HARPS Observations of the 2012 Transit of Venus

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On 6 June 2012 the black disc of Venus passed across the Solar disc, taking nearly eight hours to complete the transit. The event was followed by millions of people worldwide. The transit of Venus is one of the rarest astronomical events, occurring approximately every 120 years. By means of HARPS spectroscopic observations, and using the Moon as a mirror, we detected the Rossiter–McLaughlin effect due to the eclipse by Venus of the Solar disc with a precision of few cm s^{-1}. The observation demonstrates that this effect can be measured even for transits of exoplanets of Earth size, or even smaller, provided enough photons can be collected by a very high resolution and extremely stable spectrograph, such as the planned HIRES instrument for the E-ELT.

A bit of history

In 1627, Kepler, in one of the first applications of the Copernican view of the cosmos, first predicted that there would be transits of the inner planets and the transit of Venus in 1631 in particular. However, Kepler had died in 1630 and Gassendi, who was the first to document a transit of Mercury, also missed the predicted transit since this transit of Venus could not be observed from Europe. However the young (22 years old) British astronomer Jeremiah Horrocks realised that transits of Venus occur in pairs separated by eight years, and in 1639 he and his friend William Crabtree were the humans to observe the phenomenon. Horrocks (1618–1641) wrote a poem commemorating the event:

... Thy return
Posterity shall witness; years must roll
Away, but then at length the splendid sight
Again shall greet our distant children's eyes.

Since then only six other transits have taken place in three epochs, namely 1762–1769, 1874–1882 and 2004–2012; there will not be another Venus transit until December 2117. As shown in Figure 1, taken from an old book by Proctor (1874), the cycle of the transits of Venus is precisely 243 years, so that of 2012 was similar to the one observed by James Cook from Tahiti in 1769 during his first voyage around the world, which led to the discovery of New Zealand and the Cook Islands. The observations by Cook and the astronomer Charles Green were recorded in a paper (Cook & Green, 1771) from which a figure is reproduced in Figure 2. In 1716 the Royal Astronomer Sir Edmund Halley, in an article entitled "A new Method of determining the Parallax of the Sun, or his Distance from the Earth", published in the Philosophical Transactions (Halley, 1716), suggested the use of observations of the transit of Venus to find a value for the distance of the Earth from the Sun, i.e. the astronomical unit (AU):

We therefore recommend again and again, to the curious investigators of the stars to whom, when our lives are over, these observations are entrusted, that they, mindful of our advice, apply themselves to the undertaking of these observations vigorously. And for them we desire and pray for all good luck, especially that they be not deprived of this coveted spectacle by the unfortunate obscuration of cloudy heavens, and that the immensities of the celestial spheres, compelled to more precise boundaries, may at last yield to their glory and eternal fame.

Astronomers did indeed organise major expeditions to the remotest parts of the world to obtain an estimate of the magnitude of the astronomical unit. From an initial value of about 10 million kilometres, as set by the ancient Greeks, the AU was increased to 120–155 million kilometres at the end of the 18th century and further refined by measurements during the transits of the 19th century to 149 341 924

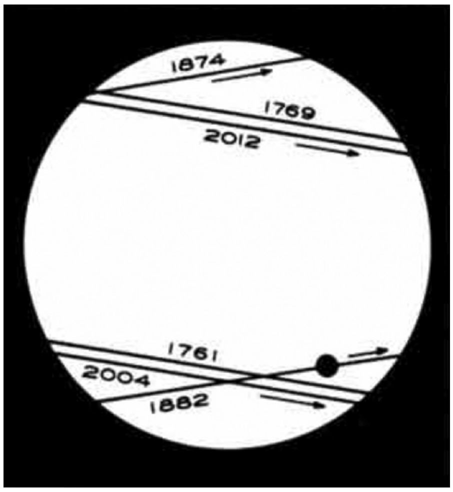


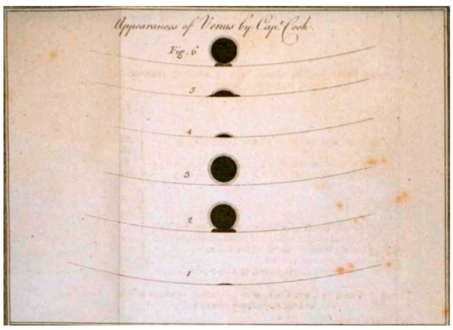
Figure 1. Sketch of the transits of Venus by Richard Antony Proctor (Proctor, 1874).

(± 96 076) kilometres, thanks to photographic recording (Harkness, 1888). A stunning video of the 2012 transit of Venus was captured by the Solar Dynamics Observatory and can be seen on the NASA website[1].

Science with the transit

In 1874 the young Kingdom of Italy organised an astronomical expedition to Madhapur, India, with the aim of observing the transit of Venus spectroscopically for the first time. In 1875 the Italian astronomer Tacchini sent a telegram from Calcutta: "First observations disturbed by small clouds – Good results spectroscopic and ordinary – Spectrum of Venus observed, details probably related to its atmosphere." (Pigatto & Zanini, 2001). We know today that this was not possible,

Figure 2. Drawing of the observations of the 1769 transit of Venus from Tahiti, taken from Cook & Green (1771).



since the atmosphere of Venus is too tiny to be detected in this way. However, after 138 years, on the occasion of the last transit, we found a new way to exploit spectroscopic observations of the transit of Venus by detecting the very small Rossiter–McLaughlin (RM) effect. When a body passes in front of a star the consequent occultation of a small area of the rotating stellar surface produces a distortion of the stellar line profiles, which can be measured as a drift of the radial velocity. The phenomenon was observed in eclipsing binaries by McLaughlin (1924) and Rossiter (1924) and in the Jupiter-like planets (Queloz et al., 2000), but becomes increasingly difficult to observe when the eclipsing body is as small as a planet and, in particular, for an Earth-sized planet such as Venus. The RM effect has been observed in about 60 extrasolar planets, providing important information on the angle between the sky projection of the orbital axis and the stellar rotation axis, and showing that several exoplanets have tilted orbits.

Most surprisingly, the integrated light of the Sun at high spectral resolution, which is needed to reveal the RM effect, is extremely difficult to obtain with direct observations. The simplest workaround is to collect the Solar light as reflected by the Moon or by other minor bodies of the Solar System. Chile was out of the visibility strip for the transit of Venus (c.f., Figure 3); a few weeks before the event we submitted a Director's Discretionary Time (DDT) proposal to observe the RM effect from Chile at night. The purpose was to detect the RM effect caused by the transit of Venus using the almost full Moon as a mirror (DDT 289.D-5015).

There are a few differences that have to be considered. Due to the different spatial location, the transit of Venus as seen from the Moon has a slightly different timing and projection on the Solar disc from that which is seen from Earth. The Moon was about eight degrees ahead of the Earth and Venus reached the Sun–Moon alignment with a delay of about two hours. The transit was also slightly longer than from Earth since the Moon was above the rotation plane of the Earth–Sun.

Our observations with HARPS began at 2 h:44 m UT on 6 June 2012 when the Moon reached about 40° above the horizon at about mid-transit and continued until the end of the transit, and for some time afterwards. The observations comprised a series of 245 spectra, each with an integration time of 60 s with 22 s of readout, and delivered a signal-to-noise ratio of ~ 400, each at 550 nm at a resolving power of R ~ 115 000. The first 227 observations cover the phases between about mid-transit to the end and for about two hours after the passage. Eighteen additional observations were also taken at twilight a few hours after the passage, and were used to fix the reference of the Solar radial velocity.

The radial velocities were obtained by the HARPS pipeline. Simultaneous spectra were collected with a reference ThAr lamp and used to correct overnight instrumental drifts, which were about 40 cm s^{-1} at the beginning and undetectable, i.e. less than 20 cm s^{-1}, after a couple of hours of observations. The relative motions of the Moon with respect to the Sun and the usual one due to the observer were accounted for. The barycentric radial velocities were then measured relative to the out-of-transit Solar radial velocity, which was measured as the mean value of all the out-of-transit observations and had a value of 102.53 ± 0.10 m s^{-1}. This latter quantity comprises the zero offset of the mask used in the cross-correlation by the HARPS pipeline, plus specific motions of the Sun on that day. The resulting radial velocities and their temporal evolution in phase with the transit are shown in Figure 4. The values show clearly the Solar 5-minute oscillations of the p-modes, but also a clear trend in phase with the passage of Venus in front of the receding hemisphere, with a half amplitude modulation of ~ 80 cm s^{-1}.

For the configuration of Venus, Sun, Moon and Earth it is possible to make a very accurate model for the RM effect, which considers Solar differential rota-

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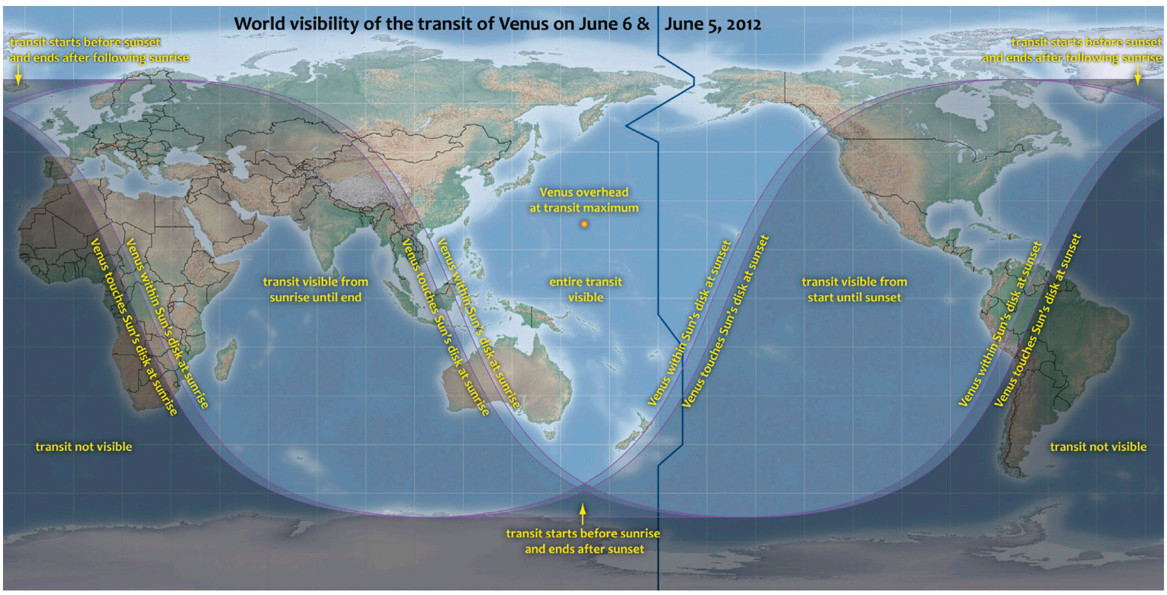

Figure 3. Visibility of the transit of Venus on 6 June 2012 as seen from the Earth. From the Moon it is slightly different, being longer and delayed by a couple of hours (see text).

tion, limb darkening and Solar axis inclination. The theoretical model is compared with the observations in Figure 4 as a continuous blue line. Note that this is not a fit to the data but an independent theoretical model of the RM effect. Once the p-mode oscillations have been filtered out, the radial velocity difference between the model and the observations is –4 cm s^{-1}. This offset can be entirely ascribed to our ability to establish the out-of-transit Solar radial velocity needed for the normalisation; this latter is known with an uncertainty of ~ 10 cm s^{-1}.

This is the smallest radial velocity effect ever detected with HARPS and it demonstrates that the RM effect can be detected despite the fact that the radial velocity change due to Venus is comparable to that of the Solar oscillation. The RM effect is one of the most promising ways by which astronomers plan to study exoplanets and new high resolution spectrographs at the E-ELT are also proposed for this purpose. The present observations show that an RM effect as small as those caused by Earth-like planets eclipsing their host star could be detected even in the presence of a comparable stellar jitter.

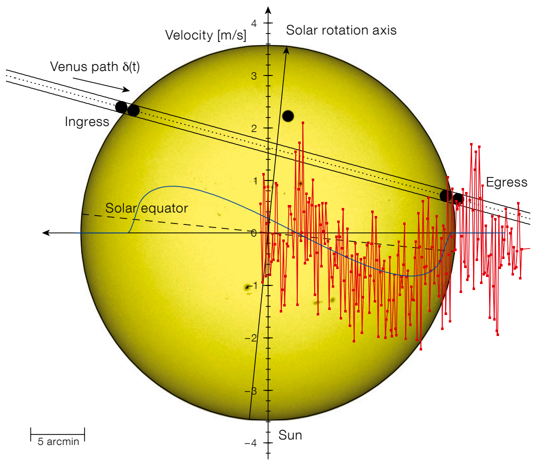

Figure 4. The Solar disc from the Solar Dynamics Observatory image of the Sun on 6 June 2012 with the path of the transit of Venus as seen from the centre of the Moon drawn in. Radial velocity measurements (the red points connected by the red line) from the 227 Solar spectra during the transit are shown (*x*-axis is time). The thin continuous blue line shows the theoretical RM effect. The radial velocities show clearly the 5-minute Solar oscillations as well as a decrease in the second part of the transit, up to 80 cm s^{-1}, due to the partial coverage of the receding Solar hemisphere by Venus.

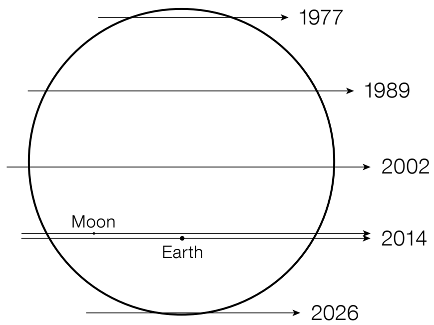

Figure 5. The tracks and dates of the Earth's transits across the Solar disc as seen from Jupiter are shown, adapted from a figure in Meeus (1989). For the transit in 2014, the Moon, at a distance of 1′47.4″ from Earth, is also shown. The Moon will produce its own eclipse of a small portion of the Solar disc, with an estimated RM effect of only ~ 2 cm s^{-1}.

Goodbye until 2117 (or is it?)

The next transit of Venus will occur in December 2117 so the observations described here cannot be repeated or improved by any other kind of instrument. The only other transit visible directly from the Earth in the next few years will be the one of Mercury on 9 May 2016, which occurs during the day in South America, between 11:12 and 18:42. However, we may not need to wait for 105 years for another similar opportunity. In the Solar System other transits can be seen from the other planets too, with only the exception of the innermost planet Mercury. More interestingly, the Earth too is seen transiting in front of the Sun from the outer planets. A transit occurs every time the heliocentric conjunctions take place near one of the nodes of their orbits. Accurate computations of the transits of all planets of the Solar System were made by Meeus (1989). He found that the Earth will be seen transiting the Sun from Mars in 2084. More interestingly the Earth will be seen transiting the Sun from Jupiter on 5 January 2014, and then again in 2026. As shown in Figure 5, where all the passages are drawn, the transit of 2026 will be a grazing one, quite unfavourable for any kind of observation. So effectively the transit occurring next year is a unique event, providing an opportunity to repeat the experiment, but with an Earth transit instead of that of Venus.

The predicted RM on this occasion will also be even smaller. From Jupiter the angular size of Sun is 369 arcseconds and of the Earth 4.2 arcseconds, so that the predicted modulation of the RM effect is only about about 20 cm s^{-1}. Interestingly, together with the Earth, the Moon will also produce a transit on the Solar surface. The transit of the Moon will be delayed by about four fours from the transit of the Earth.. The RM effect due to the Moon will only be about 2 cm s^{-1} and is probably beyond the limit of our technique. This is a unique configuration where we can possibly detect the RM effect of an Earth-size planet together with its moon. The presence of moons could be quite a common configuration among exoplanets and this will represent a sort of unique test-bench experiment. As for all unique experiments, a certain dose of good luck is required in order to have a clear sky. This is something that Jeremiah Horrocks certainly had when he first observed the transit of Venus through the cloudy English sky.

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Links

[1] Solar Dynamics Observatory Venus transit video: http://www.nasa.gov/mission_pages/sunearth/multimedia/venus-transit-2012.html