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The Earth transiting the Sun as seen from Jupiter’s moons: detection of an inverse Rossiter–McLaughlin effect produced by the opposition surge of the icy Europa

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ABSTRACT

We report on a multiwavelength observational campaign which followed the Earth’s transit on the Sun as seen from Jupiter on 2014 January 2014. Simultaneous observations of Jupiter’s moons Europa and Ganymede obtained with high accuracy radial velocity planetary searcher (HARPS) from La Silla, Chile and HARPS-N from La Palma, Canary Islands were performed to measure the Rossiter–McLaughlin effect due to the Earth’s passage using the same technique successfully adopted for the 2012 Venus Transit. The expected modulation in radial velocities was of $\approx 20 \text{ cm s}^{-1}$ but an anomalous drift as large as $\approx 38 \text{ m s}^{-1}$, i.e. more than two orders of magnitude higher and opposite in sign, was detected instead. The consistent behaviour of the two spectrographs rules out instrumental origin of the radial velocity drift and Birmingham Solar Oscillations Network observations rule out the possible dependence on the Sun’s magnetic activity. We suggest that this anomaly is produced by the opposition surge on Europa’s icy surface, which amplifies the intensity of the solar radiation from a portion of the solar surface centred around the crossing Earth which can then be observed as a sort of inverse Rossiter–McLaughlin effect. In fact, a simplified model of this effect can explain in detail most features of the observed radial velocity anomalies, namely the extensions before and after the transit, the small differences between the two observatories and the presence of a secondary peak closer to Earth passage. This phenomenon, observed here for the first time, should be observed every time similar Earth alignments occur with rocky bodies without atmospheres. We predict that it should be observed again during the next conjunction of Earth and Jupiter in 2026.

Key words: radiation mechanisms: general – techniques: radial velocities – eclipses – solar–terrestrial relations – planets and satellites: general – planet–star interactions.

1 INTRODUCTION

Transits of Venus and Mercury in front of the Sun are major historical events but also other transits can be seen in the Solar system from other planets each time the heliocentric conjunctions take place near one of the nodes of their orbits, with the exception of the innermost Mercury. In particular, the Earth can be seen transiting in front of the Sun from other planets. These are rare events which were predicted in detail by Meeus (1989). For instance, the Earth will be seen transiting the Sun from Mars only in 2084. As seen from Jupiter, a transit took place on 2014 January 5. Next passage

will be grazing and will occur in 2026. During these transits, the integrated solar light can be recorded as it is reflected by the planets from which the Earth is seen transiting in front of the Sun, offering a surrogate direct watch as we showed with the observation of the Venus transit of 2012 June 6 when we followed the transit as if it were seen from the Moon (Molaro et al. 2013).

We planned an observational campaign to observe the Earth’s passage in front of the Sun that took place in 2014 January. One of the motivations for this observational campaign was the detection of the Rossiter–McLaughlin (RM) effect on which we report in this work. The RM is a radial velocity (RV) drift caused by the distortion of the stellar line profiles due to the occultation of the rotating stellar disc by an intervening body. The effect was first predicted by Holt (1893), and discovered by Schlesinger

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(1911), and later confirmed by Rossiter (1924) and McLaughlin (1924) in the eclipsing binaries β Lyrae and Algol, respectively. Schneider (2000) suggested that the transit of a planet could also be detected in the line profile of high signal-to-noise stellar spectra of rotating stars, and a Jupiter-like planet was first observed in HD 209458 by Queloz et al. (2000) with an amplitude of $\pm 30 \text{ m s}^{-1}$. The detection of the RM effect provides information on the planet radius, the angle λ between the sky projections of the orbital axis and the stellar rotational axis. Since then about 90 other Jupiters have been observed, often with very tilted orbits (Fabrycky & Winn 2009; Triaud et al. 2010; Albrecht 2012; Brown et al. 2012). The smallest RM effect detected is due to the Venus transit in front of the Sun of 2012 June 6 by Molaro et al. (2013) who used the integrated sunlight as reflected by the Moon at nighttime to record about half transit by means of the high-precision high accuracy radial velocity planetary searcher (HARPS) spectrograph at the 3.6 m La Silla ESO telescope. The observations performed in correspondence of the passage of Venus in front of the receding solar hemisphere showed that the planet eclipse of the solar disc was able to produce a modulation in the RV with an amplitude of $\approx -1 \text{ m s}^{-1}$. The RV change is comparable to the solar jitter and is more than one order of magnitude smaller than that of extrasolar hot Jupiters.

The amplitude of the RV anomaly stemming from the transit is strongly dependent on the projected radius of the eclipsing body and on the component of the star's rotational velocity along the line of sight (Ohta, Taruya & Suto 2005; Giménez 2006; Gaudi & Winn 2007). A transit across a star with high projected rotational velocity produces a RV signature larger than across a slow rotator. The RV drift ΔV_s is given by

$$\Delta V_s = \frac{k^2}{1 - k^2} \cdot \Omega_s \cdot \delta_p \cdot \sin I_s, \quad (1)$$

where Ω_s is the stellar angular velocity, δ_p is the projected position of the planet on the stellar surface $\delta_p = (X_p^2 + Z_p^2)^{1/2}$, I_s is the inclination between the stellar spin and the y-axis and $k = R_p/R_s$ is the ratio between the planet and stellar radii (Ohta et al. 2005).

During the Earth's transit of 2014 January 5, the projected size of the Earth was about 1.3×10^{-4} of the solar disc. Assuming a solar rotation velocity of $v \sin I_\odot = 1.6 \pm 0.3 \text{ km s}^{-1}$ (Pavlenko et al. 2012), the expected RM effect is of the order of $\pm 20 \text{ cm s}^{-1}$. Furthermore, our Moon is also transiting the solar surface but with a delay of about four hours with respect to the Earth. This type of configuration should be quite common in transits of extrasolar planets which likely have also their own moons. The expected RM effect due to the Moon's occultation is of only few cm s^{-1} .

2 OBSERVATIONS

2.1 Timing of the transit

In Fig. 1, the Earth, the Moon and their trajectories are shown as they would appear to an observer on Jupiter (or on one of its moons) on 2014 January 5. First contact was at solar latitude of $-23^\circ 8'$ while the exit was at $-35^\circ 7'$. The heliographic latitude of the centre of the disc, the solar Bo angle, was of $-3^\circ 6'$ and therefore the Sun was showing the South Pole to Jupiter with an inclination of 6° east of the solar axis. From the Jovian system, the black disc of the Earth was of 4.2 arcsec while the whole solar disc was of 369 arcsec. The total duration of the passage was of $9^{\text{h}}40^{\text{m}}$.

Jupiter itself is not a good sunlight reflector due to its high rotational velocity and to the turbulent motions of its atmosphere. Its major solid moons are better reflective mirrors. The geometrical

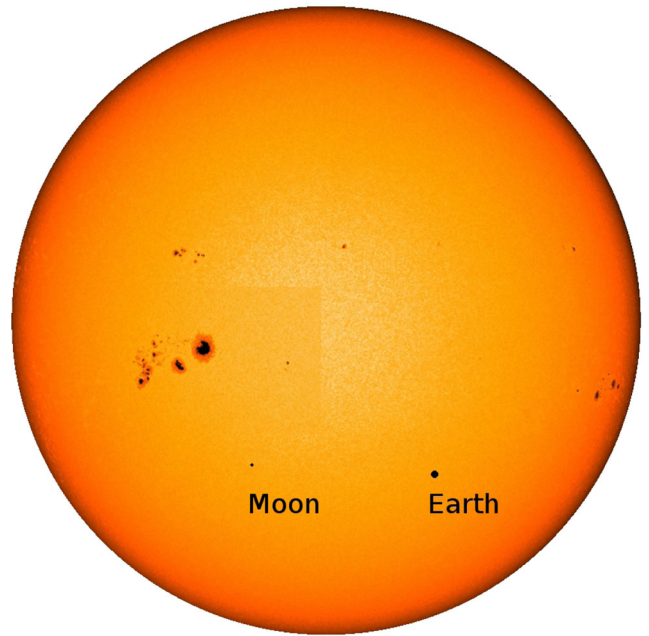


Figure 1. Composite image of the Sun with Earth and Moon as seen from Europa at 19 UT of 2014 January 5. The sizes are in scale with the Earth's size of 4.2 arcsec and the solar disc's size of 369 arcsec. The solar image is from SDO/NASA HMI Intensitygram at 617.3 nm on 2014 January 5 and shows prominent solar spots in the approaching solar hemisphere.



Figure 2. Front view of the Jovian system on 2014 January 5 from an observer on the Sun or on the Earth. From Jupiter the Earth transit started at MJD 56662.70, while its moons arrive somewhat in advance to the alignment, of about one hour for Ganymede and about 30 minutes for Europa, while Io went behind Jupiter during the event.

configuration of the Jovian system is illustrated in Fig. 2 from an observer on the Sun. The timing of the Earth's transit varies from one moon to another. In January, the moons were seen approaching Jupiter and therefore arrived at the alignment slightly before the planet. The Earth transit on the reference frame of the Jovian system started at MJD 56662.70 from Jupiter, but it was seen by about 30 minutes in advance from Europa and about one hour from Ganymede.

On 2014 January, Jupiter could be seen at best from the Northern hemisphere, but there was not a suitable site where Jupiter could have been observed during the entire 10-hour transit. The moon Europa was the best suitable replacement for Jupiter, providing the most extended coverage of the transit for about 6 h from La Palma and offering a limited possibility from La Silla to follow for ≈ 1 h the end of the transit. From La Silla, it was possible to observe the beginning of the night when Jupiter was rising at 20° over the horizon, but remaining always quite low and reaching 35° at the end of the transit. The transit could not be observed from Mauna Kea either and high-resolution facilities that could deliver very precise RV measurements were not available in other astronomical sites. Thus, La Palma and La Silla were the only sites where the phenomenon could be followed with high-resolution spectrographs suitable to deliver the required RV precision.

2.2 The observations

The observations comprise a series of spectra taken with both HARPS-N and HARPS of the Jupiter’s moons Europa and Ganymede covering the range from 380 to 690 nm. At the epoch of the observations, Europa and Ganymede were fully illuminated and had a visual magnitude of 5.35 and 4.63 mag and apparent diameters of 1.02 and 1.72 arcsec, 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 $R = \lambda/\Delta\lambda \approx 115\,000$. The two spectrographs at La Silla and La Palma are twins. Both are in vacuum, thermally isolated, stable and equipped with an image scrambler which provides a uniform spectrograph pupil illumination which is essential for high-precision RV observations. HARPS was able to deliver a sequence of observations with a dispersion of 0.64 m s^{-1} over a 500-d baseline for the RV curve of an extrasolar planetary system composed by three Neptune-mass planets (Lovis et al. 2006).

The observations started as soon as Jupiter’s moons became observable from the two sites. We started observing Ganymede from both telescopes on the night preceding the transit to determine the pre-transit characteristic solar RV. At La Palma, the observations began on 2456661.983 MJD till 56662.265 MJD and La Silla on 56662.088 MJD till 56662.321 MJD.

The following night we observed Europa from both telescopes to cover the second fraction of the transit as much as possible. At La Palma, observations started at MJD 56662.859 and ended at MJD 56663.265, while at La Silla observations were taken in the interval between MJD 56663.070 and 56663.330.

In the night following the transit, we made observations of both Europa and Ganymede to determine the post-transit characteristic solar RV only from La Silla. Observations of Europa were taken from 56664.068 MJD to 56664.167 MJD, followed by a sequence of observations of Ganymede till 56664.327 MJD.

3 RADIAL VELOCITIES

We used HARPS and HARPS-N pipelines to obtain the RVs from the observations. The pipelines return an RV value from the cross-correlation of the spectrum with a G2 V flux template which is the Fourier transform spectrometer (FTS) obtained by Kurucz at the McMath–Pierce Solar Telescope at Kitt Peak National Observatory (Kurucz et al. 1984). The FTS solar spectrum is calibrated on to the telluric emission lines and is known to have an offset in the zero-point of the order of 100 m s^{-1} (Kurucz et al. 1984; Molaro & Monai 2012). The pipeline returns the radial velocity RV_p relative to the Solar system barycenter by taking the apparent position of the target. We thus subtracted the barycentric radial velocity correction, the BERV, which was recorded in the fits headers to compute the proper kinematical corrections. These included 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 RV components of the motion of the moons relative to the Sun at the instant the light was emitted by the Sun (Molaro & Centurión 2011; Lanza & Molaro 2015). The sunlight reflected by Jupiter’s moons is shifted by the heliocentric RV of the moon with respect to the Sun at the time the photons left Jupiter’s moon and were shifted by the component of the Earth rotation towards the moon at the time the photons reach Earth. The latter is the projection of the asteroid motion along the line of sight adjusted for aberration, and comprises both the RV of the moon and the component from the

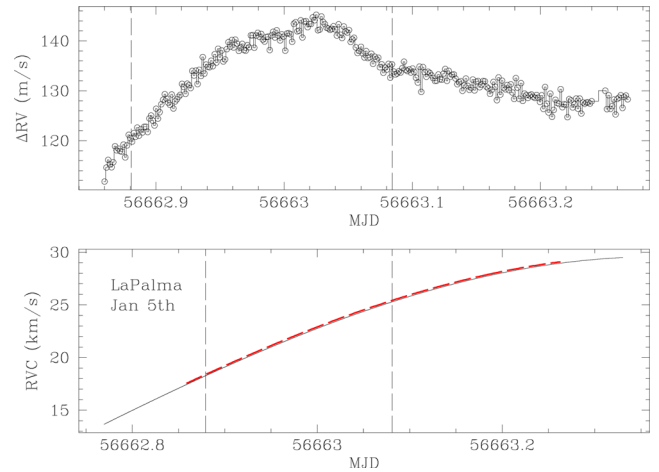


Figure 3. RVs measured from the Europa spectra of January 5 with HARPS-N observations. The top panel provides the RV corrected for the kinematical motions of the observer and of the moons, which are shown in the bottom panel with a black line. The red-dotted lines are the observed RVs. Notice the 5 m oscillation of the Sun which is responsible for high-frequency variations of an amplitude of $\pm 1\text{ m s}^{-1}$.

Earth rotation. Thus, the radial velocity is

$$RV = RV_p - BERV - (RV_{\text{moon-obs}} + RV_{\text{moon-}\odot}). \quad (2)$$

The quantities are computed by using the JPL horizon ephemerides.¹ The average rate in the RV change of Ganymede and Europa is of about 11 and 12 m s^{-1} per minute, respectively. During the exposure of one or two minutes, this velocity change produces some spectral smearing. However, we apply the corrections to mid-exposure values and since the spectral smearing is symmetrical to a good approximation it does not result into a net shift in the measured RVs.

Fig. 3 in the top panel shows the corrected RVs for the observations taken at La Palma on January 5. These are obtained from the RVs returned by HARPS pipeline once the kinematical corrections described above, and shown in the bottom panel of the figure, are applied.

The values do not show clear discontinuities in connection with the Earth transit and suggest a complex behaviour. It must be noted that there is a known offset in absolute RVs which originates from the use of the FTS solar spectrum as a template. This was measured in 102.5 m s^{-1} (Molaro et al. 2013) in coincidence of the Venus transit with an uncertainty of the order of few m s^{-1} which depends on the solar activity of that day.

Both spectrographs benefit of a second fibre which supplies ThAr spectra simultaneously with observations and that can be used to correct for instrumental RV drifts occurring over the night. The RV differences with respect to the previous calibration provide the instrumental drifts for both spectrographs.

3.1 The RV anomaly

The whole set of corrected solar RVs obtained from the Jupiter moon’s spectra taken in the course of the three nights from both sites is shown in Fig. 4 after subtraction of the RV baseline. At the

¹ Solar System Dynamics Group, Horizons Web Ephemerides Systems, JPL, Pasadena, CA 91109 USA <http://ssd.jpl.nasa.gov>

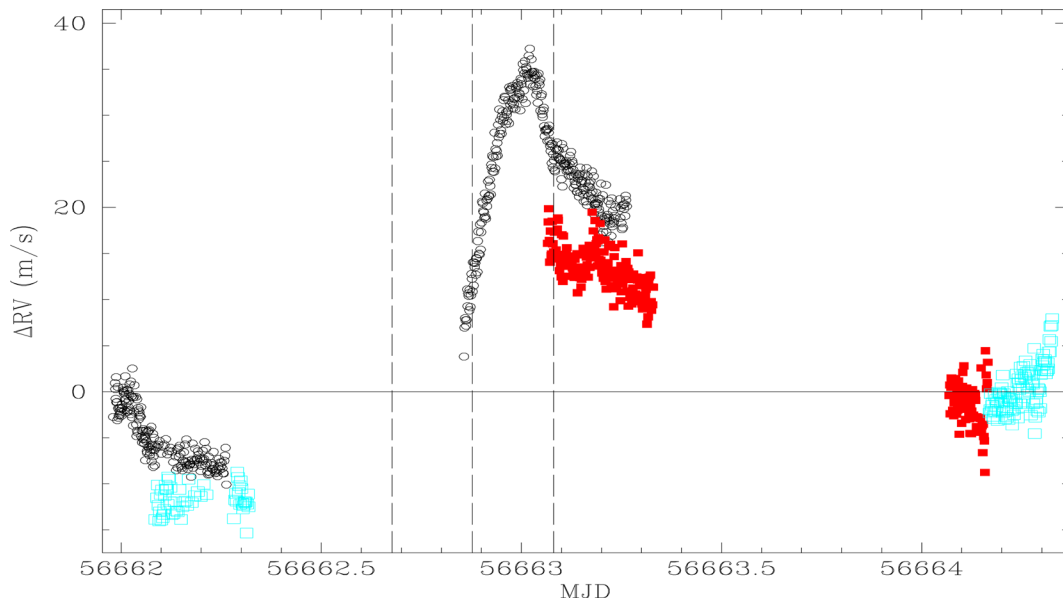


Figure 4. RVs measured on 2014 January 4–6. Open black circles are observations of Europa from La Palma while colour squares are observations of Ganymede (cyan) and Europa (red) from La Silla. A constant offset of 107.5 m s^{-1} as measured far out from the transit is taken as the instrumental baseline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

beginning of the observations, the RV is of 107 m s^{-1} while at the end it is at 108 m s^{-1} , and we adopt here a baseline of 107.5 m s^{-1} for simplicity. The observations taken at La Palma show a sudden drop by about 7 m s^{-1} after about one hour. Moreover, at the start of La Silla sequence the RVs were slightly lower with a difference of about 4 m s^{-1} between the two spectrographs.

In the following day, La Palma observations started at about mid-transit with RVs rising very quickly till they reached a peak of 37 m s^{-1} . After the peak, the RVs declined monotonically showing a break in the slope in correspondence to the end of the transit. The vertical lines in the figure mark the start, middle and end of the transit for Europa. To note that the peak of the RV is reached at MJD 56662.5 in correspondence of $3/4$ of the Earth passage in the receding solar hemisphere and the change in the slope in declining which corresponds to the end of the transit. Both of them will be discussed in the next section where we provide an interpretation of the phenomenon.

In the night following the transit, we made observations only from La Silla. The RVs are back to the values of the night preceding the transit. The observed pattern is completely at odd with our expectations. In the fraction of transit covered by observations, the Earth was eclipsing the receding solar hemisphere and the RM effect should have produced a small blueshift of the lines as a result of the prevalence of light coming from the approaching solar hemisphere. On the contrary, we observed a change in the RV of 37 m s^{-1} of opposite sign, i.e. more than two orders of magnitudes greater than expected. Moreover, the RVs did not show any sharp change in correspondence of the end of the transit. When the observations from the two spectrographs overlap in time, the RV behaviour is similar in HARPS and HARPS-N, although there is a non-negligible offset between the two measurements.

The anomaly in RV cannot have an instrumental origin. This is demonstrated by the fact that the two observatories are giving consistent results and similar RV anomalies have never been observed with HARPS. An example of the precision which can be achieved in

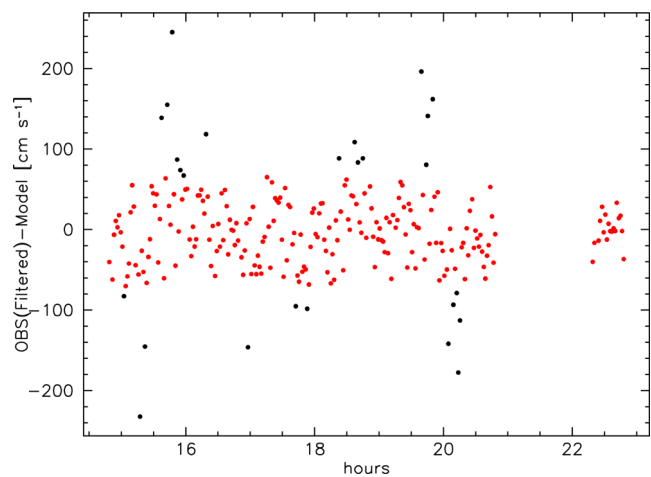


Figure 5. Residuals of the difference in units of cm s^{-1} between the observed RVs and the RM model for the 2012 Venus transit described in Molaro et al. (2013) but with the 5 min oscillation filtered out. This illustrates the level of precision which can be achieved with HARPS at the sub m s^{-1} level in contrast with the RV anomaly observed for the Earth's transit which is more than two orders of magnitude larger.

RVs with HARPS is the observations of the Venus transit of 2012, which were taken with the same technique adopted here. For the Venus transit, we obtained a remarkable agreement between the predicted RM effect and observations. In Fig. 5, the difference between the RM model computed for the Venus passage described in Molaro et al. (2013) and the observations are plotted after the observations were filtered for the 5 min solar oscillations. The residuals of the observations versus the model are of 0.55 m s^{-1} , while the absolute difference is of -2 cm s^{-1} , a difference which is within 1σ of the error in the normalization of the observations with the RVs observed after the transit. These observations were treated in the same way

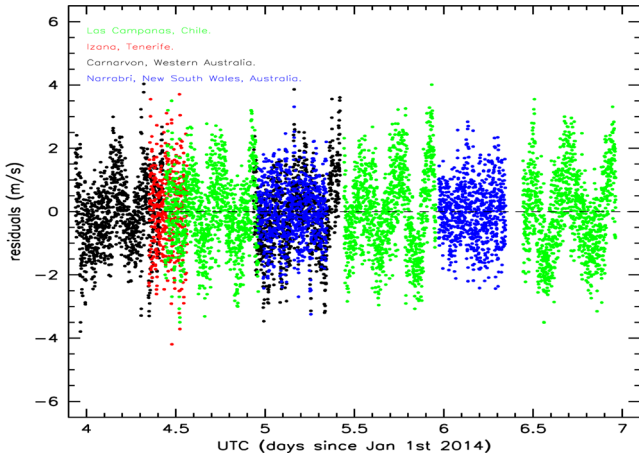


Figure 6. BiSON solar observations archival data containing velocity residuals in the same days of our observations. The data are from Narrabri, New South Wales, Australia (red points), Carnarvon, Western Australia, (black), Izana, Tenerife (red) and Las Campanas, Chile (green). Courtesy of Steven Hale.

as those we are dealing here showing that large anomalies in RVs from HARPS are not plausible. Moreover, inspection of asteroid observations taken with HARPS in its life span of 12 years shows that RV deviates from the mean by no more than $\approx 5 \text{ m s}^{-1}$. Such deviations are likely correlated with the solar magnetic activity as can be inferred from the presence of solar spots and plages on the solar surface (Lanza et al. in preparation).

Solar spots could also affect the RV of the solar lines and indeed in Fig. 1 the solar image of January 5 shows the presence of several solar spots which could contribute at the level of few m s^{-1} . The characteristic change is on a time-scale of solar rotation and no effect is expected during the relatively short duration of the Earth transit. The RV baseline before and after the transit also includes any contributions originated by the presence of these solar spots. To check if short-time strong solar activity occurred in coincidence of the transit, we inspected the Birmingham Solar Oscillations Network (BiSON) archives containing solar velocity residuals in the first days of 2014 January. The data were captured from the sites of Narrabri, New South Wales, Australia, Carnarvon, Western Australia, Izana, Tenerife and Las Campanas, Chile and provide a continuous monitoring of the solar activity in proximity of the event. The other two sites of Los Angeles and South Africa were offline in those days due to bad weather. The BiSON velocity residuals in Fig. 6 do not show any anomaly at the level observed, and suggest that the anomaly in RV we detected does not depend from an anomalous activity of the Sun. In the next sections, we will see that according to our proposed explanation it is not a surprise that BiSON does not see the RV anomaly.

The effects of a microlensing on to the RM effect in the case of transiting planets have been studied in detail by Oshagh et al. (2013). The RM can vanish in the extreme cases of particularly massive planets, but it has never been found to be inverted as we observed. Moreover, the size of the Einstein ring due to Earth observed from Jupiter is of only 47 km which is not expected to produce any significant attenuation of the RM effect.

Therefore, we think that this effect is real, and we suggest that it is due to the opposition surge on to the icy Europa as we argue in detail in the next sections after a brief introduction to the nature of this effect.

3.2 The opposition surge effect

The opposition surge is a brightening of a rocky celestial surface when it is observed at opposition. The increase in brightness is a function of phase angle and gets greater and greater as its phase angle of observation ϕ approaches zero. The existence of the opposition surge was first recorded by Gehrels (1956) but the precise physical origin is not yet completely understood and shadow hiding and coherent backscatter have been proposed.

The former stems from the fact that when the light hits a rough surface at a small phase angles all shadows decrease and the object is illuminated by its largest extent. It was Hugo von Seeliger who back in 1887 explained the increase in albedo of Saturn's rings to the corresponding reduction of the shadows on the dust particles of the rings at opposition.

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 of the intensity while as the phase angle increases the constructive interference decreases. Coherent backscatter has been observed in radio wavelengths and detailed physical models are presented in Hapke, Nelson & Smythe (1993), Hapke (2002) and Shkuratov & Helfenstein (2001).

It is also possible that both coherent backscatter and shadow hiding are operating. Which mechanism is dominant depends on the physical properties of the surface such as porosity, the mean free path and the single particle albedo. Currently, theory is unable to predict the amplitudes for either mechanism (Schaefer, Rabinowitz & Tourtellotte 2009). Considering both explanations, the opposition surge is also known as the Seeliger–Hapke effect.

3.3 An inverse RM effect

In the following, we argue that the opposition surge can explain the RV anomaly observed in proximity of the Earth transit. A characteristic feature of the opposition surge is the brightening of the planet as the phase angle ϕ decreases. Solar photons which graze the Earth have smaller angles than photons coming from regions of the solar disc far away from the Earth 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. Along its passage, the Earth acts as a lens and the light magnification produces a RV drift which is opposite in sign to that expected from an RM effect, but of identical physical origin. The enhancement of a portion of the solar disc produces a distortion in the solar line profiles with an asymmetric contribution from the two solar hemispheres of the same kind of the RM. The opposite sign is because instead of an occultation there is an enhancement of the emission in a restricted area of the solar surface. Instead of receiving less radiation from the hemisphere the Earth is crossing, due to its occultation of the solar disc we are receiving more radiation from it because of the enhancement produced by the opposition surge effect of the reflecting body. This effect not only compensates the effect of the partial solar eclipse by Earth but is able to produce an opposite RV drift by orders of magnitude stronger.

Opposition surge has been observed in Jupiter's moon Europa and has become prominent for phase angles less than $\phi < 1^\circ$ (Simonelli & Buratti 2004). The Jovian moon has a comparatively young surface rich in water ice which produces a high albedo. In

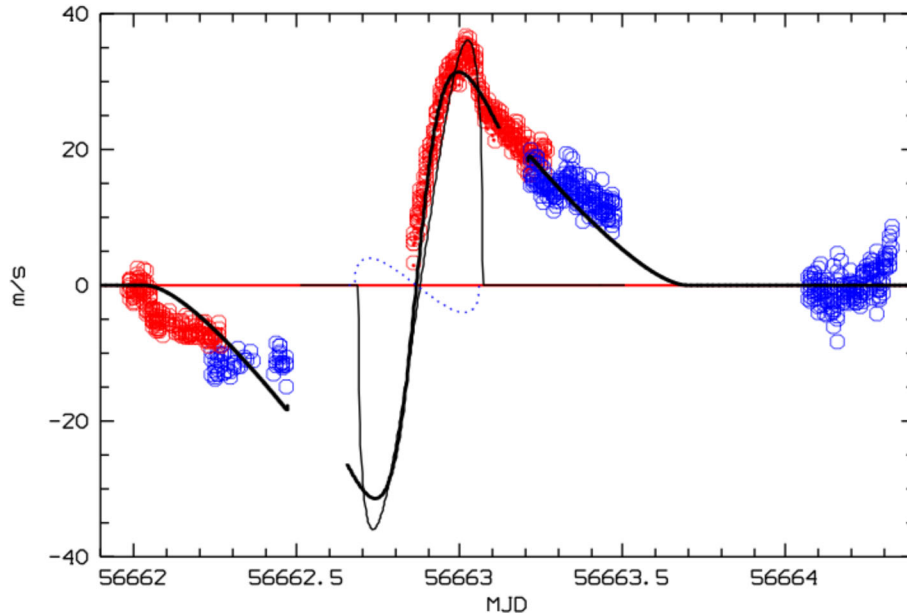


Figure 7. Model of the inverse RM RV drift induced by an increase in the solar emissivity in the region behind the Earth trajectory due to the opposition surge. The thin black line shows the drift expected from a small area moving with the Earth, while the thick line shows a drift coming from a larger area with radius of ≈ 10 arcmin required to match the start of the RV drift. The gap between the two models is due to the numerical impossibility to compute an RM effect for total eclipse. The data points from La Silla (blue points) are delayed by 0.1468 MJD to compensate for the longitude difference between the observatories of La Palma and La Silla. See the text for the details. The blue-dotted line shows how the expected RM effect but amplified by a factor of 50 since the real one would have the thickness of the line. The inverse RM effect detected is about 400 times larger than the expected RM due to the Earth transit.

these conditions, coherent backscatter is expected to dominate over shadow hiding. However, near-infrared Cassini observations have been interpreted as the opposition surge cannot be produced by coherent backscatter alone, but that it must have a significant shadow hiding component even in the presence of high albedo (Simonelli & Buratti 2004).

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 Earth position.

However, a simplified model which accounts for the asymmetrical emission from the two rotating solar hemispheres can explain most of the features of the RV curve we observed.

We considered an area around the Earth with uniform enhanced emission and we computed the effect in RV as if it were due to the RM effect. The sign of the RV drift is reversed to simulate the emission instead of the eclipse. The theoretical RV anomaly of the Sun during the transit is computed using the formalism of Giménez (2006). Since there is a degeneracy between the area and the intensity of emission, we just scaled the RV to the observed one but preserved the shape. The scaling factor provides the amount of light enhancement which is necessary for a given area assuming a uniform emission, while it is very likely that it changes within the area as a function of the phase angle.

We assumed the rotational velocity of the Sun V_{rot} is

$$\omega = a + b \sin^2 \phi + c \sin^4 \phi, \quad (3)$$

where ω is the solar angular velocity measured in $^\circ/\text{day}$, ϕ is the solar latitude, and a , b , c are the coefficients derived from the magnetic field pattern ($a = 14.37$, $b = -2.3$, $c = -1.62$). The corresponding rotational velocity at latitude ϕ defined by the Earth trajectory is

$$V_{\text{rot}} = 2\pi R_{\odot} \cdot (a + b \sin^2 \phi + c \sin^4 \phi). \quad (4)$$

The limb darkening coefficients of the Sun are $u_a = 0.5524$ and $u_b = 0.3637$, taken from the tables of Claret (2004), for the g filter and an Atlas model for the Sun with solar metallicity, $T_{\text{eff}} = 5750$ K, $\log g = 4.5$, $\xi = 1 \text{ km s}^{-1}$.

The theoretical variation of the solar RV during the transit computed with the above derived parameters is plotted as a thin line in Fig. 7. In this figure, it is possible to see that the RV anomaly does not end abruptly with the end of the Earth transit, but it extends further after it. This is not surprising since the opposition surge does not last for the time of eclipsing transit but it is also present when the Earth has just left or is approaching the solar disc, provided the solar rays are coming from portions of the solar disc which are at angles small enough to produce the opposition surge. For many hours after the end of the transit, the opposition surge makes the solar hemisphere just left by the Earth brighter than the most distant one. Thus, the RV is decreasing smoothly while the Earth is moving away and the phase angle is increasing.

We observe the phenomenon extending after the transit but not its end since RV is still high about six hours after the end of the transit. It is only on the following night that we measured again a constant RV. For symmetry, we can assume that the opposition surge should also have started many hours before the formal start of the Earth transit in coincidence with the sudden drop in RVs by about 7 m s^{-1} observed on January 4 at MJD 5666.204–5666.206 from La Palma observations of both Europa and Ganymede. Thus, the opposition surge effect started to be effective and produced an RV change at something about 15 h before the start of the Earth transit when the Earth was at a projected distance of about 7 arcmin from the solar edge. We emphasize that it is only the difference between the contributions of light coming from the two solar hemispheres that matters. An opposition surge which provides equal enhancement of the two solar hemispheres would produce a brightening but not any

detectable RV change. For symmetry, the RV anomaly should have ended also 15 h after the end of the transit, i.e. in a period which is not covered by our observations.

In our simplified model, we have considered a circular region centred on the Earth and a radius of 6 arcmin, namely 165 times the projected radius of the Earth as seen from Europa. In Fig. 7, the computed RVs are overplotted to the observations approximately covering the transit after scaling down the RM intensity by a factor of 30. The predicted RV rise follows the observations quite well, though it is somewhat less steep. The peak is reached when the Earth is approximately at about 3/4 of the solar receding hemisphere. This is the position where we expect the stronger effect on RV due to the combined 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 decline is observed in proximity of the Earth egress. The region with enhanced emission has been enlarged to 10 arcmin to allow the RV anomaly to extend well outside the transit.

The first half of the transit could not be observed either from La Palma or La Silla and the observations cannot track the passage of the Earth in front of the approaching solar hemisphere where the opposition surge should have produced a symmetrically negative RV behaviour. Simultaneous observations from the two observatories give slightly different RVs. Those from La Silla are always lower than those from La Palma (see Fig. 4). The difference is of about 4 m s^{-1} in the first night, and of about 10 m s^{-1} at the beginning of the second night, but they slightly decrease to few m s^{-1} as the event faded away. While we cannot exclude some systematic offset between the two telescopes at the level of few m s^{-1} , the difference observed during the opposition seems a bit too large to be explained only with this systematic. Thus, it is quite possible that different locations on Earth of the two observatories do not see exactly the same opposition surge. In particular, the distance from the Earth edge could have been relevant in determining the opposition surge intensity and therefore the RV value. The difference between the longitudes of La Palma ($28^\circ 42.89' \text{N}$, $17^\circ 54.29' \text{W}$) and La Silla ($-29^\circ 15.67' \text{S}$, $70^\circ 43.88' \text{W}$) is of 0.1468 MJD, while the distances from the equator are very similar. This means that after a time of 0.1468 MJD La Silla will be at approximately the same distance from the Earth edge as La Palma. In Fig. 7, we have shifted the data points from La Silla by this time difference and they provide a much better continuity and overlap with the values measured at La Palma. To note that this is achieved regardless of the fact that alignment of the Earth and of the Jovian systems has slightly changed in the meantime. This would imply that the intensity of the opposition surge is very sensitive to the phase angle and therefore to the location of the observer on Earth, in particular to its distance to the Earth's projected edges.

It is interesting to note the possible presence of a double peak in proximity of the maximum of the RV, which is suggestive of the presence of two components. While the broad one could be associated with a diffuse area of enhanced emission as we have discussed above, the latter narrower one could be due to a stronger emission located in proximity of the Earth. The result of an emission from a relatively small area in proximity of the Earth is plotted in Fig. 7 as a thin line which reproduces quite well the peak with a small delay of $+0.01$ MJD.

As we noted above, no RV anomalies were observed during the Venus transit of 2012 June 6. The Moon was in opposition at about 8° ahead of the Earth at a phase angle large enough to avoid the opposition surge. Yokota et al. (1999) and Buratti, Hillier & Wang (1996) with their study of Clementine data estimated a 30–40 per

cent increase in brightness of the Moon when going from 4 to 0° of phase angle. However, even if present, this should not have produced a RV anomaly since it would not have been connected to the Venus passage in front of the Sun. For similar reasons, the BiSON measurements obtained from a direct watch of the Sun do not see the RV anomaly which is produced by the magnification of a portion of the Sun induced by the opposition surge on the Earth passage.

We also note that the presence of a strong opposition surge during the Earth transit is probably the explanation of the lack of detection of the luminosity drop in the flux due to the Earth occultation which has been searched for unsuccessfully by many teams.

4 CONCLUSIONS

We followed the Earth transit of 2014 January 5 as seen from Jupiter by means of observations of Jupiter's moons Europa and Ganymede. The observations were made with HARPS spectrograph at La Silla, Chile, and with HARPS-N spectrographs from La Palma, Canary Islands, originally aimed to detect the RM effect due to the Earth passage on the face of the Sun. We followed the same technique successfully adopted for the 2012 Venus transit (Molaro et al. 2013) where the RM effect was measured and found in agreement with the theoretical model within few cm s^{-1} . In the case of the Earth transit, the expected modulation in RVs was of $\approx 20 \text{ cm s}^{-1}$. Instead, an anomalous and very large RV drift was observed. The half amplitude of the RV drift observed was as large as 35 m s^{-1} , i.e. about 400 times higher and opposite in sign.

The similar behaviour in the observations taken from both telescopes rules out an instrumental origin and suggests a physical origin which we identified as the product of the opposition surge effect on to Europa's icy surface. The opposition surge effect amplifies the intensity of the solar radiation from the portion of the Sun crossed by the Earth and produces a sort of inverse RM. This phenomenon has never been observed before and is associated with the rather unique geometry in which we observed the Earth transit. In fact, simultaneous RVs obtained by BiSON through a direct solar watch do not show the RV anomaly and rule out that they originate in the Sun.

A toy model which assumes an enhancement of the solar radiation from a projected solar region centred on the Earth's position produced by the opposition surge explains the general behaviour shown by the RV measurements. In particular, we are able to explain why the anomaly is also observed before and after the Earth transit, and the differences in RVs measured by the two observatories as due to the different distances from the Earth edge, as well as the presence of a second peak associated with the smaller projected solar region around the Earth but with greater intensity, and why we did not see a similar anomaly in the 2012 Venus transit.

The opposition surge effect provides a coherent and plausible description of the anomaly in RV as an inverse RM that we observed for the first time during the Earth transit. The effect could be observed again every time the Earth is seen in transit against the Sun from other planets or smaller bodies in the Solar system.

The next Earth transit will occur from Jupiter in 2026, but it will be a grazing transit quite unfavourable to any kind of observations (Meeus 1989). However, since we have observed the effect of the opposition surge when the Earth was at an angle as high as about 10 arcmin, we can predict that this same phenomenon can be observed again although with a minor amplitude in RVs.

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