The impact of faculae on the radius determination of exoplanets: The case of the M-star GJ 1214. *

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ABSTRACT
Precise measurements of exoplanets radii are of key importance for our understanding of the origin and nature of these objects. Measurement of the planet radii using the transit method have reached a precision that the effects of stellar surface features have to be taken into account. While the effects from spots have already been studied in detail, our knowledge of the effects caused by faculae is still limited. This is particularly the case for M-stars. Faculae can pose a problem if they are inhomogeneously distributed on the stellar surface. Using the eclipse mapping method, we study the distribution of the faculae on the surface of GJ 1214 using the Ca II H&K lines as tracers. In order to assess the homogeneity of the distribution in a quantitative way, we introduce the inhomogeneity factor IHF. IHF is 0% if the distribution is homogeneous, positive, if the plage regions are preferentially located along the path of the planet, and negative, if they are preferentially located outside the path of the planet. For GJ 1214, we derive a rather small value of IHF = 7.7±12.0%. We discuss the relevance of this result in the context of the PLATO and ARIEL missions.

Key words: planetary systems – planets and satellites: atmospheres – planets and satellites: composition – planets and satellites: individual GJ1214b –

1 INTRODUCTION
In recent years the focus of exoplanet research has shifted from the mere detection to their detailed characterization. The detailed characterization requires accurate determinations of their masses, radii and studies of their atmospheres. As up to now, transiting exoplanets are the best objects to obtain such information.

The combination of precise radius- and mass-determinations of exoplanets constrains the composition of the planets (Neil & Rogers 2020; Kuchner 2003; Léger et al. 2004; Zeng et al. 2019; Adams, Seager, & Elkins-Tanton 2008). Fridlund et al. (2020) estimates that an accuracy of better than 15% for the masses and better than 5% is required to find out what the nature of planets are. The requirement for the radius determinations thus are more stringent than for the mass determinations. Such considerations are the background of the upcoming PLATO mission (Rauer et al. 2014).

Key information is also provided by atmospheric studies such as those that will be obtained with the atmospheric characterization mission ARIEL (Tinetti et al. 2016; Puig et al. 2018). PLATO and ARIEL will both primarily use the transit method to measure planet radii to very high accuracies. In the case of ARIEL, these are obtained at many different wavelengths in the optical and infrared regime.

The accuracy with which the radii can be determined not only depends on the instrument, it also depends on how well the effects from stellar surface features can be removed. It is thus essential to develop these methods.

Stellar spots that are being occulted during transit reduce the transit depth, the planet appears to be smaller than it really is. Spots may form bands on the stellar surface and if the planet transit along such a band, it may become very difficult to account for the effects of spots. Sophisticated methods are then need to determine the true size of the planet (Morris et al. 2018).

An example for a star with two active bands is HAT-P-11 (Morris et al. 2017). Because the planet is misaligned, it is crossing the bands during transit (Sanchis-Ojeda & Winn 2011). If the planet were aligned, and if it would transit at the latitude of the bands, it would be the situation as envisaged by Morris et al. (2018).

Stars can also have spots that are not occulted during transit. In this case the planet appears to be larger than it really is. This situation would, for example, be the case if the star has polar spots and the planet transits close to the equator. This situation is particularly relevant for M-stars,
because they have polar spots. Using white-light observation of long-duration flares of fully convective M-stars Ilm et al. (2021) showed that all flares must have occurred at latitudes between 55 and 81 degrees. Zeeman Doppler imaging shows that M-stars have a complex field topology including polar spots (Donati et al. 2008; Morin et al. 2008, 2010; Barnes et al. 2015).

Stars not only have spots but also faculae, or to be more precise, facula points. Facula points pose a problem if they are clumped on the stellar surface. Studies of faculae on the Sun show that they consist of many small magnetic elements. Faculae are bright, because of the “hot wall” effect (Kobel et al. 2009). Near the disk center, they appear as bright points or filigree (Dunn & Zirker 1973; Mehltretter 1974). When observed near the limb, they are called faculae, or more precisely, facular grains (Muller 1975). Bright points, filigree and facular grains are thus different manifestations of the same phenomena (Kobel et al. 2009). Regions that appear bright in the cores of the Ca II lines are called plage regions. The plage regions are also related to the small magnetic elements. Numerical simulations show that the emission cores of the Ca II lines are the result of the acoustic wave heating and magnetic wave heating from magnetic elements (Fawzy et al. 2002a,b,c). The emission cores of the Ca II lines are thus the chromospheric signatures of the magnetic elements which we called bright points, filigree, or facular grains when observed in the photosphere.

Faculae are observed at the solar limb, because we observe a slightly higher layer at the limb than at the disk center (Kobel et al. 2009). At the disk center we either observe them as facular grains in the photosphere, or as plages in the chromosphere using Ca II lines.

Because faculae and plage regions are related, and since we use the Ca II lines in our study, we will call these regions plages.

Plage regions can also be observed on other stars by using the Ca II lines. The presence of Ca II H&K emission shows that even M-stars have plage regions. Furthermore, bright regions on the stellar surface have been detected on the late M-star TRAPPIST-1 (Morris et al. 2018). Plage regions thus seem to exist on all late-type stars including M-stars. However, our knowledge about plage regions on other types of stars is still limited, particularly for M-stars. Studying the effects of plage regions on M-stars is important, because many known low-mass planets orbit such stars. In the following we will also call the Ca II emitting regions on M-stars plage regions. Because M-stars can have polar spots, they can also have polar plage regions.

In this article we will show how the transit mapping method using the Ca II H&K lines can be used to determine how homogeneously the facula points are distributed on the stellar surface. We select the M-star GJ 1214 as a benchmark object, because it is one of the best studied M-stars hosting a planet.

In Section 2 we summarise what is known about GJ 1214 and its planet. In Section 3 we explain that the Ca II H&K lines can be used to find out how homogeneous the distribution of plage regions is. In that section we also introduce the inhomogeneity factor (IHF). The observations are presented in Section 4. In in Section 5 we determine the filling factor of GJ 1214. IHF is determined in Section 6. The impact of faculae on transit observations obtained with PLATO and ARIEL are finally discussed in Section 7.

2 THE TARGET: GJ 1214

For our study we selected GJ 1214 which is a bright, nearby M4.5-star that harbors a transiting planet (Charbonneau et al. 2009). The mass, radius, temperature and luminosity of this star are: \( M_∗ = 0.176 \pm 0.0087 \, M_☉ \), \( R_∗ = 0.213 \pm 0.011 \, R_☉ \), \( T_{\text{eff}} = 3252 \pm 201 \, \text{K} \), and \( L = (4.05 \pm 0.19) \times 10^{-6} \, L_☉ \), respectively. The mass, radius and bulk density of the planet are: \( M_p = 6.26 \pm 0.91 \, M_⊕ \), \( R_p = 2.80 \pm 0.24 \, R_⊕ \), and \( \rho = 1.56 \pm 0.61 \, \text{g cm}^{-3} \), respectively (Anglada-Escudé et al. 2013).

GJ 1214b is a benchmark object, because the mass and radius of this planet can be obtained with high accuracy. Puig et al. (2018) also used GJ 1214b as an example for an M-star planet that is going to be observed with ARIEL.

A large number of transit observations using satellites, airplanes, and ground-based telescopes of have already been obtained (Bean, Miller-Rickey Kemptton, & Homeier 2010; Bean et al. 2011; Berta et al. 2011; Croll et al. 2011; Désert et al. 2011; Murugas et al. 2012; Fraine et al. 2013; Gillon et al. 2014; Narita et al. 2013; Kreidberg et al. 2014; Wilson et al. 2014; Nascimbeni et al. 2015; Angerhausen et al. 2017; Rackham et al. 2017). All these observations show a flat, featureless spectrum. Not even the Helium line has been detected in high resolution observations (Kasper et al. 2020).

The planet could either have a rocky core and a hazy atmosphere, or it could also be a multi-component water world (Rogers & Seager 2010; Zeng et al. 2019). GJ 1214b thus belong to the class of exoplanets were the currently available data does not allow to resolve its nature. It is thus a key target of future observations.

One possibility to solve this mystery would be the detection of the Rayleigh scattering its atmosphere. The detection of Rayleigh scattering could be possible even if the atmosphere is hazy. A tentative detection was presented by de Mooij et al. (2012) but this detection was not confirmed with observations of higher sensitivity (Nascimbeni et al. 2015). However, one problem of the attempts to detect Rayleigh scattering in the atmosphere of the planet is that faculae on the stellar surface can mimic Rayleigh scattering (Oshagh et al. 2014). Faculae can thus affect the diameter measurements of the planet as well as studies of its atmosphere.

The spots of GJ 1214 have already been intensively studied using broad band photometry (Narita et al. 2013; Rackham et al. 2017). Possibly, the most comprehensive study of this kind was carried out by Mallonn et al. (2018, 2019) who monitored the star since 2014. Mallonn et al. (2018) determined an average spot filling factor of 0.25 ± 0.09%, a temperature contrast of the spots of \( \sim 370 \, \text{K} \) and a rotation period of \( P_{\text{star}} = 125 \pm 5 \) days. Schlafman (2010) identify exoplanet systems that are likely to be misaligned using statistical methods. Since GJ 1214b is not amongst these systems, it is unlikely to be misaligned. According to Berta et al. (2011) the inclination of GJ1214 is 88.80° ± 0.25° degrees. We thus view this star nearly equator on.

The effects of spots have already been taken in to account in the analysis of the transit observations. The aim of this work is to find out what the effect of faculae are. This is
important for future observations, including attempts to detect the Rayleigh scattering. Since GJ1214 photometrically variable, not all spots are at the poles. Since spots and plage regions are usually related, it is not likely that all plage regions are at the poles. It is thus possible that the crossing of plage regions could also affect the transit light-curve.

3 THE INHOMOGENEITY FACTOR OF PLAGE REGIONS

3.1 The definition of the inhomogeneity factor (IHF)

Using the transit mapping method, Wolter et al. (2009) studied the locations of stellar spots along the path of the planet for CoRoT-2b. The same method can also be used to map out the location of plage regions along the path of the planet using the Ca II lines. In this way we can find out whether the plage regions are clumped, or homogeneously distributed on the stellar surface. A clump of plages would appear as a hump in the transit light-curve in the Ca II lines, just as Wolter et al. (2009) observed a hump in the continuum caused by spots.

By comparing the strength of the Ca II lines in- and out-of-transit, we can find out whether the filling factor is the same along the path of the planet as on the rest of star. There are three different cases:

- A.) The plage regions are homogeneously distributed on the stellar surface: In this case, the continuum emission and the emission in the line cores of the Ca II H&K would both decrease by the same amount during transit. After normalising the spectra to the continuum, the relative line fluxes would be the same.
- B) The plage regions are inhomogeneously distributed on the stellar surface, and preferentially located along the path of the planet: In this case, the decrease of Ca II H&K fluxes is larger than the decrease of the continuum. This means that the normalised Ca II H&K fluxes would undergo a decrease during transit.
- C) The plage regions are inhomogeneously distributed on the stellar surface but located outside the path of the planet. In this case the Ca II H&K fluxes would not change but the continuum flux would decrease. This normalised Ca II H&K fluxes would thus increase during transit. Case C is more likely than case B, since the area occulted by the planet is usually small compared to the total area of the plage regions.

If A is the case, the diameter measurements of the planet are not be affected by plage regions. This would, for example be the case if the filling factor is either 100%, or 0%. A star without without active regions could still have some emission in the Ca II H&K lines, because of the acoustic heating. As we will show in the next section, the filling factor of GJ1214 is neither 100%, nor 0%. If B is the case, the transit observations are affected.

In order to visualise the cases B and C, one may think of a planet that transits along equator of a star that is viewed equator-on. In case B the plage regions would be close to the equator, and in case C close to the poles.

For quantifying the impact of plage regions, we have to distinguish two possibilities: \( A_{\text{plage}} > A_{\text{planet}} \) and \( A_{\text{plage}} < A_{\text{planet}} \), with \( A_{\text{plage}} \) the area of the plage regions on the stellar surface, and \( A_{\text{planet}} \) the area occulted by the planet during transit.

To explain why it matters if the plage regions are larger or smaller than the planet let us assume case B and \( A_{\text{plage}} = 10 \cdot A_{\text{planet}} \). The maximum decrease of the Ca II H&K lines would then be 10%. However, if \( A_{\text{plage}} \leq A_{\text{planet}} \), the Ca II H&K line would completely disappear during transit, if there is one plage region which is located along the path of the planet. Thus, in one case a 10% decrease would indicate the maximum inhomogeneity, in the other, a 100% decrease. We have to distinguish two cases:

\[
\text{For } A_{\text{plage}} \geq A_{\text{planet}} : \text{IHF} = \frac{1 - \text{CaII}_{\text{IT}}}{\text{CaII}_{\text{OT}}} \tag{1}
\]

\[
\text{For } A_{\text{plage}} \leq A_{\text{planet}} : \text{IHF} = 1 - \frac{\text{CaII}_{\text{IT}}}{\text{CaII}_{\text{OT}}} \tag{2}
\]

where CaII_{IT} is the flux of the Ca II H&K lines measured during transit, and CaII_{OT} the flux out-of-transit. \( A_{\text{plage}} \) and \( A_{\text{planet}} \) are the surface areas on the star covered by plage regions and the planet during transit. Note that \( \text{CaII}_{\text{IT}} \leq \text{CaII}_{\text{OT}} \) is always fulfilled for case B. For \( A_{\text{planet}} = A_{\text{plage}} \) both equations are the same.

IHF=100% means the distribution is as inhomogeneous as possible, for example if there is just one plage region on the star. IHF=0% means that the distribution is homogeneous (case A), or at least does not affect the transit observations.

Let us assume for case C a similar situation as above, \( A_{\text{plage}} = 10 \cdot A_{\text{planet}} \) and a planet that covers 1% of the surface of the star. During transit, the flux of the Ca II H&K lines would not change but the flux of the other regions would decrease by 1.1%. After normalising the spectra, the Ca II H&K lines would increase, because the continuum decreases during transit. Like for spots, the effect of non-occulted plage regions is smaller than that of occulted ones.

IHF is negative in case C.

As will be demonstrated in Section 7 for the case of GJ1214b, the IHF-value can be used to determine the correction factor that has to be applied in order to correct the diameter measurements of the planet for a star with plage regions.

3.2 Comparing the IHF-method with other approaches and special cases of transits

An alternative method has been developed by Morris et al. (2018). In this approach, the ratio of \( \rho_0 = R_p/R_* \) to \( p_1 = \sqrt{\delta} \), is derived (\( \delta \) is the transit depth.). The basic idea is to determine \( p_1 \) from the light-curve and \( \rho_0 \) using other methods. For determining \( p_1 \), the impact parameter is estimated using the dependence of the transit duration upon the stellar density and the eccentricity of the planet’s orbit, as well as other quantities such as the planet’s orbital period. This in turn requires to determine the stellar density independently from the light-curve modeling. As Morris et al. (2018) pointed out, astroseismology could provide this information. The method thus can be used for solar-like stars.
were the density of the star has been determined using astroseismology. However, the amplitudes of stellar oscillations on M-stars are tiny (Kjeldsen & Bedding 1995). It may thus be quite difficult to obtain the stellar density from astroseismology for M-stars.

The IHF-quantity has the advantage that it is directly derived from the observations, without making any additional assumptions, or the need of additional information coming from other sources. It also works for M-stars, and for stars with activity bands. Since the Ca II emission would decrease during transit, it would be obvious that the planet has occulted active bands during transit.

The IHF-quantity can also be used to derive $p_0/p_1$. All we need is the temperature difference between the plage regions for that (See Section 7).

If the planet orbits over the poles and occults active regions located at the north and the south pole, it would also be case B.

The IHF-quantity has also the advantage that it is proportional to the change of the depth of the transit due to plage regions. For example, if the depth changes by 100 ppm for IHF=10% then it would change by 200 ppm for IHF=20%. The IHF quantity thus is a measure how much the transit depth is changed because of plage regions.

4 OBSERVATIONS AND DATA REDUCTION

We observed GJ 1214 continuously from July 29, 2017 UTC 23:34 until July 30, 2017 UTC 03:25 with UVES at the VLT (ESO program 099.C-0175(A)). The mid-point of the transit was at $T_e = \text{BJD} 2457964.552073 \pm 0.00032$ (Kasper et al. 2020). The middle of the transit was on July 30, 2017 UTC 01:15. The transit lasted from 00:49 to 01:41. The ingress and egress takes only 6 min. During the 3 hours and 51 minutes of observations, we obtained 18 spectra with exposure times of 12 min. We obtained five spectra before the transit, five during the transit, and eight spectra after it. The observations before the transit were obtained at airmass 1.31 to 1.18, during transit at airmass 1.18 to 1.15, and after it at airmass 1.15 to 1.29. The spectra cover the wavelength range from 325.9 to 449.3 nm in the blue and 472.6 nm to 683.5 nm in the red arm of the spectrograph. The resolution of the spectra is $\lambda/\Delta \lambda = 52000$ with the 0.8 arcsec slit used. The standard ESO reduction pipeline was used. We also reduced the spectra also with IRAF to make sure that the results do not depend on the data-reduction process.

5 THE PLAGE FILLING FACTOR

For deriving the inhomogeneity factor (IHF), we have to find out whether $\Delta \text{plage} > \Delta \text{planet}$ or $\Delta \text{plage} \leq \Delta \text{planet}$ (equation 1 and 2). For determining the filling factor, we use the flux of the Ca II H&K. Solar and stellar observations show that the unsinged magnetic field strengths and the flux of the Ca II H,K lines are related (Schrijver et al. 1989; Loukitcheva, Solanki, & White 2009; Morgenthaler et al. 2012; Chatzistergos et al. 2019). This relation does not depend on the magnetic cycle and it can be applied to all G, K, and M-stars. The relation is linear for large magnetic field strength. For weak fields, it becomes non-linear. Solar observations of high spatial resolution show that there are two sources of the Ca II flux. A basal flux of nonmagnetic origin, and a component that is related to the magnetic field (Loukitcheva, Solanki, & White 2009). Theoretical studies show that the basal flux is due to the acoustic heating of the chromosphere (Fawzy et al. 2002a,b,c). Comparing theory with observations, Fawzy et al. (2002b) find that the relative contribution of the acoustic heating decreases with decreasing mass of the star. This means, the basal flux is less important or M-stars than for solar-like stars.

Because our aim is to find out what the maximum effect of plage regions could be, it is assumed that the flux of the Ca II H,K is only due to active regions. If some of it is of nonmagnetic origin, the effects due to plage regions would be smaller. Strictly speaking, the filling factor (ff) thus is an upper limit, because some of the flux of the Ca II H,K lines could be due to acoustic heating.

The (upper limit of the) filling factor (ff) is determined from the ratio of the flux of the Ca II H,K of GJ 1214 to the reference star (ref) with a known filling factor:

$$ff_{G=1214} \leq \frac{F_{\text{CaII, G=1214}}}{F_{\text{CaII, ref}}} \cdot ff_{\text{ref}}$$ (3)

A reference star is a star of the same spectral type as the target were the filling factor and the magnetic field strength has been measured.

We use AD Leo (=GJ 388) as a reference, because there are several measurements of the filling factor and the magnetic field strength. AD Leo is an M4.5 star with a rotation period of 2.23 days and $T_{eff} = 3414 \pm 100$ K (Di Maio et al. 2020). Saar & Linsky (1985) derived $ff = 73 \pm 6\%$ and $B = 3800 \pm 260$ G. Cranmer & Saar (2011) found $ff = 60\%$ and $B = 4000$ G. Shulyak et al. (2017) determined a magnetic field strength of $ff = 3100 \pm 100$ G.

The total flux of the Ca II H lines of GJ 1214 is $(13.0 \pm 0.5) \times 10^{24}$ erg s$^{-1}$ and that of the Ca II K line is $(8.0 \pm 0.5) \times 10^{24}$ erg s$^{-1}$. Using these values, the Ca II H,K fluxes of AD Leo, and taking also the slight differences between the two stars in to account, we obtain $ff \leq 6.8 \pm 1.0\%$ for GJ 1214.

Fawzy et al. (2002b) calculated the flux of the Ca II H,K for stars due to acoustic and magnetic wave heating for stars with spectral types in the range between F5 and M0. GJ 1214 is outside this range but if we extrapolate this relation, we end up with filling factors in the range between 5 to 10%. The value of 7% thus is reasonable.

This means, we have to use equation 1 for calculating IHF, because the planet occults only 1.39 $\pm 0.25\%$ of the stellar surface. We find $\Delta \text{planet}/\Delta \text{plage} = 0.204 \pm 0.047$. Since the spot filling factor is only 0.25 $\pm 0.09\%$ (Mallick et al. 2018), most of the magnetic flux is in the plage regions.

6 THE HOMOGENEITY OF THE PLAGE REGIONS

The pseudo-Equivalent Width (pEW) of GJ 1214 obtained are given in Table 1. We prefer to call these pseudo-equivalent width, rather than equivalent width, because we measure only the equivalent width the emission core. Fig. 1 shows the normalized values obtained during the night. We
Plage regions and transits

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Figure 1. Normalized equivalent widths of the Ca II-H (blue) and Ca II-K (green) lines of GJ 1214. The red line shows the trend subtracted.

Figure 2. Spectrum of the Ca II-H line of GJ 1214, before (dark yellow), during (red) and after (blue) the transit. Below is the difference between the spectra taken in- and out-of transit. There is no significant difference.

Figure 3. Same as Fig. 2 but for the Ca II-K line.

normalized the values for this figure, so that both lines can be shown in the same figure.

The spectra taken before (dark yellow), during (red) and after (blue) the transit are shown in Fig. 2, and Fig. 3. The lines at the bottom of the figure are the difference between the spectra taken in- and out-of transit. One may think that the Ca II K line is higher after the transit then during transit (Fig. 3). However, this difference is not significant.

Because both lines show exactly the same behavior, we sum up the pEWs of both lines to increase the accuracy. We derive: pEW = −3.956 ± 0.052 Å before the transit, and pEW = −4.019 ± 0.084 out-of transit. The difference thus is 0.063 ± 0.099 Å. Thus, there is no significant change of the Ca II H,K lines during transit. GJ 1214 thus corresponds to case A in Section 3. All values derived are listed in Table 2.

Using the values with the trend subtracted, we obtain IHF = 7.7 ± 1.2%. The errors are relatively large, because the planet occults only a small fraction of the plage regions. Nevertheless, we conclude that there is no evidence that the plage regions are clumped.

Using IHF, we can now calculate how large the affect for PLATO observation would be, in other words, we can calculate \( p_0/p_1 \). According to the numerical simulations by (Beeck et al. 2015), the average temperature difference between a region with a magnetic field strength of 500 G and non-magnetic region is only 20 K for early-type M-stars. Let us assume that that the decrease of the strength of the CaIIHK-lines is not an upper limit but a real decrease of 6.3% during transit. In this case the brightness of the star would change by 41 ppm. Thus, faculae do not pose a big problem for the PLATO-, as well as ARIEL-observations of GJ 1214b. However, the effects of faculae could be much

7 DISCUSSION AND CONCLUSIONS

Oshagh et al. (2014) modeled the effects of faculae that are occulted during transit. In their model, they assumed an M-dwarfs of 3000 K and planets with \( R_p/R_{\text{star}} = 0.05 \) to 0.15. The authors furthermore assumed that the faculae are 100 K hotter than the normal photosphere and cover between 0.25 and 6.25% of the surfaces of the star. The values obtained for GJ 1214 are thus within the range of this model. However, Oshagh et al. (2014) could not know, if the faculae are distributed homogeneous or inhomogeneous on the stellar surface.

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larger for other stars. It is thus useful to observe the transits in Ca ii H,K of all stars that ARIEL will observe and also for the planet host stars that PLATO will detect. Since the design goal of PLATO is a photometric accuracy of 94 ppm (Rauer et al. 2014), plage regions may affect the diameter measurements in some objects. The effects of faculae should thus be included into simulations, like those presented by Samadi et al. (2019).

The method can also be generalized using other lines that trace only active regions. For solar-like stars the CO-lines in the infrared, which originate only from spots, would be an option.

In interesting aspect pointed out by Işik et al. (2020) is that, at least on solar-like stars, there are not only active latitudes but also active longitudes. Such a clustering of active regions leads to an enhancement of the photometric variability compared to random distribution of active regions.

The detailed analysis of the impact of active regions remains to be an issue for precise measurements of the diameters of planets. For the PLATO mission, spectro-polarimetric observations are planned for the most interesting targets (PLATO-WP 145200). However, such observations are very demanding and thus can only be carried out for very few objects. Observations of the Ca ii H,K represent a cheap alternative and can be obtained for many stars (PLATO-WP 11 and WP 14).

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DATA AVAILABILITY STATEMENT

The data underlying this article are available in the ESO Science Archive Facility http://archive.eso.org/cms.html.

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