775 Å -

- Don't include the optically thick MgII h and k lines at ∼2800 Å (Hawley et al. 2007) -

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2.2. Chromospheric Light-Curve: Thin-Shell Approximation

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For optically thin chromospheric lines:

$$\delta_{\rm LB} = \frac{A_t}{\pi R_*^2} \approx \frac{1}{2} \left(R_p/R_*\right)^{3/2} \tag{2}$$

$$\delta_{\rm UD} = \left(\frac{R_p}{R_*}\right)^2 \tag{3}$$

where $\delta_{\rm LB}$ is the limb brightnened transit depth and $\delta_{\rm UD}$ is the uniform disk transit depth

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- Eric's figure: projection of planet shadow onto curved surface -

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2.3. Dependence on Planet Size

-Chromospheric transit depths are deeper for the same size planet

-Chromospheric transit depths for small planets are closer to the depths for large planets - Eric's figure: limb-brightnened vs. uniform-disk egresses for two different size planets

-Chromospheric transits allow you to look for transits of giant stars

2.4. Isothermal Chromospheric Models

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- We use the coronal approximation (optical thinness of chromosphere) - Eric's figure of a limb-brightned star

- we assume an opaque photosphere which creates a discontinuity

- A more accurate prediction can made with an exponential emissivity

— When the scale height is larger than the planet, it's a smoother, longer-lived transit

— When the scale height is smaller than the planet, it gets sharper, but starts loosing flux when we can't see the emission from the far side

2.5. Comparison to SOHO data

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- Compare our models to lightcurves from SOHO FeIX images (or lightcurves from STEREO observing the moon crossing the sun)

- explain discrepencies

- discuss differences between M-dwarf or giant chromoshperic transit vs. a sun-like chromospheric transit

3. The Effects of Stellar Activity

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- Starspots - are they a problem?

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- Compare Transit lifetime to flare lifetimes - Select and list more quiescent stars that would be good candidates

4. Signal to Noise Calculations

- What does the NUV flux and (R_p/R_*) have to be to make this feasible?

5. Targets for UV Observations

- I think this is going to be M-dwarfs and giants

- stars where our method beats conventional photometry - Report GALEX fluxes

- Possible telescopes - Swift, Hubble or GALEX

5.1. Chromospheric Science

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- In addition to UV transit timing, we could also study chromospheres -

- We can map out spots and even see how they might migrate as done by Huber et al. (2010)

6. Conclusion

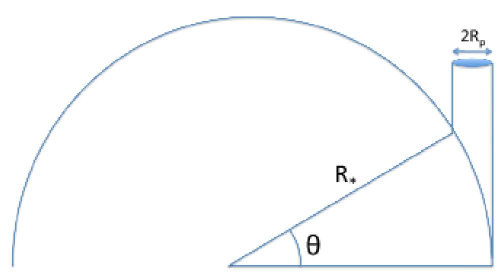

Fig. 1.— Edge-on view of area of shadow cast by the planet at the edge of the star.

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