The GROUSE project III: Ks-band observations of the thermal emission from WASP-33b

Context. In recent years, day-side emission from about ten hot Jupiters has been detected through ground-based secondary eclipse observations in the near-infrared. These near-infrared observations are vital for determining the energy budgets of hot Jupiters, since they probe the planet’s spectral energy distribution near its peak.

Aims. The aim of this work is to measure the Ks-band secondary eclipse depth of WASP-33b, the first planet discovered to transit an A-type star. This planet receives the highest level of irradiation of all the transiting planets discovered to date. Furthermore, its host star shows pulsations and is classified as a low amplitude δ Scuti.

Methods. As part of our GROUnd-based Secondary Eclipse (GROUSE) project we have obtained observations of two separate secondary eclipses of WASP-33b using the LIRIS instrument on the William Herschel Telescope (WHT). The telescope was significantly defocused to avoid saturation of the detector for this bright star (K~7.5). To increase the stability and the cadence of the observations, they were performed in staring mode. We collected a total of 5100 and 6900 frames for the first and the second night respectively, both with an average cadence of 3.3 seconds.

Results. Unfortunately, the first night of data is unsuitable for any eclipse determination because the baseline was too short and a strong stellar pulsation peak occurred during the eclipse. On the second night the eclipse is detected at the 12-σ level, with a measured eclipse depth of 0.244±0.027 % . This eclipse depth corresponds to a brightness temperature of 3270±115 K. The measured brightness temperature on the second night is consistent with the expected equilibrium temperature for a planet with a very low albedo and a rapid re-radiation of the absorbed stellar light.

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4.1 Introduction

In recent years, there have been many measurements of thermal emission from the atmospheres of hot Jupiters, especially in the mid-infrared using the Spitzer Space Telescope (e.g. the review by Deming 2009). All the Spitzer observations probe the thermal emission of hot Jupiters only redward of the peak of their spectral energy distribution, and thus measure the planet’s light in the Rayleigh-Jeans tale of their emission spectrum.

Observations in the near-infrared, on the other hand, typically probe the planet’s emission spectrum around or even blue-ward of its peak, and therefore provide essential information on the planet’s total energy budget. During the past three years many measurements of planetary emission shortward of 2.5 µm have been obtained (Chapters 2 & 3 Sing & López-Morales 2009; Gillon et al. 2009; Rogers et al. 2009; Anderson et al. 2010; Alonso et al. 2010; Gibson et al. 2010; Croll et al. 2010a; López-Morales et al. 2010; Croll et al. 2010b, 2011; Smith et al. 2011; Caceres et al. 2011), most of these in the K-band (λ=2.15 µm) where the planet-to-star contrast is most-favourable for observations with ground-based telescopes through the available atmospheric windows.

From the combination of the measurements at multiple wavelengths, a picture is emerging that there are (at least) two classes of hot Jupiters, one class which shows a thermal inversion in their atmosphere, and a second class which do not. Fortney et al. (2008) propose that the presence of the inversion layer is set by the stellar irradiation, where at high levels of irradiation the planet’s stratosphere is hot enough to keep a strongly absorbing compound in the gas phase, while at lower irradiation levels the compound condenses out and disappears from the gas-phase.

Knutson et al. (2010) proposed an alternative scenario for the presence or absence of a strong absorber in the highest layers of the planetary atmosphere. In their scenario the absorber can be destroyed by strong UV emission from the planet’s host star, which is caused by the stellar activity. For higher levels of stellar activity, which result in a higher UV flux, the absorbing compound is removed, resulting in a non-inverted atmosphere. Note that the inference of an inversion layer has recently been questioned by Madhusudhan & Seager (2010), who point out that for several planets there is a degeneracy between the atmospheric temperature structure and the chemical composition of the planet’s atmosphere.

In this paper we present observations of two secondary eclipses of the very hot Jupiter WASP-33b (Collier Cameron et al. 2010) in K$_s$-band. These are part of the GROUnd-based Secondary Eclipse project (GROUSE), which aims to use ground-based telescopes for exoplanet secondary eclipse observations in the optical and near-infrared. As part of this project we have already published our K$_s$-band detections of the secondary eclipses of TrES-3b (Chapter 2) and HAT-P-1b (Chapter 3).

WASP-33b is currently the only known planet to transit an A-type star (T$_{\text{eff}}$=7430±100K) orbiting its host star in ~1.22 days. This makes WASP-33b the most irradiated planet known to date, with an irradiation of 1.2·10$^{10}$ erg/sec/cm$^2$. This high level irradiation results in an expected day-side equilibrium temperature of 3250K. Recent observations by Smith et al. (2011) indeed show a very high brightness temperature at 0.9 µm. In addition, since the host star is relatively hot, the expected UV flux it receives is also high, approximately 1.7·10$^9$ ergs/sec/cm$^2$ for wavelengths short-wards of 1500, making it an ideal candidate to investigate the influence of a high UV flux.
In addition to being the first transiting planet discovered to orbit an A-type star, WASP-33b is also the first planet discovered to transit a pulsating star. In the discovery paper, Collier Cameron et al. (2010) find evidence for non-radial pulsations in their spectral time-series, and tentatively classified WASP-33 as a $\gamma$ Doradus pulsator, which is a class of non-radial pulsators with periods around 0.3 days and longer (see e.g. Handler & Shobbrook 2002). Recently, Herrero et al. (2011) analysed photometric time series for WASP-33 and found a pulsation period of 67 minutes, which, when converted into the pulsation parameter $Q$, the product of the pulsation period and the square-root of the mean stellar density (e.g. Breger 1990; Handler & Shobbrook 2002), is comparable to that of $\delta$ Scuti stars, and well outside the range of $\gamma$ Doradus stars. The observed stellar pulsations will have a measurable impact on the transit and eclipse measurements for this planet.

In Sect. 4.2 we present our observations and data reduction. In Sect. 4.3 stellar pulsations and the light curve fitting are presented. Subsequently we discuss the results in Sect. 4.4, and finally we will give our conclusions in Sect. 4.5.

### 4.2 Observations and data reduction

#### 4.2.1 Observations

The first secondary eclipse of WASP-33b was observed in the $K_s$-band with the Long-slit Intermediate Resolution Infrared Spectrograph (LIRIS; Acosta-Pulido et al. 2002) instrument on the William Herschel Telescope (WHT) on La Palma during the night of August 18, 2010 (hereafter night I). The observations started at 00:45 UT and lasted for $\sim 4.5$ hours. The weather conditions during the night were photometric, as can be seen from the raw light curves shown in the top panel of Fig. 4.1.

The pixel scale of LIRIS is 0.25 arcsec per pixel, yielding a field-of-view of 4.2 by 4.2 arcminutes, large enough to observe both WASP-33 and a reference star of similar brightness simultaneously. Since WASP-33 is very bright, exposure times of 1.5 seconds were used in order to avoid saturation of the detector. As an additional measure to prevent saturation, the telescope was strongly defocused. This is a well proven strategy also used for other GROUSE observations (Chapters 2 and 3), which should also reduce the impact of flat-field inaccuracies by spreading the light over many pixels. To keep the observations as stable as possible, and in order to reduce the cycle time, the observations were performed in staring mode. Since this method does not allow for background subtraction using the science frames, a set of 297 dedicated sky frames were obtained after the observations for sky-subtraction purposes. A total of 5100 science frames were obtained during the observations and the average cadence was 3.3 seconds. The first three frames of a sequence of frames are known to suffer from the reset anomaly, which is seen as an anomalous structure in the background. These frames are therefore excluded from further analysis, which results in the exclusion of 106 frames during this night.

On the night of September 20, 2010 (hereafter night II) another eclipse of WASP-33b was observed from 22:35 UT to 05:00 UT. During the first part of the observations the conditions were photometric, however during the last few hours of the observations occasional clouds moved across the image, absorbing up to 65% of the light (see Fig. 4.1). The observational strategy was identical to that of the first night. In short, an exposure time of 1.5 seconds was
Figure 4.1 — Raw lighcurves for WASP-33 and the reference star (multiplied by 2.08 for plotting purposes) for the night of August 18, 2010 (top panel) and for the night of September 20, 2010 (bottom panel). The vertical dashed lines indicate the expected beginning and end of the targeted eclipse. The solid, grey, lines show the airmass during the nights, scaled to match the stellar flux in the first hour of the observations.
used, the telescope was defocused, and the observations were performed in staring mode, with a separate set of 162 images at the end of the observations for background subtraction. A total of 6900 science frames were obtained with an average cadence of 3.3 seconds per frame. As with the first night the first three frames of every sequence were excluded (207 frames in total), since they suffer from the reset-anomaly.

4.2.2 Data reduction

The data-reduction for both nights was performed in the same way. All frames were corrected for crosstalk along rows of the detector, which is present at a level of $10^{-5}$ of the total flux along the rows of all four quadrants. Subsequently we performed a non-linearity correction on all the frames using our own non-linearity measurements which were created from a set of dome-flats at a constant level of illumination but with varying exposure times. After these corrections all the images were flat-fielded using a flat-field created from bright and dark twilight flats.

A background map was constructed from the set of dithered images obtained after the eclipse observations. These images were reduced in the same way as the science images, and, after filtering out the discrepant pixels in time to remove (faint) stars, were subsequently combined. The resultant background map was then scaled and subtracted from the individual science images.

After background subtraction, aperture photometry was performed on both WASP-33 and the reference star using an aperture of 18 and 26 pixels for night I and night II respectively. Any residual sky background was determined in annuli between 30 and 50 pixels for night I and between 40 and 60 pixels for night II. The flux in the annuli was clipped at $5\sigma$ to avoid outliers in the background (such as hot pixels) from affecting the data. Finally, the light curve of WASP-33 was normalised with that of the reference star, and the resultant light curves for the two nights are shown in the top panels of Figs. 4.3 and 4.4.

4.3 Correction for systematic effects and stellar pulsations

4.3.1 Stellar pulsations

In the discovery paper Collier Cameron et al. (2010) note that the host star of WASP-33b is a non-radial pulsator, possibly belonging to the γ Dor class of variable stars. Herrero et al. (2011) obtained observations of the star and found a dominant period of 68.5 minutes, which, using the criterion on the Q value (see Handler & Shobbrook 2002), leads them to classify the star as a probable δ Scuti pulsator. Recently, Smith et al. (2011) observed a secondary eclipse of WASP-33b in a narrowband filter at 0.91 μm, and found three pulsation periods in their data, at 53.62, 76.52 and 41.85 minutes, all with amplitude between 0.4 mmag and 0.9 mmag.

For our data, the stellar pulsations are clearly visible in the light curve for night I, while for night 2 the variability is less apparent. In order to determine the period(s) of the stellar pulsations, a periodogram of the light curves was created. Since the planetary eclipse signal and possible systematic effects can influence the periods found in the data, both a scaled eclipse model as well as a model for the systematics based on instrumental effects (see section 4.3.2) were fitted to the data using a simple linear regression algorithm and subsequently subtracted.
Chapter 4. The GROUSE project III: The secondary eclipse of WASP-33b

For night I the strongest peak in the periodogram is found at a period of 64.5 minutes, and there is a weaker peak at 43.2 minutes. For night II, there are four peaks visible, the strongest peak is found at 52.1 minutes, while three weaker peaks are found at 43.3, 65.3 and 83.9 minutes. In both datasets we find a periodic signal at \(~65\) minutes, which differs from the period of 68.5 minutes found by Herrero et al. (2011). However, the short time span covered during each night is not sufficient to get a very tight constraint on the period, and therefore the periods could be consistent with 68.5 minutes. The \(~43\) minute period is seen in the measurements from both our nights, as well as in the data from Smith et al. (2011). The period around \(~52\) minutes is

Figure 4.2 — Normalised periodograms of the light curves for the two separate nights. The top panel shows the periodogram for night I and the bottom panel shows the periodogram for night II.
Table 4.1 — Fitted parameters and uncertainties from the MCMC analysis of the lightcurves of WASP-33b, for the method where the systematic effects are fit with instrumental parameters (x-position, airmass and sky level) and for the method where a polynomial ($c_1$ to $c_3$) is used to correct the baseline. $P_1$ to $P_4$ are the periods used for the stellar pulsations, and $A_1$ to $A_4$ are the corresponding amplitudes.

| Parameter | Night 1 | Night 2 |
|-----------|---------|---------|
|           | unit    | Ins.Pars. | Poly | Ins.Pars. | Poly |
| $F_p/F_*$ (%) | 0.140±0.007 | 0.092±0.017 | 0.245±0.009 | 0.246±0.018 |
| x         | 0.06±0.01 | —         | -0.12±0.02 | —         |
| airmass   | -0.76±0.03 | —         | 0.34±0.03  | —         |
| sky       | 0.27±0.03  | —         | -0.53±0.03 | —         |
| $c_1$     | —       | 0.42±0.01 | —       | 0.10±0.01 |
| $c_2$     | —       | -0.09±0.02| —       | -0.01±0.02|
| $c_3$     | —       | 0.10±0.01 | —       | -0.13±0.01|
| $P_1$ (minutes) | 63.95±0.39 | 62.00±0.51 | 52.65±0.39 | 52.28±0.51 |
| $P_2$ (minutes) | 43.22 (fixed) | 43.34 (fixed) |
| $P_3$ (minutes) | —       | 65.29 (fixed) |
| $P_4$ (minutes) | —       | 83.90 (fixed) |
| $A_1$ (%)  | 0.095±0.004 | 0.082±0.005 | 0.056±0.006 | 0.058±0.006 |
| $A_2$ (%)  | 0.041±0.004 | 0.042±0.004 | 0.017±0.005 | 0.014±0.005 |
| $A_3$ (%)  | —       | 0.011±0.006 | 0.011±0.006 |
| $A_4$ (%)  | —       | 0.031±0.006 | 0.013±0.006 |

found in both our second night of data as well as in the data from Smith et al. (2011), although there it is not the dominant frequency. We caution, however, that the periodograms used for the frequency analysis were created with data that was only partially corrected for systematic effects, and therefore can still be influenced by residual (quasi) periodic systematic effects.

### 4.3.2 Light curve fitting

Since the light curve is the result of a combination of three effects, the stellar variability, systematic effects related to both the instrument and the Earth’s atmosphere and the secondary eclipse of WASP-33b, a fit for all three effects is performed simultaneously.
Figure 4.3 — Light curves for the secondary eclipse of WASP-33b for the night I (left panels) and night II (right panels). Top panels: the light curves of WASP-33 normalised with those of the reference star, overplotted is the best fitting 'full' model with a low order polynomial baseline correction, stellar pulsations and the eclipse. Middle panels: The light curves corrected for the trends in the baseline and stellar pulsations, clearly showing the transit. Bottom panels: The residuals after subtracting the best-fit model. The thick points with errorbars in these figures show the data binned by 50 points.
Section 4.3. Correction for systematic effects and stellar pulsations

For the stellar pulsations the period of the dominant mode is left as a free parameter, although with a penalty for the $\chi^2$ of the form $(P-P_0)^2/\sigma_p^2$, with $P_0$ the period determined from the periodogram, and $\sigma_p$ set to 1 minute. The period of the other mode(s) was kept fixed to periods found in the analysis of the periodogram as described in the previous section. For all the modes the offset in phase and the amplitude of the pulsations were allowed to vary freely.

For the fitting of systematic effects two different methods were used, for the first method, the systematic effects are considered to be due to the change of position on the detector, the airmass and the difference in sky background between the two quadrants. This is similar to what was used in the previous papers from the GROUSE project (Chapters 2 and 3). In the second method, the systematic effects are modelled using low order polynomials, as also used in Chapter 5 for the near-infrared transit observations of GJ1214b.

The secondary eclipse was modelled using the Mandel & Agol (2002) formalism. We used the parameters from Collier Cameron et al. (2010) for the impact parameter, semi-major axis,
orbital period and planet-to-star size ratio, while the orbit of the planet is assumed to be circular. This assumption is reasonable since the planet orbits extremely close to its host star, which should result into a rapid damping of eccentricity. In addition, on the second night an eclipse-shaped dip in the light curve centered on $\phi \sim 0.5$ is readily visible (see the right panel of Fig. 4.3).

In total the light curves were fitted with 9 free parameters (1 for the eclipse, 3 for the systematic effects and 5 for the stellar pulsations) for night I and 13 free parameters for night II, due to 2 additional periods found in the data. The fitting was done using a Markov-Chain Monte Carlo method, and the two nights were fitted separately. Per night 5 sequences of 2 million steps were generated, and after trimming the first 200,000 points to avoid any contamination from the initial conditions, and checking that the chains were well mixed (Gelman & Rubin 1992), these 5 chains were combined to give the final results.
Before fitting, outliers were removed by excluding all points that were more than 0.9% away from a median smoothed light curve, as well as all points for which the flux of the individual stars, corrected for airmass, dropped below 90%. In this way a total 21 and 414 points were excluded during the first and second night respectively. In addition, there is a feature present in both light curves at the same time after the start of the observations (after 0.1795±0.0025 days) that is not at an identical point during the planet’s orbit and therefore most likely due to an, as yet, unidentified instrumental effect. Excluding all the points that were obtained during this feature removes an additional 128 frames.

The best fit values of the eclipse depth for night I are 0.140±0.007% and 0.092±0.017% for the fit with instrumental parameters and polynomials respectively, while for night II the best-fit eclipse depths are 0.245±0.009% and 0.245±0.018% for the two respective cases. The results for the different fits can also be found in Table 4.1.

The difference in fits both between the two different nights as well as the differences for the first night between the two different fit methods are larger than the uncertainties in the eclipse depth as estimated from the MCMC analysis. This difference can mainly be attributed
to the relatively short out-of-eclipse baselines available for the first eclipse observation, which hamper the removal of the systematic effects from both the stellar pulsations as well as from the instrumental and atmospheric effects. This is clearly illustrated when looking at the correlations between the parameters used for the removal of the systematics and the eclipse depth, as shown in Figs. 4.5 to 4.8. Furthermore, the first night appears to suffer from a strong peak due to stellar pulsations right in the middle of the eclipse, which is not fully correctable. We therefore conclude that the first night of data is too unreliable for an eclipse measurement.

As a first step to assess the impact of correlated noise, we redid the analysis for the second night after binning the data by 50 points (~3 minutes). Although overall the parameters are the same, we find larger uncertainties in the eclipse depths with the best-fit values of 0.255±0.028% and 0.242±0.035% for the fit with instrumental parameters and polynomials respectively. To assess the impact of (uncorrected) red noise on the measured eclipse depths in another way,
the residual permutation method was used. To assess the uncertainties the best fit model is subtracted from the light curve, and these residuals are then shifted by \( n \) points, wrapping the light curve around, so that the points that are shifted beyond the end of our observations are again inserted at the beginning. The best fit model is then added back to the data, and this new light curve is fitted again. The interval between 16% and 84% of the distribution of the best-fitting eclipse depths is used for the uncertainties on the eclipse depth. To speed up the residual permutation analysis, instead of adding back the full model, which includes the stellar pulsation, trends in the baseline and eclipse depth, we only used the trends in the baseline and eclipse depth, since the correlation between the parameters for the stellar pulsations and the eclipse depth is weak. From the residual permutation analysis we also find larger uncertainties for both decorrelation methods, with eclipse depths of \( 0.244^{+0.027}_{-0.020} \% \) for a baseline fitted with instrumental parameters and \( 0.249^{+0.033}_{-0.052} \% \) for a polynomial baseline fit. In all cases the uncertainties are higher than for the MCMC analysis of the unbinned data but comparable to the MCMC analysis of the binned data, which is expected if there is red noise present.

Figure 4.8 — same as Fig. 4.7 but for night II
Figure 4.9 — Spectral energy distribution of WASP-33b. Top panel: Eclipse depths in K$_r$-band (this work) and in the SII$_{0.91 \mu m}$-filter from Smith et al. (2011). Bottom panel: brightness temperatures in the two bands. Overplotted in both panels are the expected eclipse depths/brightness temperatures for a zero-albedo homogeneous day-side (solid line), for an instantly re-radiating day-side (dashed line) and for the best-fit effective temperature (dotted line).
4.4 Results and discussion

As already mentioned in the previous section there is a large discrepancy in the eclipse depth measured on the two separate nights. It is clear from Figs. 4.3 and 4.4 that the fit for the first night is poor, which is most likely due to a combination of uncorrected stellar pulsations and the short out-of-eclipse baseline available on that night. We therefore opt to not use the measurement of night I, and only use the measurement made during the second night for the rest of this paper. Furthermore, since there is a strong correlation between the coefficients for the polynomial baseline fit and the eclipse depth (see Fig. 4.6), we use the fit of the baseline with instrumental parameters for the remainder of the paper, since the correlation between different parameters is much weaker. We note that the polynomial baseline correction for this night gives the same eclipse depth, however with a larger uncertainty.

The measured eclipse depth of $0.244^{+0.027}_{-0.020}$ % corresponds to a brightness temperature in the $K_s$-band of $3270^{+115}_{-160}$ K. This brightness temperature was calculated using the solar-metallicity NextGen models (Hauschildt et al. 1999) interpolated to the stellar parameters of WASP-33 determined by Collier Cameron et al. (2010) ($T_{\text{eff}}=7430$K, log($g$)=4.294).

Currently there is only one other measurement available of a secondary eclipse of WASP-33b. This measurement by Smith et al. (2011), obtained in a narrowband filter at $\sim 9100$Å, shows a depth of $0.09\pm0.016\%$, which corresponds to a brightness temperature of $3466\pm140$ K. This narrow-band measurement probes the spectral energy distribution at the peak, and is therefore complementary to our $K_s$-band observations, which probes the SED in the Rayleigh-Jeans tail (Fig. 4.9).

If we assume that the SED can be well fit with a single blackbody function, we find an effective temperature for the combined measurements of $T_{\text{eff},p}=3370^{+95}_{-100}$ K.

As can be seen in the middle right panel of Fig. 4.4, the eclipse appears to end earlier than expected from the model. Although systematic effects are the most likely cause of this, it is worth noting that a narrower width of the eclipse would indicate that the orbit of WASP-33b is eccentric. If this is the case, by combining the ratio between the transit and secondary eclipse durations with the time of mid-eclipse, a direct measurement of both the eccentricity and the argument of periastron is possible (e.g. Charbonneau et al. 2005). Although a full fit is beyond the scope of this work, we can estimate the change in duration from the light curve. The duration of the secondary eclipse is shorter than the transit duration by 0.01 in phase, which corresponds 90% of transit duration. From this we estimate $\sin(\omega)\sim0.05$. Since the ingress appears to be at the expected time, the time of mid-eclipse is in this case also slightly earlier than expected. From the shift we estimate $\cos(\omega)\sim0.008$. Combining these two estimates we find an eccentricity of $\sim0.05$. We again caution that systematics can easily give rise to an apparent non-zero determination of the eccentricity, which is for instance seen for the secondary eclipse of TrES-3b (Chapter 2, Fressin et al. 2010; Croll et al. 2010b). We therefore do not advocate this non-zero eccentricity scenario based on these data.

4.4.1 A low albedo and rapid re-radiation of incident light

Both currently available eclipse measurements for WASP-33b point towards a very hot day-side temperature. If we assume that the measured brightness temperatures are representative of WASP-33b’s equilibrium temperature, and are not generated deep inside the planets atmo-
Figure 4.10 — Equilibrium temperature of WASP-33b for different albedo and re-radiation factors. Solid contours show lines of constant temperatures and 150 K intervals. Overplotted are lines of constant temperature for the measured brightness temperatures (dashed lines), labeled with the bandpass they were observed in. The dashed line labeled “Avg.” indicates the line for constant temperature of the effective temperature determined from the two measurements. Vertical (dashed) lines indicate the re-radiation factors for a homogeneous day-side temperature (f=1/2), and for an instantly reradiating day-side (f=2/3).

In Fig. 4.10 we show a simple model of the equilibrium temperature as a function of albedo and re-radiation factor. In this figure we show the contours of constant equilibrium temperature as a function of albedo and re-radiation factor. In addition we show lines of constant temperature for the measured brightness temperatures, as well as for the effective temperature determined from these measurements. As can be seen the measurements require a very low albedo and a very short re-radiation time scale, such that all the stellar flux is absorbed and rapidly reradiated without having time to advect to the night-side of the planet. This is consistent with the findings of Cowan & Agol (2011), who study the albedo and redistribution efficiencies for a large sample of hot Jupiters, and find that the hottest planets (in their sample) have a low albedo and a low efficiency of the advection of absorbed stellar flux to the planet’s night side.
The very low redistribution efficiency suggests that the planet has an inversion layer, where the re-radiation timescales are short (Fortney et al. 2008). Knutson et al. (2010) hypothesise that an increase in the UV-flux from an active star, especially in Lyman \( \alpha \), can cause a shift in the photochemistry such that the efficient absorber is removed from the gas-phase. The high incident UV-flux on WASP-33b, which appears to have an inversion layer, would argue against this, although the flux in its the Lyman \( \alpha \) line is relatively modest. To investigate the influence of the UV-radiation, photochemical modelling will be necessary (e.g. Zahnle et al. 2009).

4.5 Conclusion

We have presented our results of \( K_s \)-band observations of the secondary eclipse of WASP-33b, the most irradiated planet known to date. Although we have two nights of observations, the measurements on the first night suffer from strong residual systematics that cannot be fully corrected due to the short out-of-eclipse baseline. The measured eclipse depth for the second night is 0.244\( ^{+0.027}_{-0.020} \) \%, which results in a brightness temperature of 3270\( ^{+115}_{-160} \) K. This high brightness temperature, if representative for the planet’s equilibrium temperature, requires a very low albedo and a high (\( \tau \gtrsim 0.5 \)) reradiation factor.

Combining our \( K_s \)-band measurement with the measurement of Smith et al. (2011), we can fit a simple blackbody function to the spectral energy distribution, and determine an effective temperature of \( T_{\text{eff},p}=3370^{+95}_{-100} \) K.

We also find that stellar pulsations of the \( \delta \) Scuti host star, WASP-33, appears to have switched modes between the two nights, which are located a month apart, and also differ from the measurements by Herrero et al. (2011). We caution, however, that this could be due to systematic effects which could also have strong periodicities.

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