Simultaneous HARPS and HARPS-N Observations of the Earth Transit of 2014 as Seen from Jupiter: Detection of an Inverse Rossiter–McLaughlin Effect

Paolo Molaro[1]
Lorenzo Monaco[2]
Mauro Barbieri[3]
Simone Zaggia[4]
Christophe Lovis[5]

[1] INAF – Osservatorio Astronomico di Trieste, Italy
[2] Departamento de Ciencias Fisicas, Universidad Andres Bello, Santiago, Chile
[3] Departamento de Fisica, Universidad de Atacama, Copiapo, Chile
[4] INAF – Osservatorio Astronomico di Padova, Italy
[5] Geneva Observatory, University of Geneva, Versoix, Switzerland

Although there will not be another transit of Venus visible from the Earth until 2117, transits of other planets, including Earth, will be visible from other planets. We describe high resolution spectroscopic observations of the transit of Earth visible from Jupiter in January 2014 made with the HARPS North and South spectrographs. A Rossiter–McLaughlin effect was observed but with reverse sign and ~ 200 times larger. The result, presented in Molaro et al. (2015), was not at all what was expected and the explanation eventually led to the discovery of a new effect, a sort of inverse Rossiter–McLaughlin effect that has never been observed before.

Transits in the Solar System

Transits of Venus and Mercury in front of the Sun are major historical events. Johannes Kepler in 1627 predicted the transit of Venus of 1631, but died one year before the event, and Pierre Gassendi, who tried to observe the transit, missed it since it was not visible from Europe. Jeremiah Horrocks realised that transit of Venus occur in pairs separated by eight years and he successfully observed the transit in 1639. Since then only six other transits of Venus have taken place. In 1716 Sir Edmund Halley suggested the use of the transits of Venus to find a value for the distance of the Sun, the astronomical unit. Major expeditions to the most remote parts of the world were organised and a value for the astronomical unit was obtained with Halley's method.

On 6 June 2012 using the Moon as a mirror, we detected the Rossiter–McLaughlin (RM) effect due to the eclipse by Venus of the Solar disc with a precision of few cm s^{-1} (Molaro et al., 2013). When a body passes in front of a star the 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 in the radial velocity. The phenomenon was first observed in eclipsing binaries by McLaughlin (1924) and Rossiter (1924). The RM effect has now been observed in almost one hundred exoplanets, providing important information on orbital geometry and showing that several exoplanets have very tilted orbits. The Venus observations demonstrated that the RM effect can be measured even for transits of exoplanets of Earth size or smaller, and that transits in the Solar System can be studied with reflected sunlight.

The observation of the transit of Venus via the Moon implies that other transits can also eventually be seen in the Solar System, since transits from other planets occur each time heliocentric conjunctions take place near one of the nodes of their orbits, with the obvious exception of the innermost planet, Mercury. These rare events have been studied in detail by Meeus (1989), who found that the Earth will be seen transiting the Sun from Mars in 2084 and from Jupiter on 5 January 2014, and again in 2026.

Observations of the 2014 Earth transit

During transits, the integrated Solar light can be recorded as it is reflected by the planet from which the Earth is seen to be transiting in front of the Sun, thus offering a surrogate for a direct view. Jupiter itself is not a good sunlight reflector due to its high rotational velocity and to the turbulent motions of its atmosphere, but its major rocky moons are better reflective mirrors. In Figure 1 the Earth and the Moon are shown as they would appear to an observer on Jupiter on 5 January 2014. Due to the small angular size of the Earth, the predicted RM effect is extremely small, only about ~ 20 cm s^{-1}. Interestingly, together with Earth, the Moon will also produce a transit on the Solar surface, but with an even smaller RM of ~ 2 cm s^{-1}.

The timing of the Earth transit differs slightly between the moons and Jupiter itself and varies from one moon to another: the moons arrive at the alignment slightly before the planet, about 30 minutes in the case of Europa and about one hour for Ganymede. The view of the Jovian system on 5 January 2104 from an observer on the Sun is illustrated in Figure 2. The moon Io was behind Jupiter during part of the event.

Unfortunately in January 2014 there was no suitable observing site on Earth where Jupiter could have been observed during the entire length of the transit. The transit could not be observed at all from Mauna Kea and the high spectral resolution facilities that could deliver very precise radial velocity measurements for the duration of the transit were not available at other suitable astronomical sites. La Palma and La Silla were the only observatories where a fraction of the phenomenon could be followed with high resolution spectrographs that are able to deliver the required radial velocity precision.

The two High Accuracy Radial velocity Planetary Spectrographs (HARPS) at La Silla and La Palma are twins. They are both housed in a vacuum, are thermally isolated, stable and equipped with an image scrambler that provides the uniform spectrograph–pupil illumination that is essential for high precision radial velocity observations. The HARPS-N (La Palma) and HARPS (La Silla) observations that we made comprise a series of hundreds of spectra of Europa and Ganymede covering the range from 380 to 690 nm. At the epoch of the observations, Europa and Ganymede had visual magnitudes of 5.35 and 4.63 mag and apparent diameters of 1.02 and 1.72 arcseconds, respectively. The integration times of the observations were 60 or 120 s and delivered a signal-to-noise ratio of ~ 200 each at 550 nm with a resolving power of R ~ 115 000. The observations are described in Molaro et al. (2015).

We started observing Ganymede on the night preceding the transit in order to determine the pre-transit characteristic

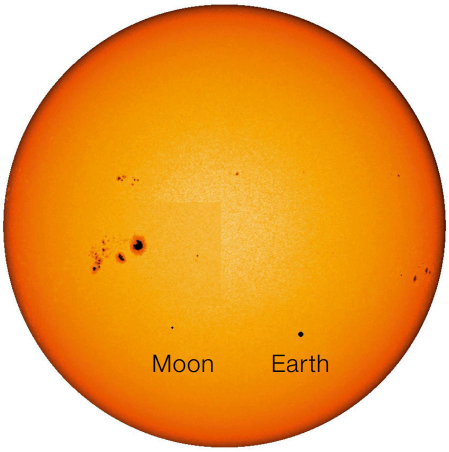

Figure 1. Composite image of the Sun with the Earth and Moon as seen from Europa at 19:00 UT on 5 January 2014. The sizes are to scale with the Earth's size of 4.2 arcseconds and the diameter of the Solar disc of 369 arcseconds. The Solar image is from a Solar Dynamics Observatory (SDO)/NASA Helioseismic and Magnetic Imager (HMI) Intensitygram at 617.3 nm on 5 January 2014 and shows prominent sunspots in the approaching Solar hemisphere. The total duration of the passage was 9 h 40 m.

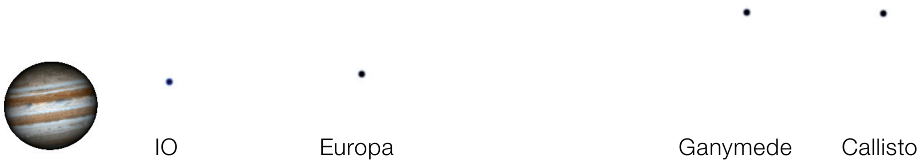

Figure 2. View of the Jovian system on 5 January 2014 from an observer on the Sun or on the Earth. From Jupiter the Earth transit started at MJD (Modified Julian Date) 56662.70, while its moons arrived somewhat in advance of the alignment with Jupiter.

Solar radial velocity. The following night we selected Europa to cover the second fraction of the transit as much as possible. In the night following the transit, we made observations of both Europa and Ganymede to determine the post-transit characteristic Solar radial velocity.

The radial velocities were obtained with the HARPS and HARPS-N pipelines, but we computed the proper kinematical corrections. These included not only the motions of the observer relative to Jupiter's moons at the instant when the light received by the observer was reflected by the moons, but also the radial velocity components of the motion of the moons relative to the Sun at the instant the light was emitted by the Sun. All these quantities have been computed using Jet Propulsion Laboratory (JPL) Horizon Ephemerides[1] following the recipies of Molaro and Monai (2012).

A radial velocity anomaly

The whole set of corrected Solar radial velocities obtained from the spectra of Jupiter moons taken over the course of the three nights from both sites, after subtraction of the radial velocity baseline of 107.5 m s^{-1}, is shown in Figure 3.

The La Palma observations show a sudden drop of ~ 7 m s^{-1} after about one hour. Moreover, at the start there is a difference of about 4 m s^{-1} between the two spectrographs, with the La Silla sequence slightly lower. In the following night at about mid-transit the radial velocity rose very quickly until it reached a peak of 37 m s^{-1} and then declined almost monotonically, with a persistent small difference between the two spectrographs. In the night after the transit, the radial velocities are back to the values preceding the transit.

The observed pattern was completely at odds with our expectations: when observed, the Earth was eclipsing the receding Solar hemisphere and the RM effect should have produced a small blue shift of the lines. On the contrary, we observed a redshift change of 37 m s^{-1}, i.e. ~ 400 times greater than expected. Also the radial velocity drift lasted well beyond the end of the transit. The anomaly in radial velocity cannot have an instrumental origin. This is demonstrated by the fact that the two observatories give consistent results and such large RV anomalies have never been observed with these spectrographs. Thus the anomaly must have a physical origin.

It is known that Solar activity could affect the radial velocity of the Solar lines and indeed in Figure 1, the Solar image of 5 January 2014, does show the presence of several sunspots. However, the characteristic change in radial velocities is on a timescale of the Solar rotation and therefore no effect is expected during a relatively short period of ~ 10 hours. We inspected the Birmingham Solar Oscilla-

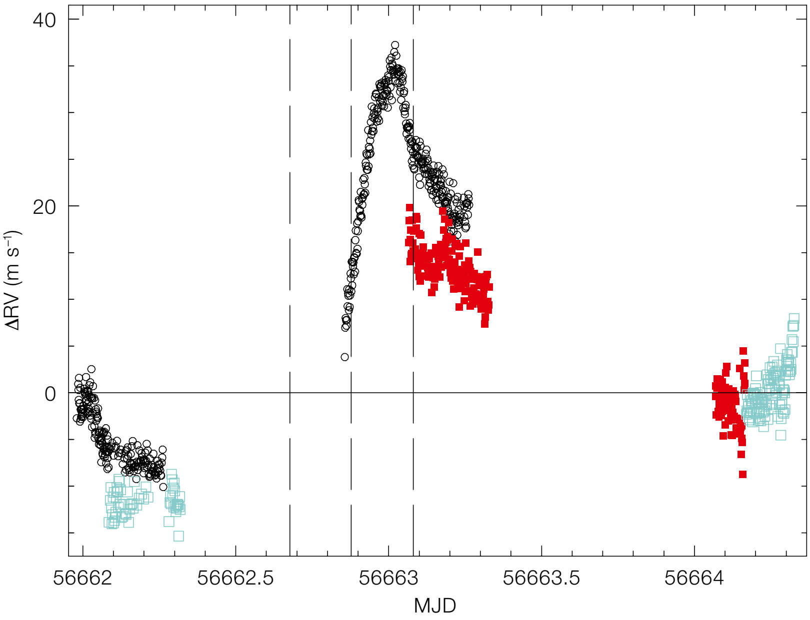

Figure 3. Radial velocities measured with HARPS on 4–6 January 2014. Open black circles are observations of Europa from La Palma while colour squares are the observations of Ganymede (cyan) and Europa (red) from La Silla. A constant offset of 107.5 m s^{-1}, as measured far from the transit, is taken as the instrumental baseline and was subtracted from the data. The vertical dashed lines mark the expected ingress and egress of the Earth's transit as seen from Europa.

tions Network (BiSON) archives containing Solar radial velocities for January 2014 to check whether short-term strong Solar activity coincided with the transit. The BiSON data were captured from several sites and provided continuous monitoring of the Solar activity proximate to the transit. The BiSON velocity residuals are shown in Figure 4 and do not show any peculiarity, thus ruling out definitively the possibility that the anomalous radial velocities depend on a peak of activity of the Sun.

An inverse RM effect induced by the opposition surge

Thus the effect is real, and it took us a whole year to understand that what is observed was due to an entirely new phenomenon produced by the opposition surge on the icy moon Europa (Molaro et al., 2015).

The opposition surge is the brightening of a rocky celestial surface when it is observed at opposition. The precise physical origin is not yet completely understood and "shadow hiding" or coherent backscatter have been proposed. The former stems from the fact that when light hits a rough surface at a small phase angle, all the shadows decrease and the object is illuminated to its largest extent. In the coherent backscatter theory, the increase in brightness is due to a constructive combination of the light reflected from the surface and by dust particles. The constructive combination is achieved when the size of the scatterers in the surface of the body is comparable to the wavelength of light. At zero phase, the light paths will constructively interfere, resulting in an increase in the intensity, while as the phase angle increases constructive interference decreases.

A characteristic feature of the opposition surge is the brightening of the planet as the phase angle decreases. During the transit, Solar photons which graze the Earth have smaller angles than photons coming from regions of the Solar disc far away from the Earth's edge. Thus they produce an effective increase in the radiation coming from the region of the Sun just behind the Earth as it moves across the face of the Sun. During its passage across the Sun, the Earth acts as an effective lens and the light magnification produces a radial velocity drift which is opposite in sign to that expected from a Rossiter–McLaughlin effect, but of identical physical origin.

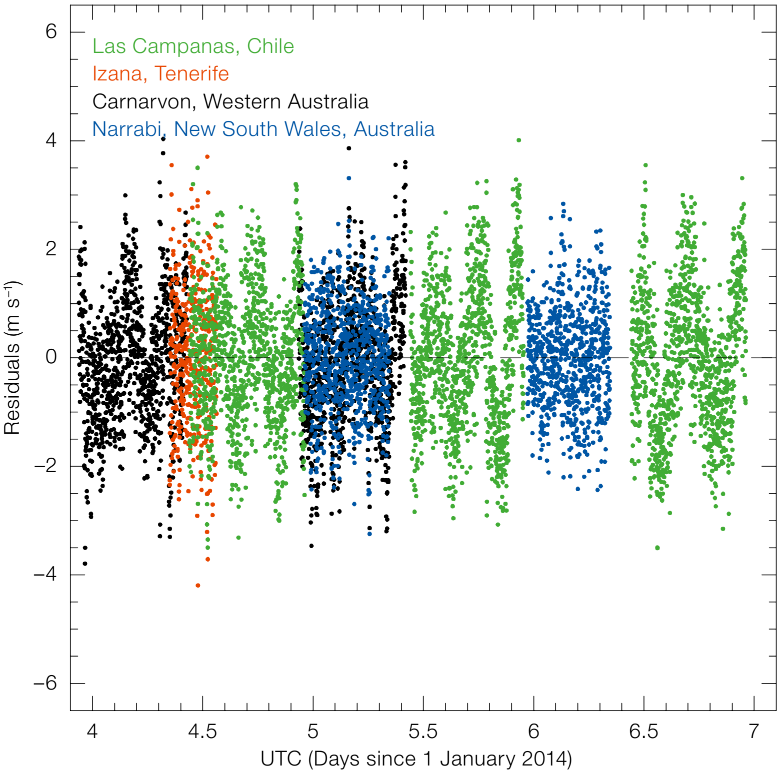

Figure 4. Archival BiSON Solar observations containing velocity residuals on the same days as our transit observations. The data are from: Narrabri, New South Wales, Australia (red points); Carnarvon, Western Australia (black); Izana, Tenerife (red); and Las Campanas, Chile (green). Courtesy of Steven Hale.

Thus, instead of receiving less radiation from the Solar hemisphere that the Earth is crossing, we are receiving more radiation because of the enhancement produced by the effect of the opposition surge of the reflecting body. This effect not only compensates for the partial Solar eclipse by the Earth, but is able to produce an opposite and much stronger radial velocity drift.

A toy model

The opposition surge is not fully understood and we cannot make a quantitative prediction of the distribution of the light enhancement as a function of the angular distance from the position of the transiting Earth. However, a simplified model, which accounts for the asymmetric emission from the two rotating Solar hemispheres, can explain most of the features of the RV curve that we observed.

In a simplified model we considered a circular region centred on the Earth of radius 6 arcminutes and with uniformly enhanced emission, and computed the effect in RV as if it were due to the RM effect, but reversing the sign to simulate the emission rather than the eclipse. The theoretical RM during the transit is computed using the formalism of Gimenez (2006). Since there is a degeneracy between the area and the intensity of emission, we simply scaled the radial velocity to the observed one, but preserved the shape.

The result is plotted in Figure 5. The predicted radial velocity rise follows the observations quite well. The peak is reached when the transiting Earth is at about three quarters of the Solar receding hemisphere. This is the position where we expect the strongest effect on the radial velocity due to the combined

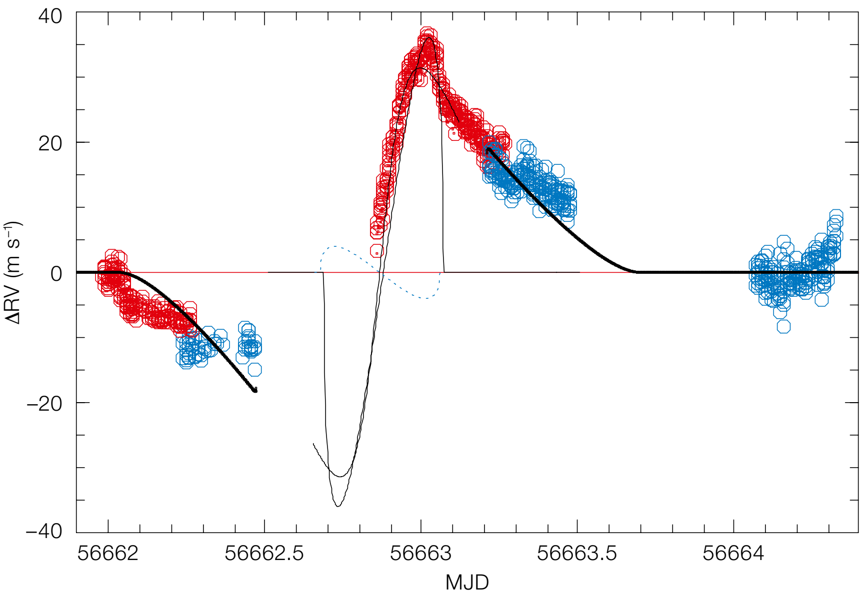

Figure 5. Model of the inverse Rossiter–McLaughlin RV drift induced by an increase in the Solar emissivity in the region behind the Earth's transit trajectory due to the opposition surge. The thin black line shows the drift expected from a small area moving with the Earth, while the thick line shows a drift coming from a larger area with a radius of ~ 10 arcminutes required to match the start of the radial velocity drift. The gap between the two models is due to the numerical impossibility of computing an RM effect for the total eclipse. The data points from La Silla (blue) are delayed by 0.1468 MJD to compensate for the longitude difference between the observatories of La Palma and La Silla. The blue dotted line shows the expected Rossiter–McLaughlin effect amplified by a factor of 50. The inverse RM effect detected is about 400 times larger than the expected RM due to the Earth's transit.

effect of the almost tangential rotational velocity and of the limb darkening of the Sun. During the decline, a break in the slope with a more gentle decrease is observed in proximity to the Earth's egress. The region with enhanced emission has been enlarged to 10 arcminutes to allow the RV anomaly to extend well outside the transit.

It should be noted that the model simulation does not end abruptly with the end of the Earth transit. This is because the opposition surge is also present when the Earth has just left the face of the Sun. For many hours after the end of the transit, the opposition surge makes the Solar hemisphere that has just been left by the transiting Earth brighter than the more distant one and the radial velocity decreases smoothly while the Earth is moving away.

The RVs are still high many hours after the end of the transit and it is only during the following night that we again measured a constant normal radial velocity. Assuming the opposition surge is quite symmetric, it probably started and ended ~ 15 hours before and after the transit, when the Earth was at a projected distance of about 10 arcminutes from the Solar limbs.

As we have already noted, the almost simultaneous observations from the two observatories give slightly different radial velocities. The RV values from La Silla are always lower by 4 to 10 m s^{-1} than those from La Palma, and in particular during the transit event. This difference is too large to be explained only by systematics and it is quite probable that the different locations on Earth of the two observatories experience a slightly different opposition surge. In other words, the distance from the Earth's edge could have been relevant in determining the intensity of the opposition surge and therefore the radial velocity value. The time difference between the longitudes of La Palma and La Silla is 0.1468 MJD (modified Julian date), while they have similar distances from the equator. This implies that, after this time interval, La Silla will be at approximately the same distance from the Earth's edge as La Palma. In Figure 5 we have shifted the data points from La Silla by this time difference and it is possible to see that they provide a much better continuity and overlap with the values measured at La Palma, regardless of the fact that the alignment has slightly changed in the meantime. This finding indeed suggests that the intensity of the opposition surge is very sensitive to the location of the observer on Earth, and in particular to the distance to the Earth's projected edges.

There is also the possible presence of a double peak around the position of the maximum of the radial velocity, which is suggestive of the presence of two components. While the broad component could be associated with a diffuse area of enhanced emission, the narrower component could be due to a peak of emission localised in proximity to the Earth. The result of simulated emission originating in a relatively small area around the Earth is plotted as a thin line in Figure 5 and it reproduces the peak quite well.

Prospects for another transit

The next Earth transit from Jupiter will occur in 2026, but it will be a grazing transit. However, since we have observed the effect of the opposition surge when the Earth was at an angle as high as ~ 10 arcminutes, we can predict that this unique phenomenon can be observed again, although with a lower amplitude in radial velocity. We really hope to have a very high resolution spectrograph (e.g., HIRES) at the European Extremely Large Telescope (E-ELT) to follow this new Earth transit.

References

Gimenez, A. 2006, ApJ, 650, 408
McLaughlin, D. B. 1924, ApJ, 60, 22
Meeus, J. 1989, *Transits* (Richmond, Virginia: Willmann-Bell)
Molaro, P. et al. 2013, MNRAS, 429, L79
Molaro, P. et al. 2013, The Messenger, 153, 22
Molaro, P. & Monai, S. 2012, A&A, 544, 125
Molaro, P. et al. 2015, MNRAS, 453, 1684
Rossiter, R. A. 1924, ApJ, 60, 15

Links

[1] Solar System Dynamics Group, Horizons Web Ephemerides, JPL: http://ssd.jpl.nasa.gov