UV lines as a tracers for the XUV-fluxes of stars and the PLATOspec project

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Abstract Observations in the UV-regime are very important for exoplanet research, because many diagnostically important lines for studying stellar activity are in this regime. Studying stellar activity is not only important because of its negative effects on the determination planetary parameters, but also because the XUV-radiation from the host stars affects the photochemistry and the erosion of planetary atmospheres. Unfortunately, the XUV-region is only accessible from space. However, since the XUV-radiation is correlated with the Ca II H&K-lines, we can use these lines to study the XUV radiation indirectly. The Ca II H&K-lines for relatively bright stars can be observed with PLATOspec, a new high-resolution echelle spectrograph in development for the ESO 1.5m telescope at La Silla. One advantage compared to instruments on larger telescopes will be that large programs can be carried out. There will be two modes for obtaining precise RV-measurements. In the future, the CUBES instrument on the VLT will be able to study the same lines to probe the XUV-radiation in much fainter targets.

Keywords extrasolar planet · stellar activity · Ca II HK-lines · PLATO · ARIEL
The next generation of exoplanet missions: PLATO and ARIEL

The discovery of the first exoplanet around a Sun-like star, 51 Peg b opened up a totally new field of research in astronomy [18]. The radial-velocity (RV) method used for this discovery initially allows to determine only $M_{\text{p, min}} = M_p \times \sin i$ ($M_p$ mass of the planet and $i$, the inclination of its orbit). If we observe many stars, we obtain a statistical mass distribution of the whole ensemble. Statistically, the true mass of a planet is $M_p \sim 4/\pi \times M_{\text{p, min}}$. Complementary to the RV-method is the transit-method, which allows to determine the radii and inclinations of the planets. Combining the two allows to determine the true masses, radii and hence the densities of exoplanets. Density measurements are currently the best way to constrain the composition of exoplanets. Gas-giants in our solar-system have densities between 0.7 and 1.6 g cm$^{-3}$, rocky planets between 3.9 and 5.5 g cm$^{-3}$. Exoplanets have been found that have densities as low as 0.7 g cm$^{-3}$ (e.g. Kepler 51) and higher than 5.5 g cm$^{-3}$ (e.g. K2-106 b, K2-229 b and 107c). There are also exoplanets with intermediate densities in the range between 1.6 and 3.9 g cm$^{-3}$. Exoplanets are turn out to be much more divers than the planets in our solar-system. Finding out, what the nature of all these planets are, is one of the most interesting questions of exoplanet research.

Studying hot Jupiters is all but boring, as we do not really know how they form. Do they form via disk-induced migration, high-eccentricity migration, or in in-situ? The discovery of WASP-107 b, a planet mass in the Neptune regime and a radius of Jupiter, can best be explained with a formation at large distance with subsequent migration [20]. However, WASP-47, a system with a hot Jupiter sandwiched between an inner and an outer low-mass planet favors in-situ formation [2]. It thus looks like that there is more than one pathway of planet formation [12]. To unravel this mystery, we have to determine the masses, and radii of many exoplanets accompanied by studied of their atmospheres.

The evolution of planetary atmospheres is a complicated process which involves many factors. One of the most important factors is the amount of XUV-radiation (X-ray + EUV) that the planets receive. The XUV-radiation is the driving force for the photochemistry of planetary atmospheres and it is likely to play a key role for the erosion of planetary atmospheres. As we will discuss in the section 2, UV-lines can be used as tracers for the XUV-radiation from the host stars which can otherwise only be studied by satellites.

The big leap forward in exoplanet research will be the exoplanet characterization mission PLATO (PLAnetary Transits and Oscillations of stars)[23], and the atmospheric characterization mission ARIEL (Atmospheric Remote-sensing Infrared Exoplanet Large-survey) [21]. PLATO is foreseen to be launched in 2026, and ARIEL in 2029.

PLATO will use the transit-method to find planets down to the size of the Earth orbiting, solar-like stars at distances up to the habitable zones, and determine their radii with extraordinary high precision. The payload consists of 24 ‘normal’ and 2 ‘fast’ cameras. The fast cameras will be used to monitor
stars of \(4 \leq V \leq 8\) mag. The prime targets of the normal cameras will be stars brighter than \(V \leq 11\) mag. It is estimated that PLATO will discover 4000 super-Earths and Earths, of which 40-70 will be in the habitable zones. The aim is to determine the masses of these planets using the RV-method. As we will explain in the Section 3, this is all but easy because of the stellar activity. As already mentioned, stellar activity also plays an important role for the mass-loss and photochemistry of planetary atmospheres. It is also of key importance for the existence of life. Stellar activity thus has to be studied for all planet host stars, particularly for those that harbor potentially habitable planets.

ARIEL is the first space mission dedicated to measuring the chemical composition and thermal structures of hundreds of transiting exoplanets. ARIEL has three photometric channels in the VIS (0.5-0.6 \(\mu m\), 0.6-0.81 \(\mu m\), 0.81-1.0 \(\mu m\)) and three spectroscopic channels in the NIR (1.1-1.95 \(\mu m\), R=20; 1.95-3.9 \(\mu m\), R=100, 3.9-7.8 \(\mu m\), R=30). ARIEL will observe 1000 preselected transiting planets, of which 50-100 will be studied intensively. Since the signal from the atmosphere is proportional to radius of the planet times the scale height, the prime targets are planets with large scale heights. The scale height is given by \(H = k_B T / (\mu g)\), with \(k_B\) the Boltzmann’s constant, \(T\) the temperature of the atmosphere, \(\mu\) the mean molecular mass, and \(g\) the surface gravity of the planet. Most ARIEL targets will have temperatures in the range between 1000 to 2000 K. More than half of them will be larger than \(4 R_{\text{Earth}}\). The high temperature of the targets not only increases the signal-to-noise ratio of the spectra, it also ensures that the atmospheres are well mixed. In summary, most of the ARIEL targets will be close-in, relatively large planets orbiting relatively bright stars.

One of the experiments that will be carried out by ARIEL is the determination of the C/O-ratio in hot Jupiters. C/O \(\sim 1\) would indicate that the planet has formed beyond the snow line, and C/O \(\sim 0.5\) would indicate a formation inside the ice-line. However close-in planets receive a lot of XUV/UV-radiation which drives the photochemistry in planetary atmospheres. We thus need to study the XUV- and UV-radiation as well, at least indirectly.

We also need to measure the masses of the planets, because that determines the scale height. What we also need are the element abundances of the host star to be compared with the abundances of the planets. Because the RV-variations of hot/warm Jupiter- and a Neptune-mass planets are 200-400, and 10-22 m s\(^{-1}\), respectively, we do not need an extreme RV-precision. In summary, what we need for PLATO and ARIEL is the possibility to study stellar activity, the possibility to determine stellar parameters and an RV-precision of 10 m s\(^{-1}\), or better.

2 The Ca\textsc{ii} H&K and other UV-lines tracers for the XUV-radiation

For understanding the evolution of planets, it is essential to understand the erosion processes of planetary atmospheres. While different processes have
been suggested, atmospheric losses due to the XUV-radiation from the host \((\lambda < 91.2 \text{ nm})\) certainly plays an important role \([15], [16]\). While the main erosion phase for planets of solar-like stars is during the first 100 Myrs, extreme mass-losses have also been observed on planets orbiting stars older than that, for example WASP 12b \([14]\) and WASP-121 b \([6]\). Studying the activity of stars hosting planets with extreme mass-loss is the best way to learn more about these processes.

Unfortunately, the wavelength region \(\lambda < 91.2 \text{ nm}\) can only be observed from space. However, Sreejith et al. \([26]\) showed that the amount of X-ray and EUV-radiation correlates well with the Ca\text{II} H&K flux. The flux of the star at XUV-wavelength can thus be estimated from the flux of the Ca\text{II} H&K lines.

Flares contribute to 20-50% of XUV-flux in young stars \([10]\). It is thus important to study the flare activity for understanding atmospheric erosion and photochemistry of planetary atmospheres. The contribution from flares is critical, because the temperatures of flares are higher than that of the corona. That means, the XUV-spectrum of the flares is harder, and the photons penetrate deeper into the atmospheres of the planets. The basic properties of the flares can be determined from diagnostic emission lines, most of which are in the UV-regime that can still be observed by ground-based telescope \([8]\). Because active stars have a large number of small flares, the lines from flares are present most of the time. Monitoring of such flares is one of the cases being developed for the new CUBES instrument for the VLT (see Zanutta et al, this volume). However, for observations of the Ca\text{II} H&K lines (393 & 397nm) in bright stars a smaller telescope than the VLT can suffice. In Section 4, we present plans for the new PLATOspec instrument for the 1.5m telescope at La Silla, that will neatly complement future CUBES observations of fainter, more demanding targets.

3 Stellar activity and the RV-jitter

As already outlined in Section \([1]\) we have to determine not only the radii but also the masses of exoplanets. Ideally the masses should be determined by using the RV-method, rather than TTVs. Numerical simulations by \([5]\) showed that 100 RV-measurements allow to detect planets with K-amplitudes that are 1.5 (1) times larger than the noise-level of the measurement. After carrying out the RV-fitting challenge Dumusque et al. \([7]\) conclude that \(K/N > 7.5\) gives a 80-90% recovery rate, where \(K/N = \frac{K_{pl}}{RV_{rms} \times \sqrt{N_{obs}}}\). This means, for \(N=100\), \(K_{pl} \geq 0.75 \times RV_{rms}\). If we aim for the detection of a planet with \(10(4) M_{\text{Earth}}\) at one AU, we require 100 RV-measurements with an accuracy better than 1.2 (0.5) m s\(^{-1}\).

Instruments like CARMENES, HARPS HAPS-N, routinely achieve an RV-accuracy of about one m s\(^{-1}\), and the design-goal of ESPRESSO is an RV-accuracy of 0.1 m s\(^{-1}\). However, the RV-accuracy does not only depend on the precision of the instrument, it also depends on the activity-level of the star. Suárez Mascareño et al. \([27]\) have studied the relation between Ca\text{II} H&K-
index and the K-amplitude of the activity. For a stellar-noise jitter of 0.4-0.5 m s$^{-1}$, a GK-star has to have $\log_{10}(R'_{HK}) \sim -5.0$. This is about the current solar-activity level. According to Hall et al. [11], 32% of the solar-like stars have this activity level, or are even less active. It should thus be possible to detect planets with $M_p \sim 4\, M_{\text{Earth}}$ in the habitable zone of solar-like stars if the star also has a solar-like activity level. Collier Cameron et al. [3], [4] made a study of the sun as a star using a time-series of 853 daily observations with a $250 < S/N < 400$ obtained with HARPS-N. They injected synthetic low-mass planet signals corresponding to planets of 1.2, 1.9, 2.9, and 3.7 $M_{\text{Earth}}$ with periods of 7.142, 27.123, 101.543, and 213.593 d. Using a sophisticated method that allows to remove the stellar activity, they demonstrated that such planets could be detected. The results from Collier Cameron et al. [4] thus agree well with previous estimates [5], [7].

K-stars are even better targets than G-stars, because the RV-amplitudes caused by planets in the habitable zones are larger. In this case, the limit is about $2\, M_{\text{Earth}}$. In summary, planets with about 2-4 $M_{\text{Earth}}$ can be detected orbiting solar like stars if their activity level is low. It is thus important to monitor the PLATO targets extensively in Ca$\text{II}$ H&K before attempting to determine the masses of the planets.

4 PLATOspec

4.1 Science goal and requirements for the instrument

As we have outlined in sections 1, 2, 3, PLATO and ARIEL will be the next big steps in exoplanet research. However, for these missions we need extensive ground-based support observations. Amongst these are extensive studies of the Ca$\text{II}$ H&K lines and RV-measurements with an accuracy of 10 m s$^{-1}$, or better. Given that PLATO will discover 4000 planets that calls for a dedicate instrument just for these observational needs. We thus initiated the PLATOspec project, which has three scientific aims:

i.) Measure the flux in the Ca$\text{II}$ H&K lines of planet host stars.

ii.) Determine the stellar parameters Teff, log(g) abundance, and space velocity of planet host stars.

iii.) Determine the masses of hot and warm Jupiters, and hot Neptunes.

Requirements of the instrument:

1.) High efficiency at a wavelength of 390 nm.

2.) Location at suitable site: The instrument needs to be located at a site with more than 2000 hours of suitable observing conditions which also has a high sky-transmission in the UV.

3.) Resolution and wavelength coverage: $R \sim 70000$ (4.2 km s$^{-1}$) and a wavelength coverage of 360-680 nm.

4.) RV-accuracy: A quick scan mode with an RV-accuracy better than 10 m s$^{-1}$ for stars down to V=11 mag, and a high-precision mode with an RV-accuracy of 3 m s$^{-1}$ for special targets.
Fig. 1 The ESO 1.5m telescope

Fig. 2 Preliminary mechanical lay out of the PLATOSpec spectrograph.
4.2 The instrument

PLATOspec is the new high-resolution high-stable spectrograph for the ESO 1.5m telescope of the Observatory La Silla (Fig. 1). The Project is lead by the Czech Academy of Science (PI Petr Kabath) in equal share with two main partner institutes, the Observatory of Tautenburg (CoPI Artie Hatzes) and the Center of Astro Engineering UC (CoPI Leo Vanzi). In addition the Masaryk University from the Czech Republic and the Universidad Adolfo Ibanez from Chile join the project as minor partners in 2021.

PLATOspec will be a fibre-fed Echelle spectrograph that will be placed in a climatized room. The telescope is being refurbished and upgraded in 2021. The focal ratio of the telescope is F/14.9 which provides a scale of about 9.2 arcsec/mm at its focal plane. This allows projecting an aperture of about 2 arcsec diameter of the sky onto a 50 µm core fiber. In particular 1.8 arcsec at F/3.8 or 2.0 arcsec at F/3.4 with suitable feeding optics. An octagonal fiber can be used for optimal scrambling of the near field illumination.

The instrument concept follows similar instruments of the same class such as FEROS [17], CORALIE [22] or CHIRON [28] (Fig. 2). In particular our team will use as reference the spectrograph FIDEOS [29] and TCES the Echelle spectrograph of the 2-m-Alfred Jensch telescope at Thüringer Landessternwarte Tautenburg because of our direct experience with them. TCES has $R \sim 67000$, and an iodine cell (IC). For very bright stars, we have achieved an accuracy of 1.2 to 1.7 m s$^{-1}$ with a similar instrument [13].

There will be two mode for precision RV-measurements:

1.) The medium precision RV-mode: In this mode the simultaneous calibration technique with an ThAr hollow-cathode lamp (HCL) is used. PLATOSpec will not be evacuated, only temperature stabilized to a level of about 0.1 C. Experience with similar instruments show that an accuracy of 8 m s$^{-1}$ can be achieved. In particular the results of FIDEOS indicates that an RV precision of 4-5 m s$^{-1}$ is possible. A further improvement of this mode are possible. Experiments with TCES shows that the main shifts are caused by changes of the pressure. By including a device to measure the pressure changes during
the night and using this information in the data-pipeline, the drifts can be minimized.

2.) A high precisions RV-mode: In this mode, an iodine cell (IC) is inserted in to the beam so that the star-light goes through it. The IC provides a very dense grid of lines between 510 nm to 620 nm. The IC will be used for modeling precisely the drift of the spectrograph and the changes of the point spread function. Since only small part of the spectrum is used for the RV-measurements and 30% of the light is absorbed in this case, this mode is recommended only for relatively bright stars. We expect that RV-precision of about 3 m s\(^{-1}\), similar to TCES, will be achieved.

We expect that the instrument will become operational in 2023.

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