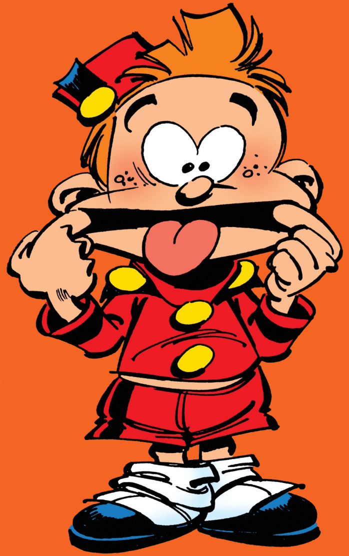
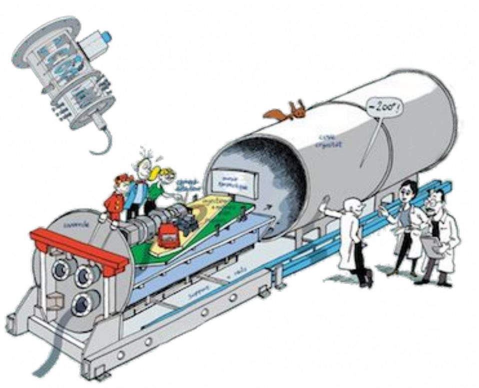


Les 5 ans de SPIRou, quelques leçons à retenir

Étienne Artigau, 10 mai 2023

SPIRou en bref



- Bref historique
  - 2008: Idée d'un équivalent IR à ESPADONS par JFD
  - Financé par le CFHT
  - … puis abandonné
  - Puis financé en partie par la FCI
  - Début de la construction en 2015
  - Livré en 2017
  - Mai 2018: Premières lumières au CFHT
- Collaboration internationale
  - France, Canada, Suisse, Portugal, Brésil, Taiwan et Portugal
- Spectropolarimètre
- 0.98-2.5µm
- Requis de stabilité à 1 m/s
- SLS
  - 200 nuits pour l'étude des Ms et polarimétrie des étoiles jeunes

~1 publication/mois depuis les 1ères lumières

SPIRou :
scientific rationale

Ref : SPIROU-2000-IRAP-RP-00503
Date : 2014 Apr 11
Page : 1 /63

SPIRou :
scientific rationale

Prepared by	Date
JF Donati, X Delfosse, E Artigau, R Doyon	2014 Apr 11
Approved and accepted by	Date

Vous pouvez blâmer deux des co-auteurs qui sont présents!

La prédiction est un art difficile, surtout lorsqu'elle concerne l'avenir

(Marc Twain, Groucho Marx ou Winston Churchill… les avis divergent)

Summary	SPIRou is a nIR spectropolarimeter/velocimeter proposed as a new-generation CFHT instrument mostly aimed at **detecting & characterizing Earth-like planets in the habitable zone of low-mass stars** and at investigating how **magnetic fields impact star/planet formation**. We present here a detailed science case describing thoroughly the various science topics that SPIRou will tackle with unprecedented precision, and in particular the foremost ones for which SPIRou is expected to be world-leader. As a conclusion, we list the scientific specifications needed to tackle these issues, with a special emphasis on the need for observing in the K band and in polarized light.

SPIRou is expected to be world-leader: hunting & characterizing habitable exo-Earths around low-mass stars on the one hand, and investigating magnetized star/planet formation on the other hand.

SPIRou plans to concentrate on two main scientific goals. The first one is to

search for & characterize habitable exo-Earths orbiting low-mass & very-low mass stars (LMSs & vLMSs) using high-precision radial velocity (RV) measurements. This search will expand the initial, exploratory studies carried out with visible instruments (e.g., HARPS/ESO) and will survey in particular large samples of stars mostly out of reach of existing instruments. In particular, carrying out a new large-scale survey at nIR wavelengths will boost the sensitivity to habitable exo-Earths by typically an order of magnitude on planetary mass (with respect to existing instruments). SPIRou will also work in close collaboration with space- & ground- based photometric transit surveys like K2/NASA (new mission concept for Kepler, to be decided in 2014), TESS/NASA, CHEOPS/ESA, ExTrA[1] and PLATO/ESA (after being launched in 2024) to identify the true planets among the candidates they will discover.

Given their low temperatures, red & brown dwarfs are much more accessible at nIR wavelengths (see Fig 3.2 and Tab 3.2). **High-resolution nIR spectroscopy accurate to the 1 m/s level**, yielding **wide simultaneous spectral coverage** (not yet available on any telescope worldwide) therefore appears as optimal for carrying out systematic RV surveys of M & L dwarfs aimed at investigating the statistical properties of exoplanetary systems. With additional **spectropolarimetric capabilities**, one can simultaneously investigate magnetic fields and activity of all surveyed dwarfs and filter out RV curves (at least partially) from activity-induced non-planetary signals, giving a wider access to lower mass dwarfs (more active on average).

Emphase sur la précision à 1 m/s

- Quelques spectrographes optiques arrivent (en 2023) à faire mieux que 1 m/s (un seul <2014)
- Présenté comme requis absolu pour SPIRou!
- L'effort requis pour y arriver dans l'infrarouge est complètement sous-estimé dans le document
  - Équivalent de 5-6 FTE pour y arriver
  - Équivalent de 10 FTE en incluant les raffinements subséquents

Le fameux 1 m/s!

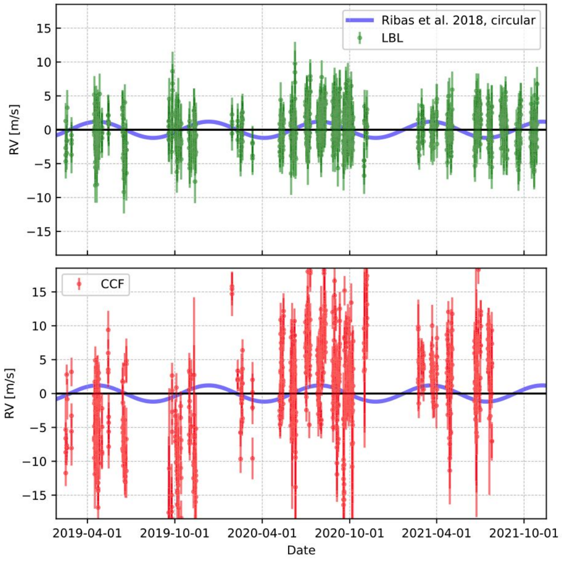
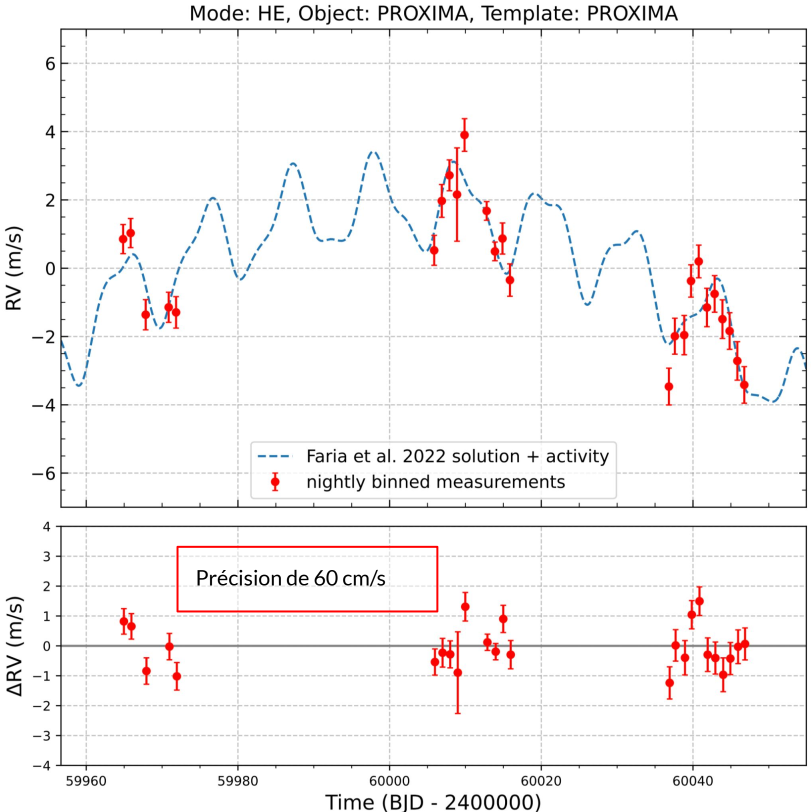


Figure 5. Radial velocity (RV) time series of Barnard's star with the line-by-line (LBL) method and the standard SPIRou cross-correlation function. No activity correction has been performed. The median LBL RV uncertainty is 2.57 m s^{-1}, only slightly smaller than the point-to-point dispersion of 2.59 m s^{-1}. The Ribas et al. (2018) circular orbital solution is shown. The data strongly favors the scenario in which the RV is constant compared to that with the candidate planet with the reported solution (see Section 5.1).

- Les premières séquences SPIRou avaient une précision RV de >5 m/s
- Les algorithmes utilisés dans l'optique fonctionnent très mals dans l'IR
  - CCF
  - Template matching (conceptuellement, devrait marcher!)
  - Wobble (100% data-driven)
- Développement de nouveaux algorithmes
  - LBL (Artigau et al. 2022)

Le fameux 1 m/s!



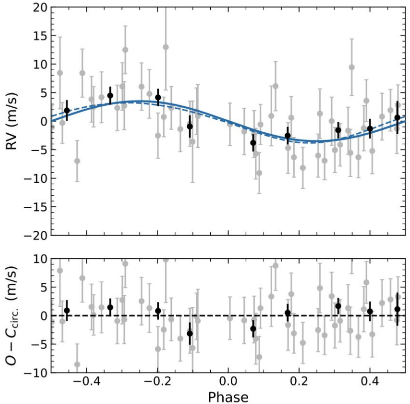
- On sait maintenant que l'on peut faire ~60 cm/s RMS dans l'infrarouge grâce à NIRPS
- Des articles prédisent une limite autour de ~1.5 m/s

Que veux dire une précision à 1 m/s

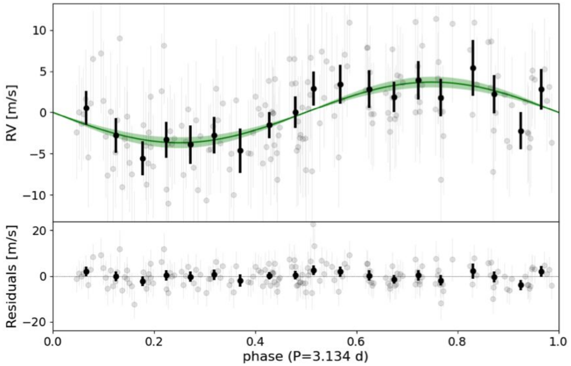
3.3. Transiting close-in exoplanets

Exoplanets transiting their host stars are especially interesting as **sensitive probes of their internal structures and atmospheres** (Charbonneau et al 2007, PPV). The planets transiting around bright stars are indeed the only ones whose masses (through RV monitoring of their orbital motion) and radii (through photometric monitoring of their transits) can be measured simultaneously, allowing one to estimate their densities and internal composition. When the host star is bright enough, transiting planets can even tell us about the composition & physics of their atmospheres, opening the new research field of exo-planetology (see Sec 6.3). Only a handful of very-bright transiting systems have been discovered up to now, most of them being giant gaseous planets.

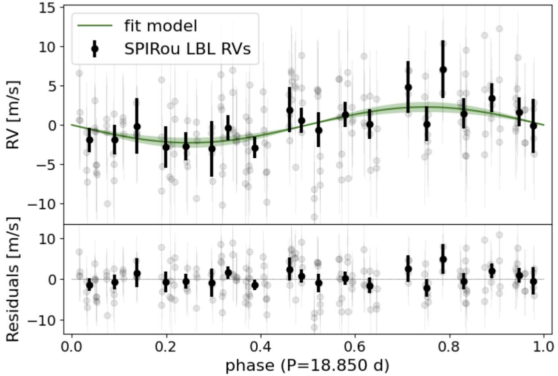
TOI-1452 (Cadieux et al. 2022)
SPIRou, K = 3.50 ± 0.94m/s



TOI-1695 (Kiefer et al. 2022)
SPIRou, K = 3.63±0.68m/s



TOI-1759 (Martioli et al. 2022)
SPIRou, K = 2.3±0.7m/s



La distribution du temps d'observation

- Le CFHT opère un instrument à la fois (SPIRoudons s'en vient en ~2025) et SPIRou est un instrument de temps clair
- Dans le meilleur des cas, on a une couverture de ~10 nuits/mois
  - Très problématique pour les périodes correspondant à la zone habitable
- L'allocation par semestre est problématique pour le pRV où on a besoin de suivis sur plusieurs semestres

C'est jamais simple …

- Longue discussion sur la correction efficace de la vitesse radiale ***on-the-fly*** grâce à la spectro-polarimétrie
- Connaissance fine de la spectro-polarimétrie concentrée dans une seule équipe
  - Une seule planète confirmée à l'aide de la spectropolarimétrie
  - Orbite fortement contrainte par des transits

C'est jamais simple ...

MNRAS **502,** 188–205 (2021) doi:10.1093/mnras/staa3702
Advance Access publication 2020 December 8

Investigating the young AU Mic system with SPIRou: large-scale stellar magnetic field and close-in planet mass

Baptiste Klein,[1★] Jean-François Donati,[1] Claire Moutou,[1] Xavier Delfosse,[2] Xavier Bonfils,[2] Eder Martioli,[3,4] Pascal Fouqué,[1,5] Ryan Cloutier,[6] Étienne Artigau,[7] René Doyon,[7] Guillaume Hébrard,[3] Julien Morin,[8] Julien Rameau,[2] Peter Plavchan[9] and Eric Gaidos[10★]

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[3] *Institut dAstrophysique de Paris, UMR7095 CNRS, Université Pierre and Marie Curie, 98bis boulevard Arago, F-75014 Paris, France*
[4] *Laboratorio Nacional de Astrofisica (LNA/MCTI), Rua Estados Unidos, 154, Itajuba, MG, Brazil*
[5] *CFHT Corporation, 65-1238 Mamalahoa Hwy, Kamuela, HI 96743, USA*
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[7] *Institut de Recherche sur les Exoplanètes (IREx), Département de Physique, Université de Montréal, C.P. 6128, Succ. Centre-Ville, Montréal, QC H3C 3J7, Canada*
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[9] *Department of Physics and Astronomy, George Mason University, Fairfax, VA 22030, USA*
[10] *Department of Earth Sciences, University of Hawai'i at Manoa, Honolulu, HI 96822, USA*

Our radial velocity (RV) time-series exhibits activity-induced fluctuations of 45 m/s rms, ~3 times smaller than those measured in the optical domain, that we filter using Gaussian Process Regression. We report a 3.9σ detection of the recently discovered 8.46-d transiting planet AU Mic b, with an estimated mass of 17.1±4.7 $M_\oplus$ and a bulk density of 1.3 ± 0.4 g cm^{-3}.

C’est jamais simple …

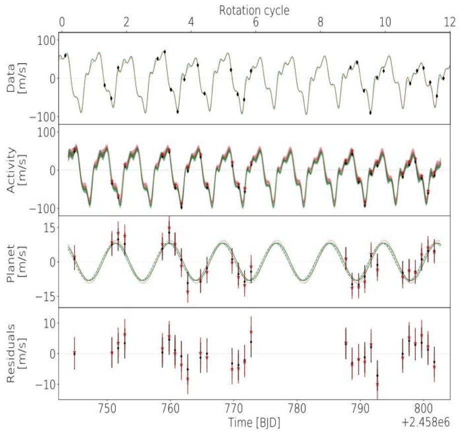

Figure 3. Best fit to the reference RV time-series. From top to bottom, we show the raw RV time-series, the stellar activity contribution, the planetary RV signature and the residuals after subtracting stellar and planetary predictions from the data. In each panel, the green solid line and red dotted line (respectively, the $\pm 1\sigma$ error bands of the GP prediction in panel 2) show the best prediction of the model respectively without and with the additional uncorrelated noise S fitted by the MCMC process. The data points (red stars and black dots when S is respectively optimized in the estimation process and fixed to 0 m s^{-1}) in panels 2 and 3 and obtained by respectively subtracting the reconstructed planet and stellar activity RV signals from the raw RVs. In panel 3, the dashed and dotted green lines indicate the planet RV signal respectively obtained when ϕ_p and P_{orb} are regarded as free parameters in the MCMC process. The residuals of the fit, shown in panel 4, exhibit respective rmss of 3.0 or 4.4 m s^{-1} when S is assumed to be null or fitted in the MCMC process.

Une grande partie de l’article est dédiée aux méthodes de reconstruction du signal d’activité et la planète a un transit. La périodicité est connue et on ajuste 1 degré de liberté

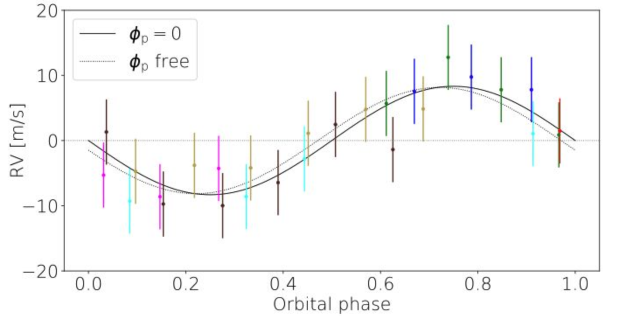

Figure 4. Activity-subtracted RV time-series (dots) folded to P_{orb} using T_0 as reference time. The subtracted activity RV signal is estimated assuming $\phi_p =$ 0 and $S = 0$ m s^{-1}. Data points of same colour belong to the same orbital phase. We plot in solid and dotted black lines, the planet RV signatures obtained assuming $\phi_p = 0$ and optimizing ϕ_p in the MCMC process, respectively.

… mais des fois on a 100% raison!

Near-IR and optical radial velocities of the active M dwarf star Gl 388 (AD Leo) with SPIRou at CFHT and SOPHIE at OHP★:

A 2.23 day rotation period and no evidence for a corotating planet.

A. Carmona[1,], X. Delfosse[1], S. Bellotti[2,13], P. Cortés-Zuleta[3], M. Ould-Elhkim[2], N. Heidari[3], L. Mignon[1,9], J.F. Donati[2], C. Moutou[2], N. Cook[4], E. Artigau[4,5], P. Fouqué[2], E. Martioli[6,7], C. Cadieux[4], J. Morin[8], T. Forveille[1], I. Boisse[3], G. Hébrard[7], R. F. Díaz[10], D. Lafrenière[4], F. Kiefer[7], P. Petit[2], R. Doyon[4], L. Acuña[3], L. Arnold[11], X. Bonfils[1], F. Bouchy[9], V. Bourrier[9], S. Dalal[7], M. Deleuil[3], O. Demangeon[12], X. Dumusque[9], N. Hara[9], S. Hoyer[3], O. Mousis[3], A. Santerne[3], D. Ségrasan[8], M. Stalport[9], and S. Udry[9]

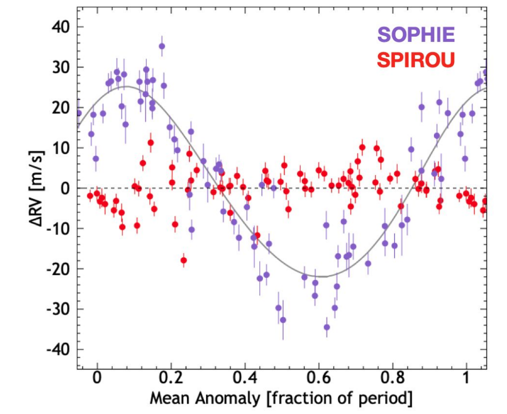

Fig. 4. Phase-folded RV measurements of Gl 388 with SPIRou in the near-IR (red dots) and with SOPHIE (blue dots) in the optical. The gray line represents the Keplerian model with a period of 2.23 days and K = 23.6 m s^{-1} derived from the SOPHIE data (Table 2).

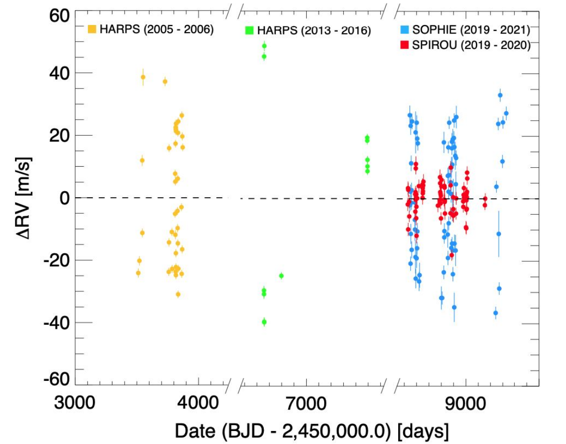

Fig. 1. New SPIRou and SOPHIE RVs, together with the archival HARPS data used in this work.

- Cas d'école de la disparition d'un signal d'activité dans l'IR
- Il semble par contre y avoir une grande disparité dans les comportements.

Pertinence RV de la polarimétrie et gain IR

A&A 672, A52 (2023)
https://doi.org/10.1051/0004-6361/202345839

Astronomy & Astrophysics

The SPIRou legacy survey

Rotation period of quiet M dwarfs from circular polarization in near-infrared spectral lines: The SPIRou APERO analysis★

P. Fouqué[1], E. Martioli[2,3], J.-F. Donati[1], L. T. Lehmann[1], B. Zaire[1,4], S. Bellotti[1,5], E. Gaidos[6], J. Morin[7], C. Moutou[1], P. Petit[1], S. H. P. Alencar[4], L. Arnold[8], É. Artigau[9], T.-Q. Cang[10], A. Carmona[11], N. J. Cook[9], P. Cortés-Zuleta[12], P. I. Cristofari[1], X. Delfosse[11], R. Doyon[9], G. Hébrard[3], L. Malo[9], C. Reylé[13], and C. Usher[8]

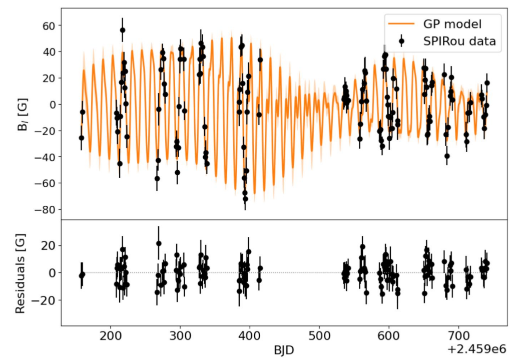

Fig. 7. GP analysis of the SPIRou B_ℓ data of Gl 410. In the top panel, the black points show the observed B_ℓ data, and the orange line shows the best-fit quasi-periodic GP model. The bottom panel shows the residuals with an RMS dispersion of 7.6 G.

- Demande une étude détaillée
- Chaque étoile est un cas à part
- Pertinent pour déterminer des périodes de rotation
  - Alimente les GP pour la correction
- Complémentaire à la photométrie

Un cas scientifique sous-estimé?

6.3. Exoplanet atmospheres

De Kok et al. (2014, A&A 561, 150) perform simulations of high-resolution spectroscopic observations to identify new ways of increasing the planet signal during transit or for thermal emission. They identify SPIRou **should be able to provide a valuable contribution to this field** thanks to its wide single-shot spectral domain & high throughput on the one hand (increasing the amount of information available for such studies) and to its exceptional stability (allowing a cleaner separation & subtraction of stellar & telluric lines from the planetary signal to be detected).

- Central dans la thèse d'A. Boucher
- Travaux de S. Pelletier
- Central dans le GTO de NIRPS

THE ASTRONOMICAL JOURNAL, 162:73 (19pp), 2021 August
https://doi.org/10.3847/1538-3881/ac0428

Where Is the Water? Jupiter-like C/H Ratio but Strong H_2O Depletion Found on τ Boötis b Using SPIRou

Stefan Pelletier[1], Björn Benneke[1], Antoine Darveau-Bernier[1], Anne Boucher[1], Neil J. Cook[1], Caroline Piaulet[1], Louis-Philippe Coulombe[1], Étienne Artigau[1,2], David Lafrenière[1], Simon Delisle[1], Romain Allart[1,10], René Doyon[1,2], Jean-François Donati[3], Pascal Fouqué[3,4], Claire Moutou[3], Charles Cadieux[1], Xavier Delfosse[5], Guillaume Hébrard[6,7], Jorge H. C. Martins[8], Eder Martioli[6,9], and Thomas Vandal[1]

THE ASTRONOMICAL JOURNAL, 162:233 (18pp), 2021 December
https://doi.org/10.3847/1538-3881/ac1f8e

Characterizing Exoplanetary Atmospheres at High Resolution with SPIRou: Detection of Water on HD 189733 b

Anne Boucher[1], Antoine Darveau-Bernier[1], Stefan Pelletier[1], David Lafrenière[1], Étienne Artigau[1], Neil J. Cook[1], Romain Allart[1,17], Michael Radica[1], René Doyon[1], Björn Benneke[1], Luc Arnold[2], Xavier Bonfils[3], Vincent Bourrier[4], Ryan Cloutier[5,18], João Gomes da Silva[6], Emily Deibert[7], Xavier Delfosse[3], Jean-François Donati[8], David Ehrenreich[4], Pedro Figueira[6,9], Thierry Forveille[3], Pascal Fouqué[2,8], Jonathan Gagné[1,10], Eric Gaidos[11], Guillaume Hébrard[12], Ray Jayawardhana[13], Baptiste Klein[14], Christophe Lovis[4], Jorge H. C. Martins[6], Eder Martioli[12,15], Claire Moutou[8], and Nuno C. Santos[6,16]

MNRAS 000, 1–23 (2023) Preprint 7 March 2023 Compiled using MNRAS LaTeX style file v3.0

CO or no CO? Narrowing the CO abundance constraint and recovering the H_2O detection in the atmosphere of WASP-127 b using SPIRou

Anne Boucher[1★], David Lafrenière[1], Stefan Pelletier [1], Antoine Darveau-Bernier[1], Michael Radica[1], Romain Allart[1,*], Étienne Artigau[1,2], Neil J. Cook[1,2], Florian Debras[3], René Doyon[1,2], Eric Gaidos[4], Björn Benneke[1], Charles Cadieux[1], Andres Carmona[5], Ryan Cloutier[6,], Pía Cortés-Zuleta[7], Nicolas B. Cowan[8,9], Xavier Delfosse[5], Jean-François Donati[3], Pascal Fouqué[3,10], Thierry Forveille[5], Konstantin Grankin[11], Guillaume Hébrard[12], Jorge H. C. Martins[13], Eder Martioli[12,14], Adrien Masson[15], and Sandrine Vinatier[15]

Importance d'une DRS qui marche!

- On n'oublie jamais de mettre le réseau dans un spectrographe… mais on néglige la DRS!
- Central dans la compréhension des performances
- Demandes des années de travail
  - Presque impossible à supporter pour des étudiants aux cycles supérieurs
  - Un cadeau empoisonné pour les post-docs qui veulent continuer en recherche
- Change complètement la relation entre l'équipe et le management de l'observatoire
  - NIRPS avait une précision à 60 cm/s démontrée avec des observations avant même le début des opérations scientifiques (requis à 1 m/s)
  - Pas évident que l'on pourrait démarrer le GTO sans ces résultats

Pistes de réflexion pour les prochains instruments...

- Est-ce que le modèle d'opération de l'observatoire concorde avec les objectifs scientifiques?
- Est-ce que les performances de l'instrument dépendent d'algorithmes qui n'existent pas encore?
  - Situation similaire dans l'histoire de l'imagerie haut contraste
- Est-ce que l'on a les ressources à long terme (>3 ans) pour les développer?
- Si des post-docs sont impliqués dans le développement, est-ce que l'on nuit à leur carrière?
  - Peu ou pas de publication pendant 2-3 ans!