

HARPS Observes the Earth Transiting the Sun – A Method to Study Exoplanet Atmospheres Using Precision Spectroscopy on Large Ground-based Telescopes

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Exoplanetary transits offer the opportunity to measure the transmission of long, tangential pathlengths through their atmospheres. Since the fraction of the observed stellar light taking these paths is very small, transit photometric and spectrophotometric measurements of light curves require very high levels of measurement stability, favouring the use of intrinsically stable space telescopes. By studying the Rossiter–McLaughlin effect on the radial velocity of the transited star, pure, high-precision radial velocity measurements can be used to estimate the changes in planetary atmospheric transmission with wavelength: a promising method for future studies of small planets with very large ground-based telescopes since it removes the requirement for extreme photometric stability. This article describes a successful feasibility experiment using the HARPS instrument to measure reflected moonlight during the penumbral phases of a Lunar eclipse, effectively providing an observation of an Earth transit.

Introduction

Lunar eclipses provide an opportunity to study the atmospheric properties of the Earth in a geometry that is similar to that of an exoplanet transiting its parent star. During such a transit, the small fraction of the stellar light that grazes the exoplanet's atmosphere carries the imprint of the atmospheric composition and its distribution with altitude. This signature has been detected photometrically (often spectrophotometrically) and interpreted for a number of exoplanetary systems and has provided the first

glimpses of planetary atmospheres beyond the Solar System. Analogous studies of Lunar eclipses over recent years (Pallé et al., 2009; Vidal-Madjar et al., 2010; Arnold et al., 2014; Yan et al., 2015a) have allowed us to construct a baseline to be used for future exoEarth atmospheric characterisation.

Since the atmospheric signature is encoded within a tiny fraction of the total stellar light, the photometric observations require the extreme precision and stability that can be achieved relatively easily in space. For ground-based observations however, continuous monitoring of standard stars falling within the field of view of the observing instrument is required. An alternative observational technique, based on the well-known Rossiter–McLaughlin (RM) effect, allows us to access the effective radius of the transiting planet and its variation with wavelength by making precision radial velocity measurements of the star outside of and within the transit. The classical Rossiter–McLaughlin effect was first used for the study of eclipsing binary stars (McLaughlin, 1924; Rossiter, 1924) and describes the radial velocity anomaly of a star when a body (star in the case of an eclipsing binary, or a planet) passes in front of a star, occulting a small area of the rotating stellar surface.

Our method, based on the RM effect, exploits the masking of different parts of the stellar disc as the transit proceeds, producing varying combinations of stellar rotational and surface motions that depend both on the position of the transiting planet within the stellar disc and on its effective radius. Since the effective radius is a proxy for the variation of the transmitted light as a function of wavelength, the radial velocity signal will carry information about the planet's atmospheric composition. This application of the RM effect, first suggested by Snellen (2004), has the important advantage of not requiring high photometric precision and so is very suitable for large ground-based telescope observations employing stable, high resolution spectrometers; a procedure that does not require the monitoring of reference stars.

In order to explore and test the feasibility of this RM-based technique, we have

applied it to observations of a Lunar eclipse made with the High Accuracy Radial velocity Planetary Searcher (HARPS) spectrograph on the 3.6-metre telescope at La Silla. We show that such an observation enables us to retrieve the transmission spectrum of the Earth's atmosphere at a level that clearly shows the Rayleigh scattering and the ozone Chappuis band absorption (Yan et al., 2015a).

Lunar eclipses and exoplanet transits

A Lunar eclipse is a relatively frequent astronomical phenomenon that must have excited interest since early hominids gazed at the sky. The phenomenon occurs when the Moon traverses the shadow of the Earth. During an eclipse, the Moon first moves into the Earth's penumbra making the Lunar surface brightness drop dramatically. It will then, if the geometry is right for a total eclipse, pass into the umbra to produce the deep-red Copper Moon that is mostly, but not entirely, the result of Rayleigh scattering in the Earth's atmosphere.

If your point of view was on the Lunar surface itself, you would actually witness the Earth transiting the Sun. This is similar to an observation of an exoplanet transiting its star (visualised in Figure 1) with the obvious difference in the relative angular sizes of the star and the planet. Consequently, by employing the Moon as a mirror, we are able to regard the Earth as an exoplanet and to observe its transit. Such an observation gives us the chance to test and tune methods and strategies for studying, hopefully in the near future, the transits of Earth-like exoplanets.

The HARPS observation

The typical way of observing a transit signal employs photometry, i.e., observing the light curve. However, pure, precision spectroscopic observations can also be applied by utilising the RM effect. This method has now been applied to more than 80 exoplanet systems to give information about stellar rotations and planetary orbital geometries.

In order to obtain the RM effect of the Earth transiting the Sun, we have

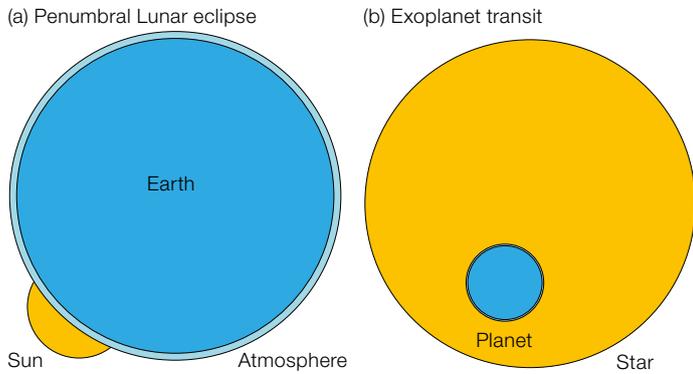


Figure 1. (a) Schematic of the Earth and the Sun viewed from the Moon during the penumbral Lunar eclipse. (b) Schematic of an exoplanet transit. The geometries of both are similar.

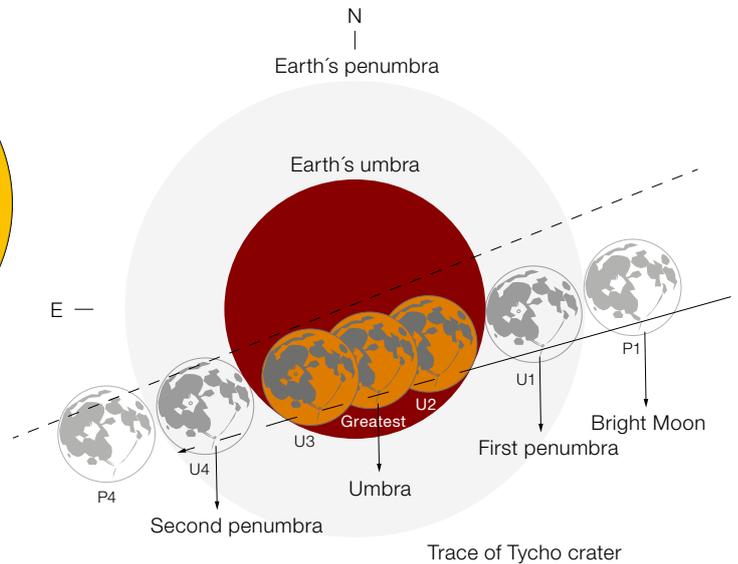


Figure 2. The trajectory of the Lunar crater Tycho during the HARPS observation. The observation covers all the stages of the eclipse. The figure is reproduced from the NASA Lunar eclipse page¹.

observed spectra of a fixed point on the eclipsed Lunar surface as the penumbral eclipse proceeded. Our observations were made throughout the Lunar eclipse of 15 April 2014, for which the entire eclipse was visible from the La Silla Observatory, using HARPS (Yan et al., 2015a). We chose to observe the Tycho crater for this observation because its albedo is high and a large part of its trajectory lies within the penumbral region (see Figure 2 for the trajectory of the crater Tycho).

In total, we obtained 382 Lunar spectra that cover all the eclipse stages, i.e., the penumbral eclipse, the umbral eclipse and out of eclipse (which we call here the bright Moon). The radial velocities (RVs) derived from these spectra are measured and are plotted in Figure 3. Here the RV caused by the orbital motions of the Sun–Earth–Moon system have been corrected using the Jet Propulsion Laboratory (JPL) Horizon Ephemeris².

The plot in Figure 3 shows the RV curve of the Rossiter–McLaughlin effect of the Earth transiting the Sun. When the Moon enters the first penumbra, the Earth begins to block the redshifted part of the Solar disc, thus the observed RV becomes negative (a negative value means the spectrum is blueshifted). At the umbral stage, the RV gradually changes from a blueshift to a redshift. The detailed umbral RV is relatively complicated because it is influenced by the actual properties (including cloud patterns) of the Earth's atmosphere as it refracts the sunlight. When the Moon enters the second penumbral stage, the RV is redshifted since the Earth obscures mainly the blueshifted rotating region of the Solar disc. The RV gradually decreases during this stage as the Moon moves out of the penumbral shadow.

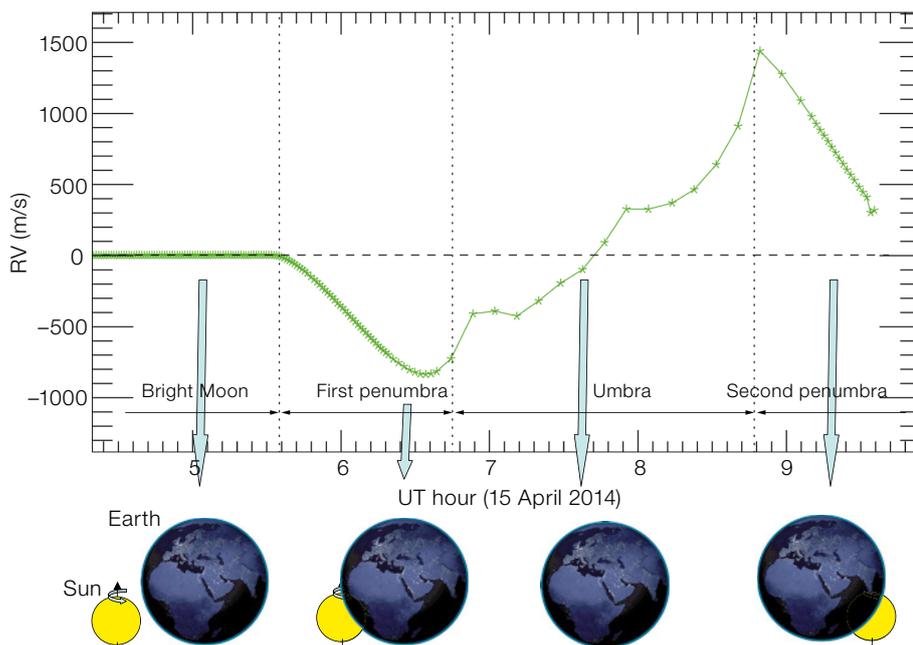


Figure 3. The observed RV during the Lunar eclipse. This is the Rossiter–McLaughlin effect RV curve of the Earth transiting the Sun. The schematic of the Earth–Sun system as viewed from the Moon is indicated at the bottom.

The transmission spectrum of the Earth's atmosphere

Transmission spectroscopy is one of the main techniques employed to characterise exoplanet atmospheres. The traditional way is to observe the planetary absorption by comparing the stellar spectra in and out of transit. With transmission spectroscopy, various molecular and atomic species in exoplanet atmospheres, such as CH_4 , H_2O , CO_2 and sodium have been discovered.

As was pointed out by Snellen (2004), the amplitude of the RM effect is wavelength-dependent because it is determined by the effective planetary radius, which is modulated by the wavelength-dependent differential atmospheric absorption. Thus the wavelength-dependent RM amplitude encodes the transmission spectrum of the planetary atmosphere.

We analysed the RM effect of the Earth transit at different wavelengths — in bands defined by the individual HARPS echelle orders — and Figure 4 shows the wavelength-dependent RM amplitudes. The Sun itself has wavelength-dependent parameters such as limb darkening and the spectral line blueshift caused by Solar convection. By utilising the fact that the stellar rotation is antisymmetric across the transit path while the surface motions are symmetric with respect to the Solar disc centre, we have removed the second of these effects and thus the structure of the RM amplitude RV curve is dominated by the Earth's atmospheric transmission.

The transmission spectrum of the Earth's atmosphere has been observed and modelled before (e.g., Yan et al., 2015b). It is known that atmospheric scattering and ozone absorption are the dominant features at optical wavelengths in the Earth's transmission spectrum. Ozone is particularly interesting because it originates from molecular oxygen and its presence is regarded as a bio-signature.

In order to better understand the result in Figure 4, we built a transmission spectral model that contains the ozone absorption and the Rayleigh scattering of the Earth's atmosphere. The model is overlaid on the RM amplitude curve and their overall

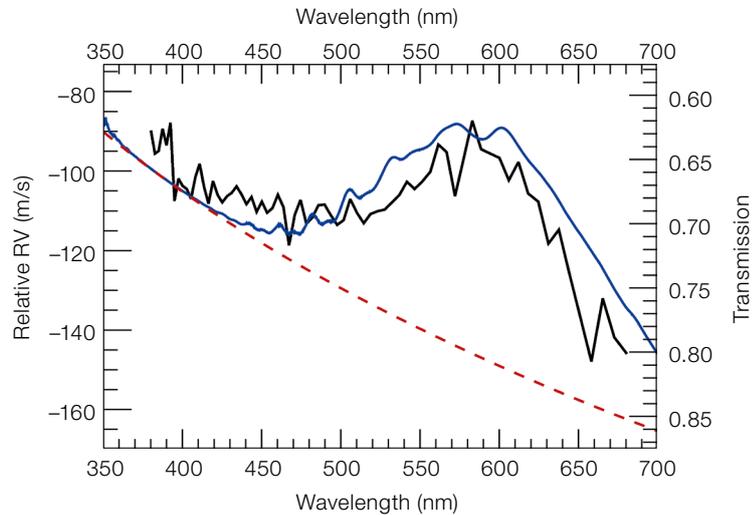


Figure 4. The RM amplitude at different wavelengths (black line). Here the RVs are relative values. The transmission spectral model of the Earth's atmosphere is also plotted (blue line) for comparison. The red dashed line indicates the Rayleigh scattering contribution in the spectral model.

structures are seen to be very similar. In the blue part of the spectrum, the RM amplitude is large because the Rayleigh scattering is strong and thus the atmosphere appears thicker. The broad peak around 600 nm is due to ozone Chappuis band absorption. The RM amplitude towards the red becomes smaller because both the ozone absorption and the Rayleigh scattering get weaker, making the effective atmospheric thickness smaller.

Exoplanet atmosphere characterisation

Our Lunar eclipse observation with HARPS demonstrates the RM effect method to be an effective technique for atmosphere characterisation. A particular advantage of this method compared to the traditional spectrophotometric technique is that no photometric reference star is needed. Thus this method is a particularly promising technique for exoplanet atmosphere characterisation using very large ground-based telescopes, such as the European Extremely Large Telescope (E-ELT).

Observing the RM effect during a Lunar eclipse is relatively easy since the Moon is much closer to the Earth than to the Sun, amplifying the transit signal. For

exoplanet transits, the radial velocity change caused by the planetary atmosphere is very much smaller and is consequently more difficult to measure. However, with the next generation very large telescopes and high precision, high stability instruments, such as the HIRES on the E-ELT and the Echelle Spectrograph for Rocky Exoplanet and Stable Spectroscopic Observations (ESPRESSO) on the Very Large Telescope, the RM method is ready to be applied to exoplanet atmospheric characterisation.

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References

- Arnold, L. et al. 2014, *A&A*, 564, A58
- McLaughlin, D. B. 1924, *ApJ*, 60, 22
- Molaro, P. et al. 2013, *MNRAS*, 429, L79
- Pallé, E. et al. 2009, *Nature*, 459, 814
- Rossiter, R. A. 1924, *ApJ*, 60, 15
- Snellen, I. A. G. 2004, *MNRAS*, 353, L1
- Vidal-Madjar, A. et al. 2010, *A&A*, 523, A67
- Yan, F. et al. 2015a, *ApJ Letters*, 806, L23
- Yan, F. et al. 2015b, *International Journal of Astrobiology*, 14, 255

Links

- ¹ The NASA Lunar eclipse page: <http://eclipse.gsfc.nasa.gov/lunar.html>
- ² The JPL Horizon Ephemeris: <http://ssd.jpl.nasa.gov/?ephemerides>