INSTITUT DE FRANCE
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Comptes Rendus

Physique

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Exoplanet science with SPIRou: near-infrared precision velocimetry and spectropolarimetry

Published online: 1 March 2023

https://doi.org/10.5802/crphys.141

Part of Special Issue: Exoplanets

Guest editors: Anne-Marie Lagrange (LESIA, Observatoire de Paris, Université PSL, CNRS, Sorbonne Université, Sorbonne Paris Cité, 5 place Jules Janssen, 92195 Meudon, France.) and Daniel Rouan (LESIA, Observatoire de Paris, Université PSL, CNRS, Sorbonne Université, Sorbonne Paris Cité, 5 place Jules Janssen, 92195 Meudon, France.)

Les Comptes Rendus. Physique *sont membres du*
Centre Mersenne pour l'édition scientifique ouverte
www.centre-mersenne.org
e-ISSN : 1878-1535

Comptes Rendus
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Exoplanets / *Exoplanètes*

Exoplanet science with SPIRou: near-infrared precision velocimetry and spectropolarimetry

Les exoplanètes et leurs étoiles vues par SPIRou : vélocimétrie de précision dans l'infrarouge proche et spectropolarimétrie

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Abstract. High-precision radial-velocity measurements in the near-infrared allow one to search for exoplanet signals around the lowest-mass stars, including young ones. Because these stars can be among the most active ones, it is essential to characterize their magnetic activity. SPIRou, installed at the Canada–France–Hawai'i telescope, was designed to explore such planetary systems and characterize their properties. With a wide spectral range and large resolving power, SPIRou is also optimized for transmission spectroscopy and for investigating the chemical composition of exoplanetary atmospheres.

Résumé. Les mesures de vitesse radiale de haute précision dans l'infrarouge proche permettent de rechercher le signal d'exoplanètes autour d'étoiles de faible masse, en incluant les étoiles précoces. Comme ces étoiles sont parmi les plus actives, il est essentiel de caractériser leur activité magnétique. L'instrument SPIRou, installé au télescope Canada–France–Hawai'i, a été conçu pour explorer de tels systèmes extra-solaires et caractériser leurs propriétés. Avec un domaine spectral étendu et un pouvoir de résolution élevé, SPIRou est également optimisé pour la spectroscopie de transmission, permettant d'étudier la composition chimique des atmosphères d'exoplanètes.

Keywords. Exoplanets, Stars, Spectroscopic techniques, Atmospheres, Magnetic fields.

Mots-clés. Exoplanètes, Étoiles, Techniques spectroscopiques, Atmosphères, Champs magnétiques.

Note. Follows up on a conference-debate of the French Academy of Sciences entitled "Exoplanets: the new challenges" held on 18 May 2021, visible via https://www.academie-sciences.fr/fr/Colloques-conferences-et-debats/exoplanetes.html.

Note. Fait suite à une conférence-débat de l'Académie des sciences intitulée « Exoplanètes : les nouveaux défis » tenue le 18 mai 2021, visible via https://www.academie-sciences.fr/fr/Colloques-conferences-et-debats/exoplanetes.html.

Published online: 1 March 2023

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1. Introduction

In 2022, more than five thousands exoplanets are known and only 8% of them are hosted by stars cooler than 4000 K approximately corresponding to the spectral types of M dwarfs. Being the most abundant stellar type in the galaxy and in the solar neighbourhood in particular, these low-mass stars are also the most diverse. They span a very large range in mass, from 0.08 to 0.6 solar mass, and a factor 200 in luminosity. Planet search with the radial velocity (RV) method is favoured for low-mass stars, as the planet signal is enhanced for a given planet mass compared to a more massive star. Planetary formation and migration models have been challenged by recent discoveries in the lower-mass end of the main sequence, that showed that multiple compact systems can exist around stars as small as Trappist-1 (0.09 $M_\odot$, [1]) where circumstellar material is sparse. Transit surveys were the first ones to unveil the large population of super-earths near the habitable zone of their host stars, deriving an occurrence rate of at least one planet per star at orbital periods of less than 100 days [2]. Microlensing surveys, which mainly probe low-mass stars due to their higher frequency, also find very large occurrences of planets—amounting to about one planet per star [3]. Since the mid 1990's, radial velocity surveys with optical spectrographs have been challenged by the low luminosity of M stars and have mainly concentrated on solar-mass stars, although pioneer work already showed a dozen confirmed or candidate planet signals found around 100 low-mass stars [4]. This is much less than the expected number of planets around such stars, given the lower limit on the planet occurrence rate estimated from transit data, implying that many more planets are still to be discovered. In this context, it was decided to design and build a near-infrared cryogenic echelle spectrograph, capable of high RV precision.

2. SPIRou

SPIRou (Spectro-Polarimètre InfraROUge) is a nIR spectropolarimeter mounted at the Cassegrain focus of the 3.60 m Canada–France–Hawai'i telescope (CFHT) atop Maunakea in Hawai'i. The spectral range is continuous from 950 to 2500 nm (spanning YJHK bands) at a spectral resolving power of about 70,000, recoded on a 4 K × 4 K H4RG detector. The Cassegrain unit is composed of an achromatic polarimeter, a tip-tilt mechanism with its guiding system, an atmospheric dispersion corrector, and a calibration device (to inject the light from calibration lamps through the instrument). The cross-dispersed spectrograph, located two floors below in a cool and stable environment, is connected to the Cassegrain unit through fluoride fibers. A calibration unit is also connected for internal flat-fielding and spectral calibration purposes. The cryogenic spectrograph is kept in vacuum and cooled down to a temperature of 70 K, with a relative thermal stability of better than 1 mK. Such a level of stability is required to suppress the opto-mechanical variations that would result from temperature changes and cause the measured RVs to vary with time. The internal stability of SPIRou has been benchmarked with a suite of internal lamps (UNe, Fabry-Pérot and a laser frequency comb) and has a typical scatter of under 0.2 m/s on a timescale of a night. The dispersion obtained on stellar spectra of M stars is of the order of 1.5 to 2 m/s. Regarding efficiency, SPIRou typically achieves a peak signal to noise ratio per detector pixel of 100 on a H 11 magnitude star in a 1 h exposure, which corresponds to a peak throughput of about 10%, everything included. SPIRou has been in operations since February 2019 and is operated in queue mode, mostly during bright time. For a more detailed description of SPIRou, its science goals and performances, we refer the user to the review paper [5].

3. Exoplanet detection and characterization with SPIRou

Science goals for SPIRou include the search for exoplanets orbiting low-mass stars, the mass characterization of transiting candidates unveiled by TESS space photometry, and the spectroscopic transmission of exoplanet atmospheres. In addition, spectropolarimetry and high-resolution nIR spectroscopy allow us to explore stellar physics, in particular the early phases of planetary system formation and the evolving magnetic fields at the surface of the host stars. Characterizing the magnetic field of the host star is of prime importance in the field of exoplanet science. With indirect methods, the intrinsic phenomena occurring at the surface of the host stars need to be investigated as much as, and simultaneously to the exoplanet signals themselves (see Section 4).

High performance in RV measurements is critical to get competitive detection limits. In the nIR domain, the ground-based spectra are plagued by variable Earth atmospheric transmission and emission. Although most absorption lines can be removed with models and comparison with a library of hot-star spectra [6], small residuals of telluric lines may remain at the percent level, and induce an extra noise in the time series. In addition, nIR detectors are more prone to persistence, causing low-S/N measurements to exhibit excess noise in addition to the photon noise. In this context, it is required to investigate new developments in the extraction pipelines for nIR velocimeters such as SPIRou in order to get RV precision matching the expected RV noise (including photon noise and the instrumental RV precision). SPIRou data are commonly extracted, calibrated, and corrected for their telluric contamination by the APERO pipeline [7]. First RV estimates are obtained primarily using the cross-correlation method. A new method called line-by-line was developed to optimize the selection of lines with respect to the micro-telluric residuals and the extracted spectral content [8]. This method is now commonly used on SPIRou spectra. It allows to get the RVs for thousands of individual lines along with the corresponding error bar, and to combine them into a single value which is more robust to outliers.

The SPIRou Legacy Survey (SLS) is a 310-night program held at CFHT for 3.5 years held from February 2019 to July 2022. In this framework, 50 nearby M stars were intensively observed in the double goal of collecting RV measurements (for exoplanet detection) and circular polarization sequences (for magnetic field characterization). In addition, about 20 TESS objects of interest with M stellar hosts were monitored in the same way to establish the planetary nature and characterize the parameters of transiting candidates. Finally, about 40 pre-main sequence stars were monitored, both to explore their stellar magnetic properties and to search for potential RV signatures of close-in giant planets. The whole set of time series is being investigated, since the survey is now finished. It is being continued and consolidated by another large program extending from 2022 to 2024, called SPICE.

Among the first highlights in exoplanet detection and characterization, one can cite the following results:

- Characterization of a rare substellar companion in close orbit to a cool star [9].

  TOI-1278 b has been identified by space photometry as a transiting body of an early M star with a 14.5 day orbital period and a percent-level transit. Its mass has been measured from SPIRou RV measurements to 18.5 ± 0.5 M_{Jup}. Such close-in massive companions—either giant planet or brown dwarf in nature—are extremely rare and may be considered a challenge for planetary formation models.
- Exploring the surrounding of the hot super-Earth desert.

  TOI-1759 b and TOI-1452 b are two sub-Neptune planets unveiled by their transit with TESS and whose mass and density were derived from SPIRou RV measurements. While TOI-1759 b turns out to be a low-mass gas planet with a bulk density of 1.3 ± 0.5 g·cm^{-3}, TOI-1452 b is a super-Earth or water-rich world with a density of 5.6 ± 1.8 g·cm^{-3}. Both planets have M-type stellar hosts. More details on the properties of these systems, including the magnetic topology of their host stars, can be found in relevant Refs. [10, 11].

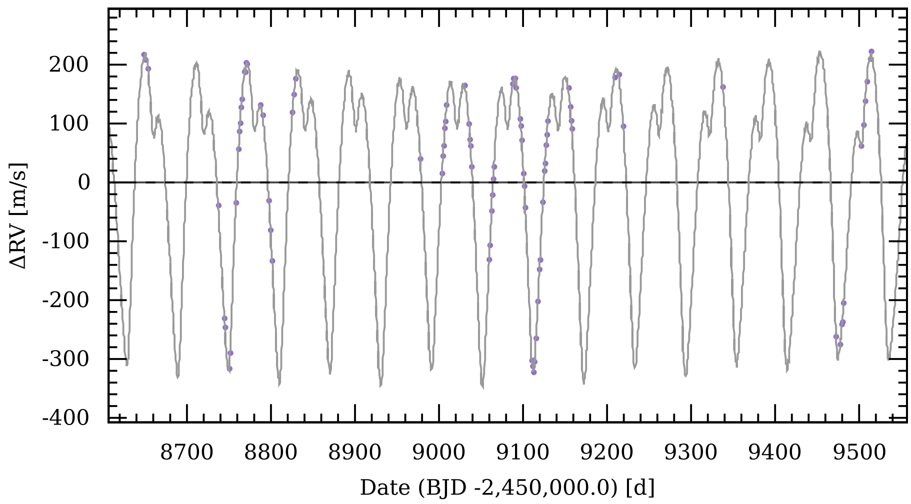

Figure 1. The SPIRou RV measurements of Gl 876 (purple dots) and the 4-planet model (grey plot) as a function of time. Each data point has an error of about 1.5 m/s and the scatter of the residuals is about 3 m/s.

- Multiple systems around low-mass stars.
  Gl 876 is the nearby M4V star where the first exoplanet was detected [12]. Since then, three more planets have been found in the system which turns out to be a very interesting dynamical system with a chain of resonances [13]. Gl 876 has been repeatedly observed with SPIRou. All four planets are recovered and further constraints on the system's dynamical evolution and potential additional planets will be derived over the years (see Figure 1), while the stellar magnetic topology will be investigated for the first time.

4. Stellar characterization

The detection of planetary signals is plagued by the intrinsic variability of the stellar-host surface. It is thus essential to work out both questions together. As in the Sun, stellar activity is a by-product of the magnetic field generated by dynamo processes acting in the convective interior. SPIRou, with its spectro-polarimetric capability, is designed to measure and characterize magnetic fields of stars. The large-scale topology of the field can be probed through the modulation of circular polarization Stokes V profiles, while the small scale magnetic field can be concentrated in spots is measured in the Zeeman broadening and intensification of lines sensitive to magnetic fields. Although the planet-search program of the SPIRou Legacy Survey has been built from a sample of low-activity M stars [14], one has to be cautious about RV signals induced by stellar intrinsic variability. Following the pioneering work that first explored potential correlations between Stokes *V* signatures and activity RV signals [15], we now see, from the abundant SLS data, that the complex modulation of the longitudinal field can be faithfully modeled with a quasi-periodic gaussian process [16, 17]. This analysis is systematically carried out for all SPIRou targets, and the method is sensitive down to large-scale fields of only a few G, and to rotation periods of more than a year.

One example in the SPIRou early science is the study of AD Leo. AD Leo is an active M3 star located at 5 pc, with a known stellar rotation period of 2.23 days [18]. A stable RV signal seen in the optical domain with the HARPS spectrograph at a period close to the rotation period has been interpreted as being the signature of a planet locked with the stellar spin [19]. Recent RV measurements obtained with SPIRou in the nIR domain did not confirm this signal. The semi-amplitude of RV variations is 20 m/s in the optical and less than 5 m/s in the nIR. Since planetary signatures are not dependent on the wavelength of observation, the optical-RV signal must thus be attributed to stellar activity, whose chromaticity is easy to interpret as caused by the wavelength-dependent spot-to-photosphere contrasts and/or Zeeman-induced line profile distortions. This combined analysis is described in [20] on the basis of SPIRou and OHP/SOPHIE data. In less active stars, it is possible that the chromatic behaviour of stellar activity is less pronounced [21]. A global analysis of the whole SLS sample will help draw general conclusions about this behaviour.

On the other hand, young stars can be hugely active, with RV modulations of tens or hundreds of m/s. For instance, AU Mic is a 20-Myr star of M1 spectral type at 9.7 pc and has photometric variations up to 5% over its 4.9 day rotation cycle and intense flaring activity. Two close-in transiting planets have also been found by TESS, orbiting AU Mic at 8.46 and 18.86 day orbital periods. An early intensive follow-up campaign with SPIRou allowed to detect with a 4-σ significance the gravitation pull by the inner planet, after the removal of an extra signal of 50 m/s amplitude due to the star's magnetic activity [22]. This work yielded the first density measurement for a Neptune-like planet younger than 200 My and triggered a number of follow-up studies and additional observing campaigns. Several tens of other young stars from 2 to 25 My are being monitored with SPIRou. Together, they will offer a set of unique constraints for star and planet formation and migration models.

5. Exoplanet atmospheres with SPIRou

A few years only after the discovery of exoplanets, it was realised that it is possible to characterize the atmosphere of transiting exoplanets from Earth: as the planet crosses the disk of its host star, the stellar light is absorbed in a way that varies with wavelength by the planet atmosphere as a result of its composition and physical characteristics (temperature, dynamics, gravity...). These observations were first performed at low spectral resolution from space, where the very large spectral range and the absence of tellurics contamination make it possible to detect the large bands of molecular absorption of, e.g., water (at 1600 nm) and carbon monoxide (2300 nm) and broad atomic lines of, e.g., sodium (580 nm), hydrogen (121 nm) and potassium (750 nm).

Since 2010, such observations have also been carried out at high spectral resolution (HRS) from the ground with visible and infrared spectrometers like SPIRou. Although limited by tellurics and a smaller spectral range, such characterization allows one to recover complementary information from space-borne observations: for example, the atmospheric dynamics is accessible through Doppler-shifted absorption and HRS allows to detect absorption features above the cloud level, thus extending the parameter space of characterisable atmospheres. In the infrared, SPIRou is expected to be the best instrument in the world to date because of a combination of (i) a large continuous spectral range making it possible to detect absorption from many different molecules, (ii) one of the highest resolving power available in this spectral range in the world (70,000), (iii) the high velocimetric stability of the instrument and (iv) arguably the best observing conditions in the best temperate astronomical site on the northern hemisphere (Maunakea). A synthetic model of the atmosphere of planet HD 209458b as would be observed through HRS with SPIRou is provided on Figure 2.

Some early highlights on exoplanet atmospheres with SPIRou include:

- The characterization of the atmosphere of HD 189733 b [23,24].

  This hot Jupiter is one of the most studied exoplanet as it was discovered early and has very favourable conditions for atmospheric characterisation. With SPIRou, we were able

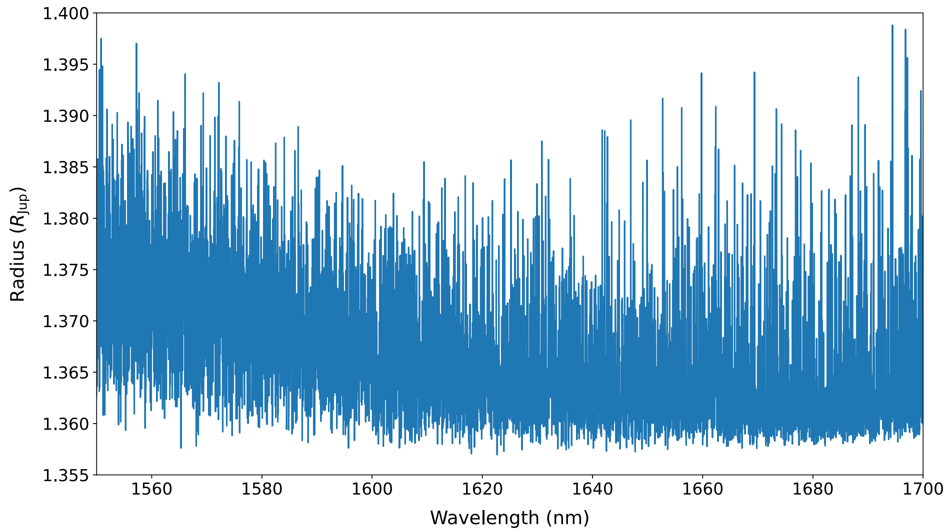

Figure 2. Synthetic apparent radius (in Jupiter radius) of the planet HD209458b as a function of wavelength, with a resolution equal to that of SPIRou, on a small subset of the SPIRou range. In this spectral range, the variations are due to the absorption by water vapor in the atmosphere of the planet.

to detect H_2O and CO, thus allowing us to derive its C/O ratio, a prime quantity to recover information about the formation and evolution of planets.

- The surprising lack of water in the atmosphere of τ Boo b [25].

  This planet is so hot that it was observed in emission (rather than transmission) spectroscopy, by differentiating the light received from Earth at different phases of its orbit. Surprisingly, there is a lack of water compared to what was expected regarding our knowledge of planetary atmospheres in the solar system and elsewhere. This probably indicates a large depletion in oxygen, which relates to the region of the disc where the planet was formed, i.e., beyond the water snowline.
- Iron and water dynamics in WASP-76 b [26].

  WASP-76 b is a ultra hot Jupiter (temperature higher than 2000 K) which orbits extremely close to its host star and seems to exhibit an asymmetric iron absorption [27]: the western limb of the planets is iron rich whereas the eastward one seems to be iron depleted. Thanks to simultaneous observations with SPIRou (infrared) and MAROON-X (visible), we are able to explore the different dynamics between iron and water, probing different pressure levels, in order to understand better the physics of highly irradiated atmospheres.

6. Conclusion

SPIRou is currently a unique new instrument, providing the full near-infrared spectral range from 950 to 2500 nm (YJHK bands) at a resolving power of 70 k, with an RV precision better than 2 m/s, along with spectropolarimetric capabilities (circular and linear polarisation). A twin instrument, called SPIP, is currently under construction for the Telescope Bernard Lyot at Pic du Midi. This will be convenient to monitor the same stars from both Hawai'i and France, in order to mitigate the sampling problems due to the diurnal cycle. It is also envisioned to combine ESPaDOnS and SPIRou at CFHT and their twins at TBL, to simultaneously observe stars and retrieve the full spectra and polarimetric information in the range 390 to 2500 nm. The power of combining RV and magnetic field measurements is a powerful tool to reach a global view of exoplanetary systems.

In the coming years, all RV and spectropolarimetric time series, and more generally all high-resolution SPIRou spectra will be available to the community for their legacy value beyond the main goals of the SLS, i.e., the study of planetary systems of nearby M dwarfs and of the impact of magnetic field on star/planet formation.

SPIRou has also proven to be a powerful instrument for the observation of planetary atmospheres. It already provided several characterizations, and is expected to deliver many more in the near future. The complementarity between low resolution from space with JWST and ARIEL (launched in 2029) and SPIRou at high resolution from the ground will be essential to understand better the formation and evolution of planetary systems.

Conflicts of interest

Authors have no conflict of interest to declare.

Acknowledgements

The authors, on behalf of the SPIRou community, fully appreciate the very significant cultural role that the summit of Maunakea has always had within the population of Hawai'i over the centuries, and are most fortunate to have the opportunity to conduct observations from this exceptional site.

We acknowledge funding from the European Research Council under the H2020 & innovation program (grant #740651 NewWorlds).

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