

GROUND-BASED NEAR-INFRARED OBSERVATIONS OF THE SECONDARY ECLIPSE OF CoRoT-2b*

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ABSTRACT

We present the results of a ground-based search for the secondary eclipse of the $3.3 M_{\text{Jup}}$ transiting planet CoRoT-2b. We performed near-infrared photometry using the LIRIS instrument on the 4.2 m William Herschel Telescope, in the H and K_s filters. We monitored the star around two expected secondary eclipses in two nights under very good observing conditions. For the depth of the secondary eclipse, in the H band we found a 3σ upper limit of 0.17%, whereas we detected a tentative eclipse with a depth of $0.16\% \pm 0.09\%$ in the K_s band. These depths can be translated into brightness temperatures of $T_H < 2250$ K and $T_{K_s} = 1890^{+260}_{-350}$ K, which indicate an inefficient re-distribution of the incident stellar flux from the planet's day side to its night side. Our results are in agreement with the CoRoT optical measurement (Alonso et al.) and with *Spitzer* 4.5 and 8 μm results (Gillon et al.).

Key words: planetary systems – techniques: photometric

1. INTRODUCTION

The observation of a secondary eclipse, or occultation of an exoplanet by its host star, is one of the few techniques that allows us to extract information about the surface or atmospheric conditions of these bodies. In the infrared, it has already been possible to detect the thermal emission of several Hot Jupiters (starting from Charbonneau et al. 2005; Deming et al. 2005), and reveal some features of their atmospheres, such as thermal inversions at high atmospheric altitudes in planets that receive very strong fluxes from their host star (Knutson et al. 2008, 2009). These studies were only possible using the *Spitzer Space Telescope* and *Hubble Space Telescope*. Using new observing techniques or new instrumentations, the precisions of ground-based photometric time-series have recently shown a significant improvement (Alonso et al. 2008b; Johnson et al. 2009; Gillon et al. 2009a; Southworth et al. 2009). Very recently, the Na absorption on one exoplanet was detected from the ground (Redfield et al. 2008), and three independent teams announced ground-based detections of the secondary eclipses of different exoplanets (Sing & López-Morales 2009; de Mooij & Snellen 2009; Gillon et al. 2009b), in z and K_s bands, thus extending the studies of exoplanets' atmospheres to ground facilities. The near-infrared windows close to 2 μm allow us to explore a wavelength domain that falls between the detections in the optical that is accessible now to space missions such as CoRoT (Baglin et al. 2002) or Kepler (Borucki et al. 2003), and the wavelengths above 3.5 μm in the reach of *Spitzer*, for which Gillon et al. (2009c) recently reported measurements on CoRoT-2b. Thus, high precision near-infrared measurements have the potential to provide additional constraints to the models of the atmospheres of these objects.

Orbiting an active G star with a 1.74 d period, the massive planet ($3.3 M_{\text{Jup}}$) CoRoT-2b (Alonso et al. 2008a) shows an intriguingly large radius of 1.47 R_{Jup} . While several of the Hot

Jupiters show this anomalous and currently poorly understood bloating, CoRoT-2b poses additional challenges to most of the proposed mechanisms to provide extra sources of energy (e.g., Bodenheimer et al. 2001; Showman & Guillot 2002; Winn & Holman 2005; Burrows et al. 2003) due to its large mass. For instance, invoking increased opacities or kinetic energy transport in the planetary interior fails for CoRoT-2b (Guillot & Havel 2009). According to these authors, the models point toward a young age for the planet/star system, and tidal dissipation due to either circularization or synchronization of the planet. The effect of on-going tidal circularization might be revealed as a shift of the secondary eclipse time with respect to its expected position according to a circular orbit.

Due to its short period and its large radius, CoRoT-2b is among the exoplanets with the largest expected secondary eclipse depth, and should thus be detectable from ground-based facilities. This fact, and the unsolved issues with the radius of the planet, motivated us to perform the observations described in this work.

After describing the way the observations were performed in the next section, we present the data analysis in detail in Section 3, which led to an upper limit for the secondary eclipse depth in the H filter and a tentative detection of the secondary eclipse in K_s . Section 4 will be devoted to the discussion of our results and their implications.

2. OBSERVATIONS

We observed CoRoT-2b during the two nights of 2008 June 12 and 19, using the LIRIS near-IR imager and spectrograph (Acosta-Pulido et al. 2002) on the 4.2 m William Herschel Telescope on La Palma island. The observations were scheduled around the new Moon, and the weather conditions were very good, with a seeing varying smoothly between 0".45 and 0".95 on the night of June 12, and between 0".6 and 1".6 on June 19. We used the image mode of the LIRIS instrument, with a K_s filter (1.99–2.31 μm) on the first night, and an H filter (1.47–1.78 μm) on the second one. In order to avoid saturation of the detector and to minimize the effect of detector cosmetics, we used the same technique as described for observations with the 1.5 m Carlos Sánchez Telescope in Alonso et al. (2008b);

* Based on observations obtained with the William Herschel Telescope, operated by the Isaac Newton Group of Telescopes and situated on the Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias in La Palma, Spain.

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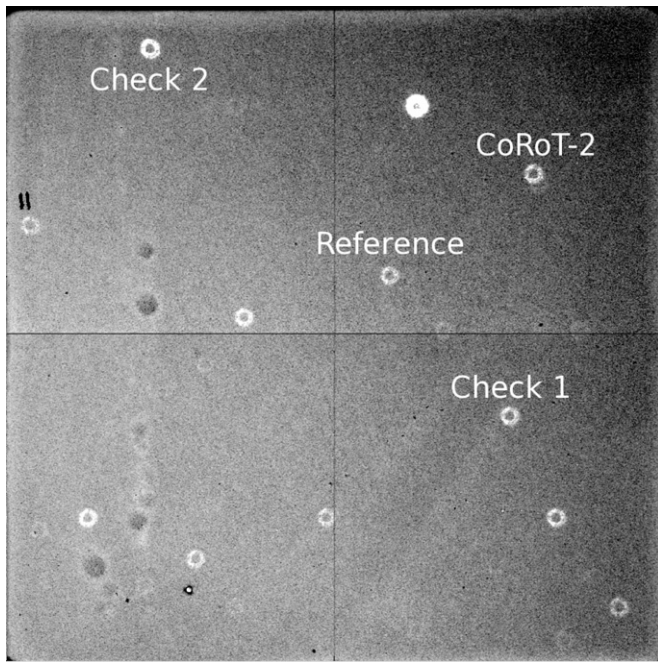


Figure 1. Sample raw image of the observed field in the K_s filter, showing the location of the target, the reference star used, and the two check stars that were used in Section 3.2 to estimate the effect of the systematic noises.

that is, we severely defocused the telescope, and obtained a ring-shaped point-spread function (PSF) with an outer radius of about 24 pixel ($6''$). The exposure time was 15 s on the first night and 17 s on the second one, with a typical overhead to read the detector and store the data of about 3 s. The flux on individual pixels of the target's PSF was never above 15 K ADUs, a dynamical regime where the detector is known to have a good linearity. Therefore, we avoided the necessity to perform non-linearity corrections of the data as done by de Mooij & Snellen (2009). In total, we obtained 1380 useful frames on the night of June 12, and 1096 on June 19, observing in both nights for about 7.5 hr around the expected times of secondary eclipses. A sample K_s -filter image is presented in Figure 1, showing the position of the target and the reference and check stars that were used during the analysis.

Following again Alonso et al. (2008b), we chose not to use any dithering pattern, but instead took twice each night a series of 10 images with the star shifted by $30''$ (offset images), in order to monitor the evolution of the image background, keeping the same exposure time. We also obtained detector calibration frames following standard techniques in IR photometry: before sunset, series of 30 images of the dome with the dome-light “on” and “off” were used to build a master flat-field image, by subtracting a combination of the images taken with the lights “on” to the combination of the images with the lights “off.” Unfortunately, we obtained noisier results when we attempted to correct our images by a division of this flat field, and we thus chose not to perform flat-fielding corrections.

3. ANALYSIS

In order to search for the signal of the secondary eclipse in the two data sets, we adapted the IDL routines used in Alonso et al. (2008b). The offset images of each night were median combined. We subtracted the mean sky background level from this combined offset image, after measuring it in a region without stars. The remaining image I_{offset} will thus account partially

for the hot and dead pixels in the image, as well as for the effects from uncorrected cosmetics in the image. We obtained the best results (lowest dispersion in the final light curve), when we subtracted I_{offset} from each science image without performing any other standard calibration. Cosmic ray impacts and remaining hot pixels were detected by applying the IDL's implementation of the top-hat morphological operator (e.g., Serra 1982), which works by applying an opening (dilation) operation to the image, and then subtracting the result from the original image. This way, small features with high flux levels in the image can be identified; they were replaced by a linear interpolation to adjacent pixels. Finally, from each science image we subtracted a sky background level that had been measured in a region without apparent stars.

The centroid of the target star was calculated by fitting a Gaussian with a non-zero revolution axis to the ring-shaped PSF. Since the target has a close companion at $4''$ distance with overlapping PSFs (1.72 mag fainter in K_s and 1.8 mag fainter in H , from the Two Micron All Sky Survey catalog) which causes the centroid not to be well centered on the target, we added systematic shifts (of -0.7 and 2.7 pixel in the x and y coordinates of the detector) to the calculated target centroid. We also obtained photometry from the ring-shaped PSFs of several reference stars with similar fluxes as the target. To avoid the introduction of additional noise from individual fits to the centers of the reference stars, we applied fixed position offsets between the target and reference star apertures. The flux was then summed inside a circular aperture centered on each star. We tested apertures between 24 and 32 pixels in radius, and obtained the best results (less dispersion in the final curve) when using 32 pixels for the H -filter data and 26 pixels for the K_s -filter night, due to the slightly different defocus applied on the two observing nights. The residual background levels were measured in a ring around each star (between two and 2.5 times the aperture radius). The mean level of the target's flux was $7.8 \times 10^6 e^-$ on the night of the K_s -filter observations, and $1.5 \times 10^7 e^-$ on the night of the H -filter data. For each data point we recorded the residual sky background levels measured in the ring around each star, the initially subtracted sky background level, the x and y positions of the stars on the detector, and the air mass, in order to be able to study the possible correlations of the flux curves against those parameters. In the following analysis, though, only the values of the positions of the stars on the detector were used to justify the exclusion of the first data points obtained in the H -filter data.

3.1. Analysis of the H -filter Light Curve

We corrected the effect of the air mass by fitting a cubic polynomial to the off-eclipse sections of the light curve until the star passed the meridian around 3h UT (or 0.62 HJD in Figure 2), and applied the fitted polynomial to the whole curve. The same procedure was used for the reference star, which was chosen among eight different stars as the one whose curve had a similar shape as the target. We noticed that even in the relatively small field of view of the instrument, the stars that were further from the target exhibited different behavior as the target, making them useless for building a reference star from a combination of several stars. The initial and corrected fluxes of the target and the reference star are plotted in Figure 2.

Next, we corrected for the flux of the close companion to the target star, which provided an extra 19% to the target flux in the H band. After the division of the target's flux by the reference star, there still remained some low frequency noise at a level of a few

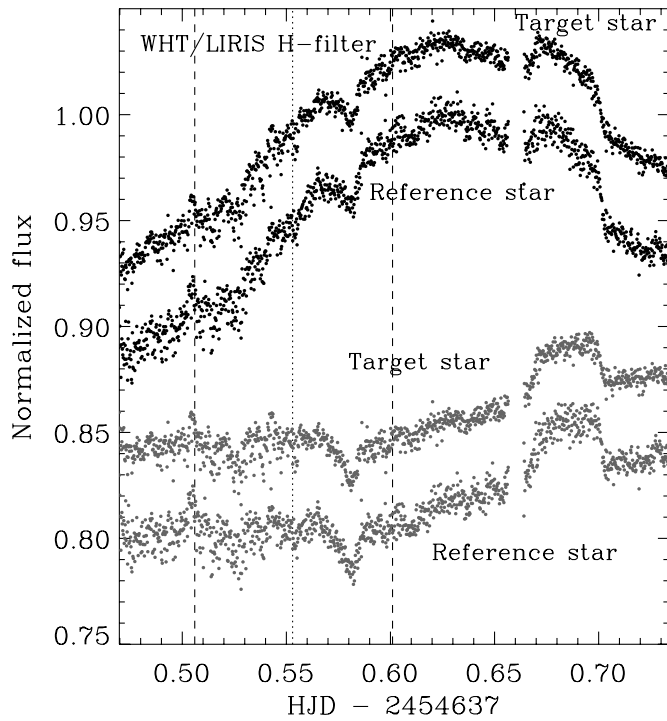


Figure 2. Light curves of CoRoT-2b and the reference star in the H filter, before correcting for the changing air mass (top, black points) and after correction (bottom, gray points). Vertical lines show the expected moments of eclipse ingress, center, and egress. See Section 3.1.

0.001 which we corrected by fitting a fourth-order polynomial to the parts outside of the predicted secondary eclipse. The final light curve is presented in Figure 3. Looking at Figure 2, the dispersion of the data is clearly higher from the beginning of the observations until approximately the mid-eclipse moment, coinciding with the observations at bigger air mass (starting from 1.8) and more jitter in the guiding of the telescope, which is most notable in the y target positions in our data (the standard deviation of the recorded y -values improves from 0.9 pixel at the beginning of the night to 0.3 pixel at the end). We suspect that this bigger jitter is due to tensions in the telescope mount when pointing at high air mass. We thus discarded these points in the further analysis, because they are suspicious of being affected by uncorrected instrumental or atmospheric effects (gray points in Figure 3). Their inclusion in the analysis would result in a deeper and temporally more severely shifted eclipse than the one presented here.

We applied three different methods to evaluate the depth and significance of the secondary eclipse signal. In the first method, we (1) removed the best-fit model from the data,⁷ where the only fitted parameter was the depth, whereas the total duration and ingress/egress duration were fixed to the values of the primary eclipse, (2) shifted circularly the residuals: in order to keep the red noise of the data unaffected, all the time stamps t_i were re-assigned to data points located at a randomly selected distance R in number of points t_{i+R} ; when $i + R > N$, then the re-assigned time stamp was t_{i+R-N} , where N is the total number of points, (3) reinserted the best-fit model, and (4) re-evaluated the fitted depth.

After several hundred realizations (with different randomly selected values of R), the final depth, which takes into account

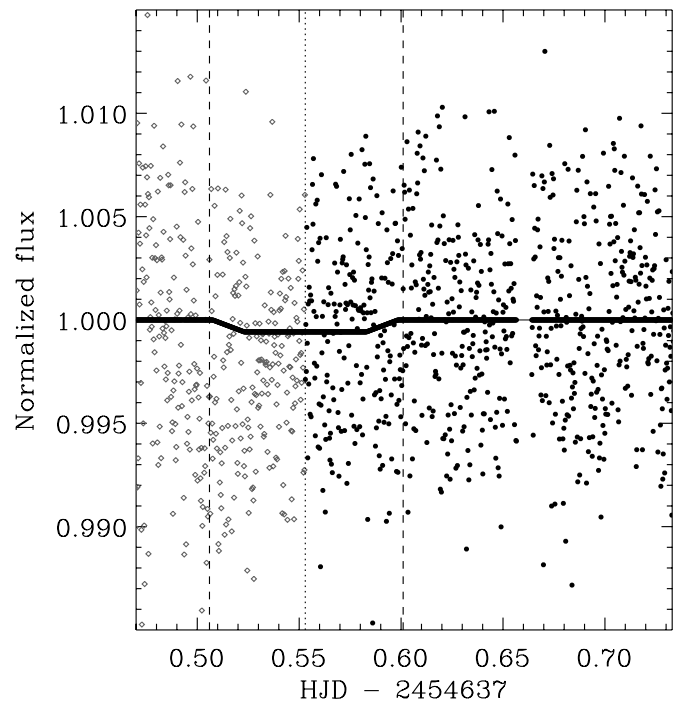


Figure 3. Fully corrected curve of CoRoT-2b in the H filter. Vertical lines show the expected moments of eclipse ingress, center, and egress. The solid line shows the best-fit trapezoid to the second-half of the secondary eclipse (points in black). The data points before the center of the eclipse (gray diamonds) are suspicious of uncorrected instrumental effects and have not been considered for the eclipse depth determination. See full description in Section 3.1.

the effect of red noise in the data, is $0.06\% \pm 0.03\%$. We plot this model as the solid line in Figure 3.

The second method consisted of the fitting of two Gaussians to (1) the flux distribution of points inside the full eclipse (138 points in the H -filter data between $\text{HJD} - 2,454,637 = 0.553$ and 0.585 , thus avoiding the moments of expected egress time in the case of a circular orbit) and (2) a subset of the points outside the eclipse (there are a total of 532 points) with the same number of points as in (1), and comparing their centers. This fit was performed to 500 subsets of (2), with randomly chosen starting points and widths (ranging from 0.0001 to 0.0007 in normalized flux values) of the histogram bins used in the construction of the flux distribution. The resulting depth is of $0.02\% \pm 0.06\%$.

Finally, we explored the χ^2 distribution of residuals from a fit to a model in a grid of eclipse centers (from -20 to $+20$ minutes from the expected center time) and depths (from 0.01% to 0.2%) of the secondary eclipse. The minimum χ^2 and the 1 , 2 , and 3σ confidence levels are presented in Figure 4, and the best-fitted depth using this method is $0.07\% \pm 0.05\%$. None of the three methods provided a statistically significant detection of the secondary eclipse in the H filter, and we can only safely provide a 3σ upper limit for the secondary eclipse depth of 0.17% .

3.2. Analysis of the K_s -Filter Light Curve

We analyzed the K_s -filter light curve in a very similar way as the H -filter one. We chose an aperture with a radius of 26 pixels, and we again corrected for the flux of the close companion to the target star, which provided an extra 16% of the flux. The plots before and after correction for the air mass with a low-order polynomial (in this case a line provided good enough

⁷ A simplified model with only depth, center, total duration, and ingress/egress duration of the occultation as parameters.

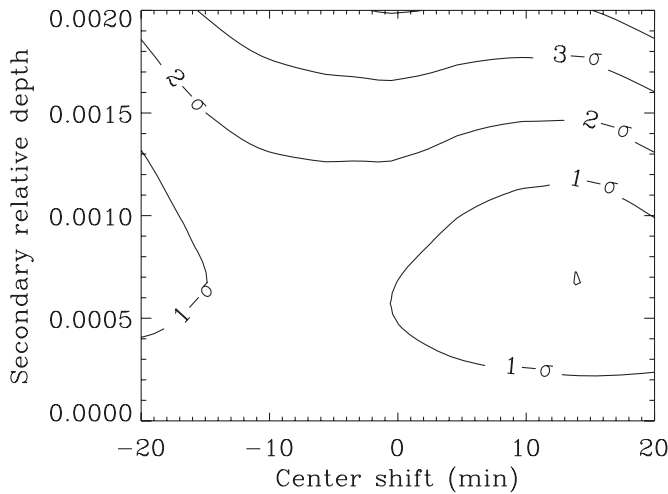


Figure 4. χ^2 space for different eclipse center times and depths in the H -filter data set showed in Figure 3, indicating the 1, 2, and 3σ confidence limits, using the third method described in Section 3.1. We conservatively interpret these results as a 3σ upper limit of 0.17% in this wavelength.

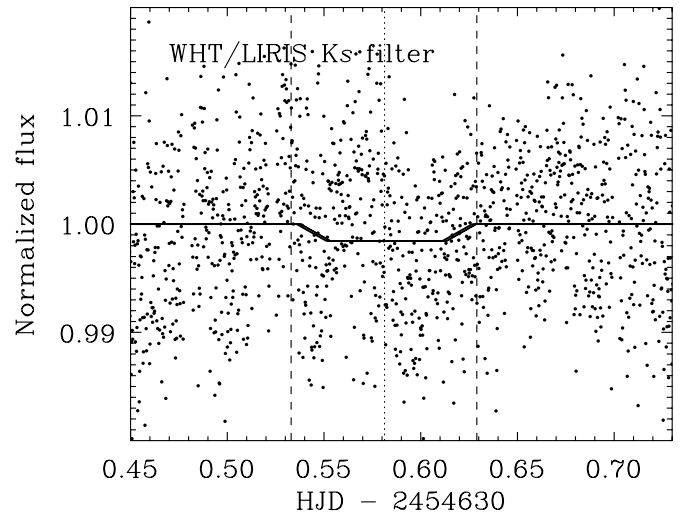


Figure 6. Light curve of CoRoT-2b in the K_s filter around the phase of secondary eclipse. The vertical lines show the expected times of first contact, eclipse center, and fourth contact, according to the ephemeris in Alonso et al. (2008a). The solid line plots the best-fit model when the eclipse center time is fixed to ephemeris, and the dashed line the best-fit model when the center time is also left free (superposed in this plot). See Section 3.2.

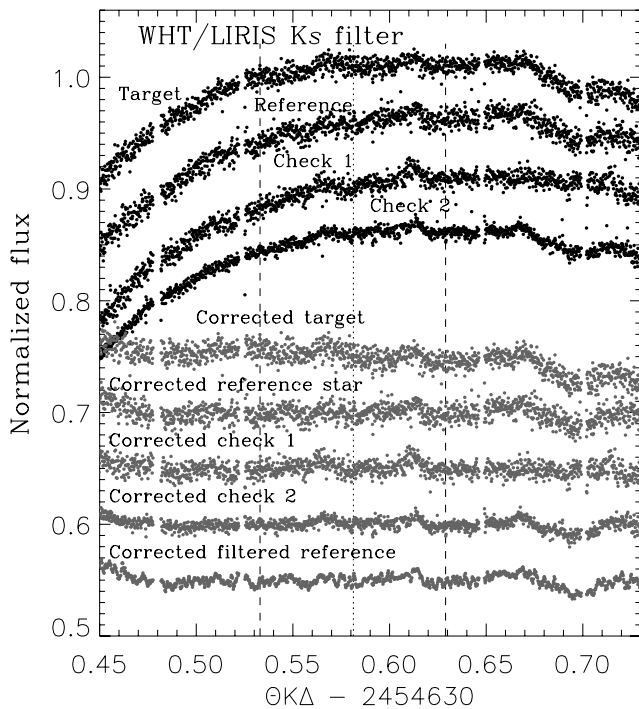


Figure 5. Similar to Figure 2, giving the light curves for the target and reference stars in the K_s filter, before (top, black dots) and after correcting for the changing air mass (bottom, gray dots). Two check stars at similar distances to the reference were also measured to validate the analysis method, and to measure the stability of the reference star. See Section 3.2.

results) are shown in Figure 5. A careful inspection of that figure reveals that there are slight differences in the behaviors of the stars, for instance just after 0.67, that depend on the apparent distance in the sky among the different stars. In order to verify that the signal we are searching for is not due to this residual systematic noise, we repeated the same analysis with two check stars located at different parts of the detector and at opposite directions from the reference star. To reduce the high frequency noise of the reference star, we applied a four-point median filter. The final light curve (after division by the flux of the filtered reference star) shows a tentative secondary eclipse event (Figure 6). We evaluated the depth and significance of

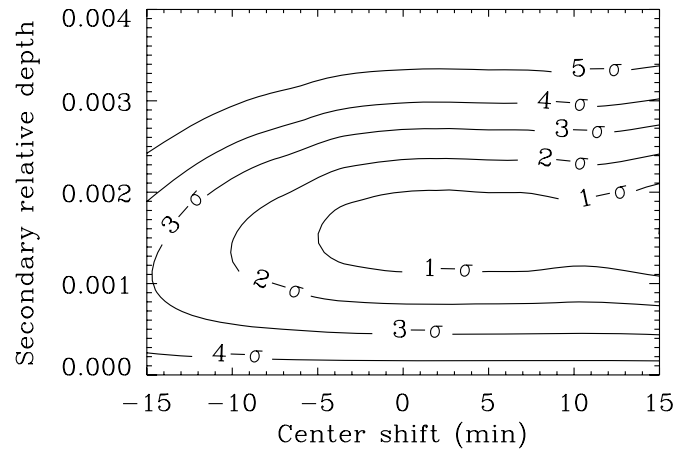


Figure 7. χ^2 space for different centers and depths of the secondary eclipse in the K_s filter (Figure 6), and the 1, 2, 3, 4, and 5σ confidence limits. A secondary eclipse with a depth of $0.16\% \pm 0.05\%$ is tentatively detected at the expected time for the case of a circular orbit. See Section 3.2.

the secondary eclipse using the same three methods described in the H -filter section. Model fitting and shifting of residuals (method 1) resulted in a measured depth of $0.17\% \pm 0.09\%$. The fit to different Gaussians (method 2, with 246 points considered to be completely inside eclipse: $0.56 < \text{HJD} - 2,454,630 < 0.61$, and 801 points in the out of transit sample) gave a depth of $0.15\% \pm 0.15\%$, while the χ^2 mapping (plotted in Figure 7) resulted in an eclipse with a depth of $0.16\% \pm 0.05\%$. The different error bars reveal the presence of systematic noise in the data that are intrinsically taken into account in methods 1 and 2, but not in the χ^2 mapping. We chose as a final value $0.16\% \pm 0.09\%$ for the eclipse depth measurement, i.e., the mean value of the three methods. The χ^2 mapping was also performed on the two check stars, and the Figure 8 shows 3σ upper limits of 0.06% and 0.05%, respectively, for a secondary eclipse, reassuring the detection of the secondary eclipse in the K_s band.

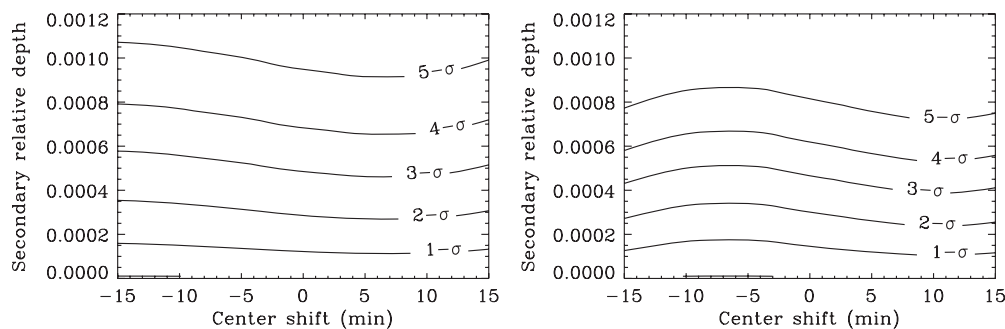


Figure 8. Same analysis of Figure 7 performed on the two check stars. No signal is detected with 3σ upper limits of 0.06% and 0.05%, thus reassuring the detection presented in the previous figure.

4. DISCUSSION

Our analysis of the near-infrared observations obtained at the H and K_s bands has allowed us to establish a 3σ upper limit to the occultation of CoRoT-2b in the H band of 0.17%, while the K_s -filter observations reveal a secondary eclipse of $0.16\% \pm 0.09\%$.

In order to convert the detected depths (or upper limits) in the two bandpasses into brightness temperatures, we took a modeled spectrum of a G8V star from the Pickles (1998) library. We calibrated the model in order to have the same total flux as a 5625 K Planck function. Under the assumption of a blackbody planetary emission, and zero Bond albedo, we computed the flux of the planet for different temperatures. Using the H - and K_s -filter response functions,⁸ we could then estimate the secondary eclipse depth for different temperatures. The 3σ upper limit on the H filter corresponds to an upper limit of the brightness temperature $T_H < 2250$ K, while the K_s -band measurement implies a blackbody emission of $T_{K_s} = 1890^{+260}_{-350}$ K. If we assume that the planet is in thermal equilibrium, then the measured re-distribution factor is of $f = 0.57^{+0.39}_{-0.32}$, which points to an inefficient re-distribution of the incident stellar flux from the planet's day side to its night side. These results are in agreement, despite their bigger uncertainties, with the values obtained from the analysis of the optical light curve from the CoRoT satellite (Alonso et al. 2009), of $T_{\text{CoRoT}} = 1910^{+90}_{-100}$ K. Recently, Gillon et al. (2009c) published secondary eclipse depths of $0.510\% \pm 0.042\%$ and $0.41\% \pm 0.11\%$ at 4.5 and 8 μm , respectively, from *Spitzer* observations which led these investigators to also favor models of inefficient heat distribution.

CoRoT-2b falls in the pM-class of planets according to the classification by Fortney et al. (2008), which exhibits hot stratospheres (temperature inversions), caused by currently debated or unknown upper atmosphere absorbers. According to these authors, such an effect might lead to the detection of “anomalously” deep secondary eclipses in the near-infrared. In the previous interpretation, we have neglected the reflected light component, which is expected to be smaller than the thermal emission at these wavelengths.

Additional observations will help to provide a firm detection in the H band, as well as to improve and confirm the observed K_s -band depth of the secondary eclipse.

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Facility: ING:Herschel; WHT (LIRIS)

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⁸ http://www.ing.iac.es/Astronomy/instruments/liris/liris_configuration.html