SPIRou: a nIR spectropolarimeter / high-precision velocimeter for the CFHT

JF Donati, D Kouach, M Lacombe, S Baratchart, R Doyon, X Delfosse, E Artigau, C Moutou, G Hébrard, F Bouchy, J Bouvier, S Alencar, L Saddlemeyer, L Parès, P Rabou, Y Micheau, F Dolon, G Barrick, O Hernandez, SY Wang, V Reshetov, N Striebig, Z Challita, A Carmona, S Tibault, E Martioli, P Figueira, I Boisse, F Pepe & the SPIRou team

Abstract SPIRou is a near-infrared (nIR) spectropolarimeter / velocimeter for the Canada-France-Hawaii Telescope (CFHT), that will focus on two forefront science topics, (i) the quest for habitable Earth-like planets around nearby M stars, and (ii) the study of low-mass star/planet formation in the presence of magnetic fields. SPIRou will also efficiently tackle many key programmes beyond these two main goals, from weather patterns on brown dwarfs to Solar-System planet and exoplanet atmospheres. SPIRou will cover a wide spectral domain in a single exposure (0.98-2.44 µm) at a resolving power of 70 K, yielding unpolarized and polarized spectra of low-mass stars with a 15% average throughput at a radial velocity (RV) precision of 1 m s⁻¹. It consists of a Cassegrain unit mounted at the Cassegrain focus of CFHT and featuring an achromatic polarimeter, coupled to a cryogenic spectrograph cooled down at 80 K through a fluoride fiber link. SPIRou is currently integrated at IRAP/OMP and will be mounted at CFHT in 2017 Q4 for a first light scheduled in late 2017. Science operation is predicted to begin in 2018 S2, allowing many fruitful synergies with major ground and space instruments such as the JWST, TESS, ALMA and later-on PLATO and the ELT.
Introduction

Detecting and characterizing exoplanets, especially Earth-like ones located at the right distance from their host stars to lie in the habitable zone (HZ, where liquid water can pool at the planet surface), stands as one of the most exciting areas of modern astronomy and comes as an obvious milestone in our quest to understand the emergence of life (Gaidos and Selsis 2007). High-precision velocimetry, measuring RVs of stars and the periodic fluctuations that probe the presence of orbiting bodies, is currently the most reliable way to achieve this goal; in particular, velocimetry allows one to validate candidate planets detected with transit surveys (with, e.g., CoRoT, Kepler, TESS, and later-on PLATO), and to estimate the densities and study the bulk composition of the detected planets from their masses and radii (Lissauer et al. 2014).

M dwarfs are key targets for this quest; beyond largely dominating the population of the solar neighborhood, they feature many low-mass planets (Dressing and Charbonneau 2015; Gaidos et al. 2016) and render HZ planets far easier to detect by shrinking the size of their HZs (thereby boosting RV wobbles and reducing orbital periods). Their monitoring with existing velocimeters like HARPS on the 3.6m ESO telescope (Rupprecht et al. 2004) is however tricky, especially for the coolest ones, given their intrinsic faintness at visible wavelengths, preventing a deep-enough exploration to detect significant samples of HZ Earth-like planets (Bonfils et al. 2013). Moreover, M dwarfs are notorious for their magnetic activity, generating spurious RV signals (activity jitter) that can hamper planet detectability (Newton et al. 2016; Hébrard et al. 2016).

Modeling the activity of M dwarfs and the underlying magnetic fields is thus crucial for filtering out the RV jitter and for maximizing the efficiency at detecting low-mass planets (Hébrard et al. 2016). Magnetic fields of low-mass stars are also expected to have a major impact on the evolution of close-in planets (Strugarek et al. 2015) as well as on their habitability (Güdel et al. 2014; Vidotto et al. 2013). Allowing one to detect and model large-scale fields of active stars, spectropolarimetry comes as the ideal complement to precision velocimetry, making it possible not only to maximise the efficiency of planet detection, but also to characterise the impact of magnetic activity on the habitability of the detected close-in planets.

Investigating star/planet formation comes as the logical complement to studying exoplanetary systems of M dwarfs. Magnetic fields are known to have a major impact at the early stages of the life of low-mass stars and their planets, as they form from collapsing dense pre-stellar cores that progressively flatten into large-scale magnetized accretion discs and eventually settle as young suns orbited by planetary systems (André et al. 2009). In this overall picture, the pre-main-sequence (PMS) phases, in which central protostars feed from surrounding planet-forming accretion discs, are crucial for our understanding of how worlds like our Solar System form. Following a phase where they massively accrete from their discs (as class-I protostars, aged 0.1-0.5 Myr) while still embedded in dust cocoons, newly formed proto-stars progressively grow bright enough to clear out their dust envelopes (at ages 0.5-10 Myr), becoming classical T-Tauri stars (cTTSs) when still accreting from their
planet-forming discs, then weak-line T-Tauri stars (wTTSs) once they have mostly exhausted their discs. These steps are key for benchmarking star/planet formation.

Spectropolarimetry is the ideal tool for constraining the large-scale field topologies of PMS stars and their accretion discs, and thereby quantitatively assess the impact of magnetic fields on star/planet formation. ESPaDOnS and Narval, the twin high-resolution spectropolarimeters respectively mounted on CFHT (Donati 2003; Donati et al. 2006) and on the 2m Télescope Bernard Lyot (TBL), already allowed to unveil for the first time magnetic topologies of PMS objects (Donati et al. 2005, 2010; Skelly et al. 2010; Donati et al. 2013, 2014) and to detect the youngest known hot Jupiters (hJs) to date (Donati et al. 2016, 2017; Yu et al. 2017, see Fig. 1), demonstrating that planet formation and planet-disc interaction are both quite efficient on timescales of less than 2 Myr. However, our knowledge of magnetic fields and planetary systems of PMS stars is still fragmentary, the intrinsic faintness of these objects in the visible drastically limiting their accessibility even to the most sensitive instruments.

SPIRou was designed to address these two forefront issues with unprecedented efficiency (Delfosse et al. 2013; Artigau et al. 2014; Moutou et al. 2015). By operating in the nIR (including the K band), it will offer maximum sensitivity to both M dwarfs and PMS stars. Moreover, by coupling spectropolarimetry with high-precision velocimetry, SPIRou will allow us to model magnetic activity and to filter-out RV curves more accurately than previously possible, and thus to achieve major progress in our exploration of planetary systems of nearby M dwarfs and in our understanding of planetary formation at early stages of evolution. In particular, thanks to its widest nIR coverage among planet hunters coupled to its unique polarimetric and activity-filtering capabilities, SPIRou will be especially efficient at detecting and characterizing planets around late-M dwarfs whose high levels of magnetic activity are notorious.

We describe below in more detail the science programmes underlying these two prime goals, to which the SPIRou Legacy Survey (SLS) of about 500 CFHT nights will be dedicated, and mention the many other exciting programmes that SPIRou will be able to efficiently tackle thanks to its unique observational assets. We also provide a technical description of SPIRou, outline the expected performances on which our ambitious Legacy Survey relies, and summarize the overall project characteristics in terms of schedule, budget and manpower. We finally conclude with SPIRou-related prospects over the next decade.

Science with SPIRou

We detail below the two main science goals to which our SPIRou Legacy Survey is dedicated; we also mention a few additional programmes that SPIRou will be able to tackle, and the worldwide science consortium thanks to which SPIRou is coming to life.
The youngest known hot Jupiter discovered around the active young sun V830 Tau flies in the inner magnetic web of its host star (blue/white lines for open/closed field) as observed with spectropolarimetry and reconstructed using tomographic techniques inspired from medical imaging.

Planetary systems of nearby M dwarfs

Much interest has recently been focused on planets of M dwarfs (Bonfils et al. 2013; Muirhead et al. 2015), with the conclusion that these stars host low-mass planets more frequently than Sun-like stars do (Dressing and Charbonneau 2015; Gaidos et al. 2016). The recent discovery of a HZ planet around Proxima Cen (Anglada-Escude et al. 2016) see also dedicated section in this book) further triggered the motivation to detect and study low-mass planets and planetary systems around nearby red dwarfs. The main goals are to reveal the planet occurrence frequencies and system architectures, to investigate how they depend on the masses of the host stars (and thus on the masses and properties of the parent protoplanetary disc), and ul-

Fig. 1 Artist view of the hot Jupiter recently detected around the wTTS V830 Tau, orbiting in the large-scale magnetic field of its host star. The field topology is reconstructed using tomographic imaging on a phase-resolved spectropolarimetric data set of V830 Tau (Donati et al. 2017).
SPIRou: a nIR spectropolarimeter / velocimeter for the CFHT

timately to better characterize the formation mechanism(s) that led to the observed
distributions of planets and systems.

Up to now, only a few such planets have been detected and characterized with
RV observations, which required in particular focusing on the brightest M dwarfs
as the only accessible targets for the few existing optical velocimeters capable of
reaching a RV precision of 1 m s\(^{-1}\). This is clearly insufficient to achieve a proper
statistical study of rocky exoplanets and more generally of exoplanetary systems
around M dwarfs. This constraint also drastically limits our chances of detecting
transiting rocky planets in the HZs of the nearest stars, i.e., the only ones for which
atmospheric characterization with the JWST will be possible (Berta-Thompson et al.
2015).

Carrying out an exploration of nearby M dwarfs extensive enough to detect and
characterize hundreds of low-mass planets and planetary systems, whose existence
is known, mandatorily requires RV observations in the nIR domain, where these
stars are brightest. This is what SPIRou aims at with the SLS, concentrating the
effort in two main directions, (i) a systematic RV monitoring of a large sample of
nearby M dwarfs (called the SLS Planet Search) and (ii) a RV follow-up of the most
interesting transiting planet candidates to be uncovered by future photometric sur-
veys (called the SLS Transit Follow-up). In both cases, SPIRou will be observing in
spectropolarimetric mode to simultaneously monitor stellar activity, unambiguously
identify the rotation period (with which activity is modulated) and reconstruct the
parent large-scale magnetic field triggering the activity. This will enable to imple-
ment novel and efficient ways of filtering out the polluting effect of activity from RV
curves (Hébrard et al. 2016), and thus to boost the sensitivity of SPIRou to low-mass
planets. This option will turn especially useful for late-M dwarfs, many of which are
rather active as a result of their higher rotation rates (Newton et al. 2016) and show
RV activity jitters of several m s\(^{-1}\) (Gomes da Silva et al. 2012; Hébrard et al. 2016).

The immediate objective of the SLS Planet Search is to:

- identify at least 200 exoplanets with orbital periods ranging from 1 d to 1 yr
  around stars with masses spanning 0.08–0.5 M\(_\odot\) to derive accurate planet statis-
tics as a function of stellar mass;
- identify a few tens of HZ terrestrial planets orbiting nearby M dwarfs, thanks to
  which we will infer a better description of the different types of planets located
in HZs;
- identifying several tens of multi-planet systems for studying the architecture of
  exoplanetary systems and their dynamical evolution;
- identifying a large population of close-in planets to investigate how they form
  and interact with the magnetospheres of their host stars.

Practically speaking, this implies carrying out a deep survey of at least 200 M
dwarfs of different masses, with typically 100 visits per star (each yielding a spec-
trum with high-enough S/N to achieve 1 m s\(^{-1}\) RV precision). Monte Carlo simula-
tions (see, e.g., Fig. 3) suggest that the SLS planet search should detect at least 200
new exoplanets, including 150 with masses <5 M\(_\oplus\) and 20 located in the HZs of
their host stars. The SLS should thus offer a yet unparalleled opportunity to explore
fig. 2 Simulation of an example SLS Planet Search assuming a sample size of 360 M dwarfs and 55 visits per star, for a total survey time of 300 CFHT nights. Filled circles indicate detected planets, open circles undetected ones and red circles (both filled and open) represent transiting planets. Blue lines show notional limits for the HZ, both in mass and temperature. Most planets more massive than 2 M\(_\odot\) located in the HZ are detected, including two transiting. A sample of sub-M\(_\odot\) planets hotter than 350 K is also detected. Using a smaller sample with more visits (as we now propose) improves the detectability of multi-planet systems.

the diversity of HZ Earth-like planets and planetary systems, and to reveal which of them are most common. With improved statistics on planets / systems around M dwarfs, our survey will constrain models of planetary formation, in particular regarding the sensitivity of planet formation to initial conditions in protoplanetary discs and to the mass of the host stars. The SLS will also probe the occurrence rate of sub-Earth-mass planets with orbital periods shorter than 10 d; the discovery of 3 Mars-sized planets in close orbits around a M5 dwarf within the very small sample of late-M dwarfs in the Kepler field indicates that such worlds are likely to be very common (Muirhead et al., 2012) in addition to being potentially fruitful targets to characterize, their very tight orbits implying high probabilities of transit. The goal is to invest 275 CFHT nights in the SLS Planet Search.

Regarding the SLS Transit Follow-up, the obvious goal is to use transiting planets as sensitive probes of their internal structures and atmospheres. Ground-based nIR spectroscopy is indeed essential to this quest, spectroscopy being mandatory to validate the planetary nature of the transiting candidate planets detected around M dwarfs through photometric monitoring, but also to measure their masses from their host stars’ RV-curve amplitudes. Whereas Kepler showed that planets smaller than 4 R\(_\oplus\) are quite common, even in compact and coplanar multi-planet systems,
it however failed to discover Earth twins close enough for further atmospheric characterization, or even to be validated and characterized through a RV follow-up. The goal of future photometric surveys is thus to detect planet candidates around brighter stars, with a specific emphasis on nearby M dwarfs.

Among them, TESS, to be launched in 2018 and predicted to detect about 300 super-Earths, is the most promising. By surveying the entire sky (with individual regions scrutinized on timescales of 27 d) and focusing on the brightest targets, TESS will monitor the light curves of more than 200,000 targets at a high temporal cadence, and 100× more at a slow cadence, during a nominal 2-yr mission. From Kepler statistics, TESS predicts the discovery of several hundreds of Earth-like and super-Earth planets, in addition to thousands of icy and gas giants, for stars brighter than $I=12$ (Sullivan et al. 2015). Most super-Earth candidates that TESS will detect will orbit around M dwarfs, with less than 30% accessible to optical velocimeters. SPIRou will thus play an essential role in validating planet candidates and in measuring their masses (Santerne et al. 2013).

The goal is to carry out a RV follow-up of the 50 most interesting transiting planet candidates uncovered by future photometric surveys including TESS, for a total of 100 CFHT nights. Monte Carlo simulations indicate that SPIRou has the capacity to validate and characterize Earth-mass planets orbiting mid-M dwarfs, including those located in the HZs of their host stars on which SPIRou will concentrate (see Fig. 2).

As SPIRou will simultaneously secure spectropolarimetric and velocimetric data, it will allow us to model at the same time the large-scale magnetic topologies and the associated activity of the host stars, and thus to filter out the RV jitter from RV curves and enhance the sensitivity to low-mass planets (Hebrard et al. 2016). Investigating how large-scale fields of M-dwarfs vary with stellar parameters (Morin et al. 2008, 2010) will unveil how dynamo processes behave in fully-convective bodies, and how such dynamo fields can either degrade or improve habitability depending on whether they anchor in the host stars or in their planets (Vidotto et al. 2013; Guedel et al. 2014).

By providing a wide and homogeneous set of nIR spectra for all types of M dwarfs, the SLS exoplanet programmes will also give the opportunity to assess theoretical atmospheric models of cool and very cool stars in much more details than what is currently possible; in particular, it will make it possible to further constrain key physical processes occurring in the atmospheres of very-cool stars and affecting their thermal and convection patterns (Rajpurohit et al. 2013; Allard et al. 2013; Passegger et al. 2016).

**Magnetic fields and star/planet formation**

Studying how Sun-like stars and their planetary systems form comes as an obvious complement to the direct observation of exoplanets in our quest to understand the emergence of life. The second main goal of SPIRou is thus to explore the impact of
magnetic fields on star/planet formation, by detecting and characterizing magnetic fields of low-mass PMS stars and their inner accretion discs.

By controlling accretion, triggering outflows and jets, and producing intense X-rays, magnetic fields critically impact the physics of PMS stars (Baraffe and Chabrier 2010; Feiden 2016) and of their accretion discs (Shu et al. 2007), and largely dictate their angular momentum evolution (Bouvier et al. 2007). In particular, magnetic fields are thought to couple accreting PMS stars with their discs; more specifically, fields carve magnetospheric gaps in the central disc regions and trigger funneled inflows & outflows from the inner discs, forcing the host stars to spin down (Romanova et al. 2004, 2011; Zanni and Ferreira 2013; Davies et al. 2014). Magnetic fields presumably affect planet formation as well (Johansen 2009), can stop or even reverse planet migration (Baruteau et al. 2014), and may prevent close-in planets, including hJs (Lin et al. 1996; Romanova and Lovelace 2006), from falling into their host stars.

The initial exploration carried out with the optical spectropolarimeters ESPaDOnS at CFHT and Narval at TBL revealed that TTSs host strong large-scale magnetic fields (Skelly et al. 2010; Donati et al. 2013, 2014) of dynamo origin (Donati et al. 2012) and whose topologies largely reflect the internal structures or the host stars (Gregory et al. 2012). Intense fields were also unambiguously detected in the inner regions of an outbursting accretion disc (Donati et al. 2005). More recently, newborn close-in giant planets, including the youngest hJ known to date (Donati et al. 2016, 2017, see, e.g., Fig. 3), were discovered around PMS stars (David et al. 2016; Yu et al. 2017), providing new evidence that planet-disc interactions plays a key role in planet formation and are likely to shape the early architecture of planetary systems. Despite this progress, our knowledge of magnetic topologies of low-mass PMS stars, and of their planet-forming accretion discs whenever relevant, is still fragmentary, and very few observational constraints are available to test models of star/planet formation.

Extending spectropolarimetric observations to the nIR domain is the most logical step forward. Low-mass PMS stars are indeed brighter in the nIR than in the optical, especially embedded class-I protostars, whereas the Zeeman effect is stronger at longer wavelengths. SPIRou thus has the potential to explore much larger samples of PMS stars than previously possible, and to vastly improve the statistical significance of our current results, in particular for embedded protostars and accretion discs for which very little information is available. To achieve this, we need to initiate a large survey aimed at thoroughly exploring how magnetic fields impact star/planet formation. This is the goal of the third SLS component, that we call the SLS Magnetic PMS star/planet survey.

In this aim, SPIRou will monitor 20 low-mass class-I protostars and 40 cTTSs with their accretion discs, as well as 80 wTTSs, selected in the 3 closest star forming regions (Tau/Aur, TW Hya and ρ Oph/Lupus). As the missing link between the youngest class-0 protostars whose fields are surveyed with ALMA / NOEMA at mm wavelengths (Maury et al. 2010) and the older cTTSs observed with optical instruments like ESPaDOnS, class-I protostars are key for fingerprinting the impact of magnetic fields on star/planet formation. Their reputedly strong fields (Johns-Krull
SPIRou: a nIR spectropolarimeter / velocimeter for the CFHT

et al. 2009), whose large-scale topologies are still unknown, will tell us how dynamos (Gregory et al. 2012) and magnetospheric accretion (Romanova et al. 2008; Zanni and Ferreira 2013; Blinova et al. 2016) behave when accretion is stronger and more episodic than in cTTSs, how large a magnetospheric gap these fields carve at disc centre, and how stars react to this process (Baraffe and Chabrier 2010; Feiden 2016). The 40 cTTSs will be medium to strong accretors or very-low-mass stars for which very few spectropolarimetric observations exist so far, thanks to which we will sample the whole range of masses and accretion patterns (Cody et al. 2014; Sousa et al. 2016). In both cases, SPIRou will have a chance to detect and characterize the magnetic fields of their inner discs, and to pin down at the same time the main disc properties (Carmona et al. 2013).

By monitoring a sample of 80 wTTSs and building on the discovery of the youngest known hJs (Donati et al. 2016, 2017; Yu et al. 2017), SPIRou will characterize the population of newborn close-in giant planets at early evolutionary stages, estimate their occurrence frequency and compare it with that of mature Sun-like stars, thereby implementing a novel way of fingerprinting planet formation and planet/disc interactions (Baruteau et al. 2014). This survey will also logically complement that of accreting PMS stars; SPIRou will characterize the magnetic topologies of the observed wTTSs to complete the magnetic panorama of young Sun-like stars. More specifically, SPIRou will work out how large-scale fields change with mass and age, at ages similar to those of cTTSs but with no impact from accretion, and infer how these fields affect the AM evolution of wTTSs through strong winds and massive prominences, and what role they play in star/planet interactions (Strugarek et al. 2015; Vidotto and Donati 2017).

The SPIRou Legacy Survey (SLS) and the synergy with major observatories

Completing the SLS requires a total of 500 CFHT nights over a timescale of 5 years. Whereas CFHT already agreed on investing 300 nights over 3 years for the SLS as a reward to the SPIRou consortium once SPIRou is installed on the telescope, the full SLS allocation of 500 nights is still pending for an official confirmation once SPIRou performances are validated in the lab.

By providing to the whole CFHT community a unique and homogeneous collection of nIR high-resolution spectra of M dwarfs and PMS stars that will be used for a wide range of various purposes, the SLS features an obvious Legacy dimension. We plan to further enhance it through a world-wide accessible data base including additional material such as stellar fundamental parameters, precise RVs, Zeeman signatures and abundances of the main telluric molecules.

All SLS programmes will exploit numerous synergies with major ground and space facilities like TESS and later-on PLATO for characterizing transiting planetary systems around M dwarfs, and the JWST for investigating planetary atmospheres. ALMA will nicely complement SLS observations by scrutinizing star/planet
Fig. 3 Modelling the RV variations of the wTTS V830 Tau with a Gaussian Process for the activity jitter and a 0.7 Jupiter mass planet in a close-in circular orbit. Raw, filtered and residual RVs are shown in the top, middle and bottom panels respectively. Observations are plotted as open symbols; the activity jitter and the planet RV signal are depicted as cyan lines in the top and middle panels respectively, whereas the combination of both is shown as a purple line in the top panel. The modelling unambiguously reveals the existence of a hJ despite its RV signal being 15× weaker than the activity jitter. The rms dispersion of the RV residuals is 37 m s$^{-1}$, i.e., close to the instrumental RV precision (Donati et al. 2017).

formation and protoplanetary discs of PMS stars beyond a few au’s from the host stars, whereas VLA/VLBA and LOFAR will be key for studying star/planet interactions in newborn hJs (Bower et al. 2016; Vidotto and Donati 2017).

Additional science goals

SPIRou will also tackle a large number of additional science programmes beyond the two main ones forming the SLS.

Studying weather patterns in the atmospheres of brown dwarfs is a particularly exciting option. These objects are known to exhibit photometric variations on short timescales (Artigau et al. 2009), attributed to the presence of atmospheric clouds rotating in and out of view, and subject to intrinsic variability. Using tomographic imaging applied to time-series of high-resolution spectra, one can recover surface
maps of the cloud patterns (Crossfield et al. 2014) and potentially their temporal evolution as well. With its high sensitivity and large spectral domain, SPIRou will come as an ideal tool for carrying out such studies.

SPIRou is equally well suited for investigating the dynamics and chemistry of planetary atmospheres in our Solar System (Machado et al. 2014, 2017), and potentially of giant close-in exoplanet atmospheres as well, even when not transiting (Snellen et al. 2010; Brogi et al. 2012). Last but not least, SPIRou will also offer the opportunity of studying at high spectral resolution extremely metal-poor stars as relics of the early universe, providing us with precious clues about the chemical evolution and formation of the Milky Way (Reggiani et al. 2016).

**The SPIRou science consortium**

The SPIRou science consortium gathers over 100 scientists from more than 30 research institutes in 11 different countries. It includes in particular a strong French and Canadian core team, illustrating the fruitful collaboration built up over the last few decades of shared observing effort at CFHT. The consortium also involves scientists from more recent CFHT partners such as Brazil and Taiwan, as well as a small number of experts from non-CFHT countries, involved in the construction of SPIRou (e.g., Switzerland, Portugal) or bringing critical expertise to the analysis of the SLS data (e.g., UK).

**The SPIRou spectropolarimeter / velocimeter**

SPIRou is a direct heritage from previous successful instruments, namely HARPS at the 3.6-m ESO telescope (Pepe et al. 2003) and ESPaDOnS at CFHT (Donati 2003; Donati et al. 2006), and whose overall characteristics are listed in Table 1. In particular, SPIRou includes a cryogenic high-resolution spectrograph inspired from the evacuated spectrograph of the HARPS velocimeter, a Cassegrain unit derived from the ESPaDOnS spectropolarimeter, a fiber-feed evolved from those of ESPaDOnS and HARPS, and a calibration/RV reference unit mirroring that of HARPS (see Fig. 4). We describe these various technical units below in more details.

**The Cassegrain unit and calibration tools**

The Cassegrain unit consists of 3 modules mounted on top of each other and fixed at the Cassegrain focus of the telescope. A CAD view of the lower two modules is shown in Fig. 5.
More specifically, we will tackle the main questions outlined above (Q1-3) by:
benefit from the enhanced capabilities that our targeted SPIRou upgrade will bring.
exploit our intimate instrument knowledge and expertise in spectropolarimetry & modeling techniques, and
and coupling velocimetry with spectropolarimetry to achieve the best results). To succeed, NewWorlds will
nearby M dwarfs), RV precision (to detect low-mass HZ planets) and jitter filtering (developing new tools
To achieve a clear breakthrough in our understanding of how new worlds form, we will
represents,
project, is highly involved in the construction, and is in charge of the integration. The consolidated cost of
now being integrated in Toulouse and will be commissioned at CFHT in 2017. Toulouse manages the whole
Switzerland and Portugal, that I lead as PI. Following a design phase that ended in May 2014, SPIRou is
The SPIRou Legacy
will buy a plug-and-play LFC and add it to SPIRou for the needs of NewWorlds.

We plan a key upgrade for SPIRou within NewWorlds, consisting of
even in the nIR where this jitter is 2-3x smaller (Crockett et al 2012),
PMS stars (Donati et al 2015), is expected to dominate this budget for most targets of interest to NewWorlds,
mandatorily requires access to the K band in addition to both ultra-high sensitivity and polarimetry. SPIRou
innovative features, in particular super-achromatic ZnSe Fresnel rhombs in the polarimeter module of the

Table 1

| Characteristic                      | Value                                                                 |
|-------------------------------------|------------------------------------------------------------------------|
| Spectral range in single exposure   | 0.978–2.437 µm with no gaps                                          |
| Radial-velocity stability           | better than 1 m s⁻¹                                                  |
| Spectral resolving power            | >70,000                                                                |
| Detector array                      | H4RG-15 HgCdTe array, 4096² 15 µm pixels                              |
| Diffraction grating                 | 306 × 154 mm 22 gr/mm R2 grating from Richardson-Lab                  |
| Cross-dispersing prism train        | 2 ZnSe prism and 1 silica prism (size 190 × 206 mm)                   |
| Velocity bin of detector pixel      | 2.3 km s⁻¹                                                            |
| Throughput performances             | S/N=110 per 2.3 km s⁻¹ bin at K≤11 in 1 hr for a M6 dwarf             |
| Polariometric performances          | circular & linear, sensitivity 10 ppm, crosstalk <2%                 |
| Spectrograph temperature            | 80 K, thermal stability 2 mK rms (goal 1 mK) on 24 hr                 |

The upper Cassegrain module essentially serves as a mechanical interface with the telescope, ensuring that the instrument aperture is ideally placed with respect to the telescope focus. It also includes an option for feeding the instrument with a fully polarized beam, allowing one to achieve a complete polarimetric diagnostic of all optical components above the polarimeter, including those located above the entrance aperture (see below).

The middle Cassegrain module includes several facilities for either calibration or observation purposes. It first includes an atmospheric dispersion corrector (ADC) cancelling atmospheric refraction in the incoming beam (down to a precision better than 0.03" up to airmasses of 2.5). It also features a tip-tilt module (TTM) stabilizing the image of the star at the instrument aperture, enough to ensure that the entrance image averaged over the whole exposure (of at least 1 sec) is stable to better than 0.05" rms. This device works in conjunction with a SWIR viewing camera (sensitive to the J and H bands), looking at the instrument entrance aperture and sending back information to the TTM at a frequency of up to 50 Hz. The main goal of the TTM is to minimize shifts of the stellar image with respect to the entrance aperture, and the systematic RV errors that may result from these shifts. The final element of this
module is a calibration wheel allowing one to inject light from the calibration unit (see below) into the instrument, and to polarize it linearly if need be.

The lower Cassegrain module first includes a focal reducer turning the f/8 incoming beam entering the 1.3′′ circular instrument aperture, into a f/4 beam with which optical fibers are fed with minimum Focal Ratio Degradation (FRD). This focal reducer is made of a doublet and a triplet working at infinite conjugate ratio, both optimized for the specific needs of SPIRou. The entrance aperture is located at the centre of a tilted mirror reflecting back to the SWIR viewing camera the incoming light that does not enter the instrument. This module also features an achromatic polarimeter located within the focal reducer, consisting of two 3/4-wave ZnSe dual Fresnel rhombs coupled to a Wollaston prism, splitting the incoming beam into 2 orthogonally polarised beams and feeding twin optical fibers. By tuning the orientation of the rhombs, one can measure the amount of either circular or linear polarisation in the incoming stellar light. By coating one of the internal reflection surfaces of each rhomb, we can ensure that the polarimetric analysis is achromatic to better than 0.5°. Finally, this module includes a cold pupil stop located after the Wollaston prism, and blocking the thermal emission from the telescope to reduce the instrument thermal background in the reddest section of the spectral range. A more detailed account of the Cassegrain unit can be found in [Parés et al. (2012)].
The Cassegrain unit can be fed from the calibration unit through the calibration wheel mentioned above. This calibration unit provides light from the various lamps needed to calibrate observed spectra. SPIRou uses a halogen lamp to collect flat field exposures (for tracking orders on the detector and correct for the spectral response of the instrument), a U/Ne hollow cathode for arc spectra (to obtain a very precise pixel to wavelength calibration), and an evacuated temperature-stabilised Fabry-Perot etalon featuring tens of thousands of sharp lines (to track the shape of the slit and monitor spectral drifts in the instrument). The calibration unit can also directly feed light into the cryogenic spectrograph through the RV reference fiber (see below), thanks to which instrumental drifts can be corrected down to a precision of better than a few 0.1 m s\(^{-1}\). The calibration unit is described in more details in Boisse et al. (2016).

**The fiber link and pupil slicer**

The fiber link includes two science fibers conveying the light from the twin orthogonally polarized beams coming out of the Cassegrain polarimeter into the cryogenic spectrograph. This item consists of a dual 35-m long 90-µm diameter circular fluoride fiber engineered by Le Verre Fluoré (LVF) from purified material, ensuring a throughput of at least 90% over the entire spectral range of SPIRou. The fiber link also includes a third shorter fiber, called the RV reference fiber, with which light from the calibration lamps can be fed directly into the spectrograph. A triple hermetic feedthrough is used to inject light from the three fibers within the spectrograph. Including transmission, FRD and connector losses, the fiber link provides an average transmission over the spectral range of \(\simeq 70\%\).

This fiber link also includes a pupil-slicer at spectrograph entrance to minimize injection losses without sacrificing the spectrograph resolving power. This pupil slicer is fed through three 1.4-m long segments of 90-µm-diameter octagonal fiber (also engineered by LVF) coming from the triple hermetic feedthrough. The combination of the circular and octagonal fibers ensures a scrambling of the near-field image between polarimeter output and spectrograph input of at least 1000.

The pupil slicer per se consists of two mirrors, one main collimator and a pupil-slicing mirror located at the focus of the collimator and slicing the pupil into 4 equal 90° sectors; the twelve individual images (4 images for each of the three fibers) formed after a second pass through the collimator are focused on a stack of twelve small mirrors ensuring that the pupils of all individual beams overlap into a square pupil once imaged onto the spectrograph grating (see Fig. 6). In addition of being extremely compact (a few cubic centimeters), this device has the advantage of simultaneously ensuring a high throughput (>90%), a high resolving power (>70,000) and sliced images with identical shapes and flux distributions (as opposed to more conventional image slicers for which slices often have different shapes), with the result of maximising image stability and thus RV precision.
SPIRou: a nIR spectropolarimeter / velocimeter for the CFHT

Figure 4. (top) Schematic view of the pupil slicer. The output from the science and RV reference fibres collimated onto a pupil-slicing mirror consisting of four flats surfaces tilted relative to each other. The pupil images are reflected back onto the collimating mirror to be re-imaged into fiber images. (bottom) Cartoon view of the pupil slicing principle.

Fig. 6 Top panel: Optical view of the SPIRou pupil slicer. Middle panel: Schematic view of the pupil slicing principle for a single fibre. Bottom panel: Test pupil slicer assembled by WinLight (left), and corresponding slit/pupil profiles for a slightly oversized beam aperture (right).

A more detailed account of the fiber link and pupil slicer can be found in Micheau et al. (2012) and Micheau et al. (2015). The first test pupil slicer for SPIRou, built by Winlight, was recently delivered to IRAP / OMP (see Fig. 6, bottom panel) and was shown to perform nominally.
The cryogenic high-resolution spectrograph

The bench-mounted high-resolution échelle spectrograph follows a dual-pupil design inspired from ESPaDOnS and HARPS (see Fig. 7). In the first half of the optical path, starting from the pupil slicer at the spectrograph entrance, the f/8 beam goes to the main collimator (1200 mm focal length, yielding a 150 mm square pupil) before being cross-dispersed with a double-pass triple-prism train (featuring two ZnSe prisms and an Infrasil one, both of height 206 mm) and dispersed in the perpendicular direction with a R2 échelle grating (of clear aperture $154 \times 306 \text{ mm}^2$, w/ 23.2 gr/mm) from Richardson-Lab; following a second pass on the collimator, the converging beam is reflected off the folding flat mirror and bounces back to the collimator. In the second half of the optical path, the cross-dispersed échelle spectrum formed near the folding flat mirror is re-imaged onto a 4k×4k H4RG detector (15 µm pixels) following a third pass on the collimator and a final focussing through a fully-dioptric 5-lens camera (500 mm focal length, clear aperture 220 mm).

This design allows to record on the H4RG detector the entire spectral range of SPIRou (0.978–2.437 µm, 47 orders from #78 to #32) in a single exposure with no wavelength gaps between orders, at a spectral resolving power in excess of 70,000, and with an average velocity size of detector pixels of 2.28 km s$^{-1}$. The spectrograph profile in the spectral direction is dominated by the slicer profile (equivalent full width at half maximum 4 km s$^{-1}$), with minor contributions from the detector pixels (1.8 km s$^{-1}$) and from the optical point-spread-function (1.5 km s$^{-1}$). This design also ensures a high total throughput of 45% detector included. For a more complete description of the spectrograph optical design, the reader is referred to Thibault et al. (2012).
The whole spectrograph is enclosed in a cryogenic dewar (of external diameter 1.73 m and length 2.87 m) and mounted on an optical bench supported at three points by an hexapod system from an internal warm support frame. The spectrograph and optical bench are cooled down to 80 K and shielded by one active and three passive thermal screens, allowing one to stabilize the temperature of the bench and optics to within better than 2 mK. This thermal stability ensures in particular that the spectral drift at detector level is $<0.7 \text{ m s}^{-1}$ on timescales of one night. This drift can be monitored, and thus mostly corrected for, by recording the RV reference spectrum simultaneously with stellar spectra; in this case, the residual spectral drift at detector level is reduced to 0.25 m s$^{-1}$. Counting in all contributors to the RV error budget, SPIRou should achieve an RV precision of 1 m s$^{-1}$ without the RV reference spectrum, and 0.75 m s$^{-1}$ when using the simultaneous RV reference spectrum.

The design of the cryogenic dewar and its thermal performances are described in more details in [Reshetov et al. (2012)]. The spectrograph cryomechanics and cooling system was demonstrated to be capable of ensuring a 80 K environment on the optical bench, with a thermal stability better than 2 mK rms on a timescale of 24 hr.

**Controlling the instrument**

The overall instrument control is fairly standard, the most challenging aspects being the control of the TTM on the mechanical side, and that of the dewar thermal stability on the temperature side. More details can be found in [Barrick et al. (2012)].

**The data simulator and reduction pipeline**

A simulated raw SPIRou stellar frame is shown in Fig. 8 in a configuration where the RV reference is recorded simultaneously with the stellar spectra associated with the two orthogonal states of the selected polarisation. Thanks to the tilted slit and the multiple slices and following the principles of optimal extraction ([Donati et al., 1997]), the SPIRou reduction pipeline is able to extract a spectrum with a velocity sampling of 1 km s$^{-1}$, i.e., 2.5× larger than the detector sampling of the original raw frame with no loss of information either in resolution or in signal to noise ratio. This ensures in particular that extracted spectra are sampled on a wavelength grid fine enough for high-precision velocimetry. More generally, tests on simulated data confirm that data reduction is compliant with all SPIRou science requirements.
Fig. 8 Simulated raw SPIRou stellar frame, with a close up on the central part of orders #53 to #57. The two stellar spectra of each order correspond to the orthogonal states of the selected polarisation, whereas the third spectrum tracks the Fabry-Perot RV reference. All three spectra feature four identical slices.

Countdown to first light and science operation

SPIRou is currently being integrated in a clean room at IRAP/OMP in Toulouse, France (see Figs. 9 and 10). The spectrograph is now accurately aligned and almost in focus (see Fig. 11). The cryomechanics and its cooling system is found to perform optimally, with the thermal stability of the optical bench already proven to be significantly better than our drastic requirement of 2 mK rms over 24 hr (see Fig. 12).

Validation tests will be carried out until the final acceptance review, currently scheduled for 2017 September. Following packing and shipping, SPIRou will be installed at CFHT in 2017 November, with first light on the sky and technical commissioning planned for 2017 December onwards. Finally, science verification will take place in 2018 Q2 before initiating SLS observations, hopefully by 2018 Q3. Regular information on how integration progresses is available from the SPIRou website at URL spirou.irap.omp.eu.
SPIRou: a nIR spectropolarimeter / velocimeter for the CFHT

The SPIRou project team

The SPIRou project team gathers partners from 7 countries / corporations, and more specifically from:

Fig. 9 Top panel: Preparing for a SPIRou cryostat cool-down phase in the SPIRou clean room. Bottom panel: Aligning the spectrograph optics on the bench while waiting for the spectrograph camera to reach IRAP / OMP; the grating, the prism train and the folding mirror are in the front, right-hand side, whereas the large parabolic collimator is in the rear, left-hand side (© S Chastanet, IRAP/OMP).
• France (IRAP/OMP in Toulouse in charge of the Cassegrain unit, the fiber link and slicer, the instrument integration and the overall project management, IPAG in Grenoble in charge of the optical design of the spectrograph, OHP/LAM in Marseille in charge of the calibration unit and of the reduction pipeline, plus technical inputs from LESIA in Paris);
• Canada (UdeM/UL in Montréal and Québec City, in charge of the spectrograph camera and detector, and NRC-H in Victoria, in charge of the spectrograph cryomechanics);
• CFHT (in charge of the overall instrument control);
• Taiwan (ASIAA in Taipei, in charge of the viewing camera and control of the TTM);
• Brazil (LNA in Itajuba, participating to the tests of the SPIRou optical fibers);
• Switzerland (Geneva Observatory, in charge of the RV reference module);
• Portugal (CAUP in Porto, participating to the construction of mechanical equipments for the instrument integration).

All partners are also participating to the funding of SPIRou (at respective levels of 2.0 MEuros for France, 0.12 MEuros for Brazil, 0.10 Meuros for Switzerland and Portugal, 0.07 MEuros for Taiwan, US$ 2.0 M for CFHT and 0.7 M for Canada) for a total construction cost of 4.8 MEuros (assuming a change rate of 0.9 Euro per US$). The work effort associated with the construction amounts to a total of 60 FTEs (35 for France, 15 for Canada, 3 for CFHT and Switzerland, 2 for Taiwan, 1 for Brazil and Portugal), implying a consolidated cost for the whole instrument of about 10 MEuros.
SPIRou is a new-generation nIR spectropolarimeter / velocimeter for CFHT, currently in integration at IRAP/OMP, France. SPIRou covers a wide spectral nIR domain in a single exposure (0.98-2.44 μm) at a resolving power of 70 K, yielding unpolarized and polarized spectra of low-mass stars with a 15% average throughput at a radial velocity (RV) precision of 1 m s$^{-1}$. It consists of a Cassegrain unit mounted at the Cassegrain focus of CFHT and featuring an achromatic polarimeter, coupled via a fluoride fiber link to a cryogenic spectrograph cooled down at 80 K and thermally stable at 2 mK rms on a timescale of 24 hr. Following integration and validation, SPIRou will be mounted at CFHT by 2017 Q4 for a first light scheduled in late 2017; science operation is expected to start in 2018 S2.

SPIRou will focus on two main science topics, (i) the quest for habitable Earth-like planets around nearby M stars, and (ii) the study of low-mass star/planet for-
Bench temperature at mid distance from the 3 control points on 2017 June 18, during the third SPIRou thermal cycle. The rms thermal stability is found to be 0.2 mK, an order of magnitude better than our goal requirement of 2 mK.

formation in the presence of magnetic fields. The SPIRou Legacy Survey is planning to dedicate about 500 nights over 5 years for carrying out forefront programmes on these two topics, in conjunction with other major ground and space facilities such as TESS, the JWST, ALMA and later-on PLATO and the ELT. SPIRou will also efficiently tackle many more programmes beyond these two main goals, from weather patterns on brown dwarfs to Solar-System planet and exoplanet atmospheres.

In particular, we expect SPIRou to detect at least 200 new exoplanets around nearby M dwarfs, including 150 with masses smaller than 5 M⊕ and 20 located in the HZs of their host stars. SPIRou also plans to carry out a RV follow-up of the 50 most interesting transiting planet candidates to be uncovered by future photometry surveys like TESS. Last but not least, SPIRou will achieve a thorough magnetic exploration of low-mass PMS stars to study how magnetic fields affect star/planet formation, and to assess how frequent hot Jupiters are at early stages of planetary formation and how critically they impact planetary system architectures.

A twin version of SPIRou for TBL at Pic du Midi, nicknamed SPIP (for SPIRou-Pyrénées), is already funded by Région Occitanie / Pyrénées-Méditerranée in France. The current plan is to start constructing SPIP in 2018 for an implementation at TBL in late 2020. Thanks to the 156° longitude shift of TBL with respect to CFHT, SPIP will be able to play a key role for monitoring stars with a higher time cadence and a denser coverage of the rotation cycles of the observed stars and of the orbital cycles of the detected planets as demonstrated by our latest coordinated observations of star/planet formation with ESPaDOnS and Narval ([Donati et al. 2016][2017]).

Last but not least, the feasibility of a SPIRou CubeSat working in parallel with SPIRou is also being studied. The goal of this CubeSat would be to achieve contin-
uous photometric monitoring in the JH bands at a precision of better than 1 mmag, over periods of up to 3 months and simultaneously with our main SPIRou observations. Such complementary data would be quite useful to further characterize the activity of the host stars and to identify the transiting planets among all those that SPIRou will detect.

Acknowledgements

This paper is dedicated to the memory of Leslie Saddlemeyer from NRC-H who passed away on 2017 Jan 09, and to that of Pierre Soler, director of OMP, who sadly left us shortly afterwards, on May 15. Both played major roles in helping SPIRou come to life. Pierre was convinced that SPIRou was to be a key instrument for astronomy, and constantly supported the IRAP / OMP team managing the project in their quest for funding the instrument. Without Leslie’s strong dedication and his invaluable contribution to the AIT phases at IRAP / OMP since the spectrograph cryomechanics was delivered, reassembled and validated in Toulouse, SPIRou would not have reached the current stage of integration. Both Leslie and Pierre will be remembered by the SPIRou team for their outstanding professional experience and their exceptional human qualities.

The SPIRou team thanks all funding agencies in France (the IDEX initiatives in Toulouse and Marseille, DIM-ACAV in Paris, Labex OSUG@2020 in Grenoble, CNRS / INSU, Université de Toulouse Paul Sabatier and Université Grenoble-Alpes, Région Occitanie / Pyrénées-Méditerranée in Toulouse), Canada (CFI, NRC), Brazil (LNA), Switzerland (Geneva Observatory), Portugal (FCT), Taiwan (ASIAA) for their financial and / or manpower contribution to SPIRou. We also thank the Board of CFHT for covering a significant fraction of SPIRou’s construction costs and allocating human resources to the project.

JFD further thanks Université Paul Sabatier, IRAP / OMP and CNRS / INSU for their strong and unfailing support for SPIRou, without which the project would not have been built. PF acknowledges support by Fundação para a Ciência e a Tecnologia (FCT) through Investigador FCT contract of reference IF/01037/2013, and POPH/FSE (EC) by FEDER funding through the program “Programa Operacional de Factores de Competitividade - COMPETE”. PF further acknowledges support from FCT in the form of an exploratory project of reference IF/01037/2013CP1191/CT0001.

References

Allard F, Homeier D, Freytag B et al. (2013) Progress in modeling very low mass stars, brown dwarfs, and planetary mass objects. Memorie della Societa Astronomica Italiana Supplementi 24:128

André P, Basu S Inutsuka S (2009) The formation and evolution of prestellar cores, Cambridge University Press, p 254

Anglada-Escudé G, Amado PJ, Barnes J et al. (2016) A terrestrial planet candidate in a temperate orbit around Proxima Centauri. Nature536:437–440

Artigau É, Bouchard S, Doyon R Lafrenière D (2009) Photometric Variability of the T2.5 Brown Dwarf SIMP J013656.5+093347: Evidence for Evolving Weather Patterns. ApJ701:1534–1539

Artigau É, Kouach D, Donati JF et al. (2014) SPIRou: the near-infrared spectropolarimeter/high-precision velocimeter for the Canada-France-Hawaii telescope. In: Ground-based and Airborne Instrumentation for Astronomy V, Proc SPIE, vol 9147, p 914715, DOI 10.1117/12.2055663

Baraffe I Chabrier G (2010) Effect of episodic accretion on the structure and the lithium depletion of low-mass stars and planet-hosting stars. A&A521:A44

Barrick GA, Vermeulen T, Baratchart S et al. (2012) SPIRou @ CFHT: design of the instrument control system. In: Software and Cyberinfrastructure for Astronomy II, Proc SPIE, vol 8451, p 84513I, DOI 10.1117/12.926392
Baruteau C, Crida A, Paardekooper SJ et al. (2014) Planet-Disk Interactions and Early Evolution of Planetary Systems. Protostars and Planets VI pp 667–689
Berta-Thompson ZK, Irwin J, Charbonneau D et al. (2015) A rocky planet transiting a nearby low-mass star. Nature527:204–207
Blinova AA, Romanova MM Lovelace RVE (2016) Boundary between stable and unstable regimes of accretion. Ordered and chaotic unstable regimes. MNRAS459:2354–2369
Boisse I, Perruchot S, Bouchy F et al. (2016) A calibration unit for the near-infrared spectropolarimeter SPIRou. In: Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Proc SPIE, vol 9908, p 990868, DOI 10.1117/12.2231678
Bonfils X, Delfosse X, Udry S et al. (2013) The HARPS search for southern extra-solar planets. XXXI. The M-dwarf sample. A&A549:A109
Bouvier J, Alencar SHP, Harries TJ, Johns-Krull CM Romanova MM (2007) Magnetospheric Accretion in Classical T Tauri Stars. In: Reipurth B, Jewitt D Keil K (eds) Protostars and Planets V, pp 479–494
Bower GC, Loinard L, Dzib S et al. (2016) Variable Radio Emission from the Young Stellar Host of a Hot Jupiter. ApJ830:107
Brogi M, Snellen IAG, de Kok RJ et al. (2012) The signature of orbital motion from the dayside of the planet τ Boötis b. Nature486:502–504
Carmona A, Bouvier J Delfosse X (2013) Perspectives for the study of gas in protoplanetary disks and accretion/ejection phenomena in young stars with the near-IR spectrograph SPIROU at the CFHT. In: Cambresy L, Martins F, Nuss E Palacios A (eds) SF2A-2013: Proceedings of the Annual meeting of the French Society of Astronomy and Astrophysics, pp 493–495
Cody AM, Stauffer J, Baglin A et al. (2014) CSI 2264: Simultaneous Optical and Infrared Light Curves of Young Disk-bearing Stars in NGC 2264 with CoRoT and Spitzer. Evidence for Multiple Origins of Variability. AJ147:82
Crossfield IJ, Biller B, Schlieder JE et al. (2014) A global cloud map of the nearest known brown dwarf. Nature505:654–656
David TJ, Hillenbrand LA, Petigura EA et al. (2016) A Neptune-sized transiting planet closely orbiting a 5-10-million-year-old star. Nature534:658–661
Davies CL, Gregory SG Greaves JS (2014) Accretion discs as regulators of stellar angular momentum evolution in the ONC and Taurus-Auriga. MNRAS444:1157–1176
Delfosse X, Donati JF, Kouch D et al. (2013) World-leading science with SPIRou - The nIR spectropolarimeter / high-precision velocimeter for CFHT. In: Cambresy L, Martins F, Nuss E Palacios A (eds) SF2A-2013: Proceedings of the Annual meeting of the French Society of Astronomy and Astrophysics, pp 497–508
Donati J, Skelly MB, Bouvier J et al. (2010) Complex magnetic topology and strong differential rotation on the low-mass T Tauri star V2247 Oph. MNRAS402:1426–1436
Donati JF (2003) ESPaDOnS: An Echelle SpectroPolarimetric Device for the Observation of Stars at CFHT. In: Trujillo-Bueno J Sanchez Almeida J (eds) Astronomical Society of the Pacific Conference Series, Astronomical Society of the Pacific Conference Series, vol 307, p 41
Donati JF, Semel M, Carter BD, Rees DE Collier Cameron A (1997) Spectropolarimetric observations of active stars. MNRAS291:658
Donati JF, Palou F, Bouvier J Ferreira J (2005) Direct detection of a magnetic field in the innermost regions of an accretion disk. Nature438:466–469
Donati JF, Catala C, Landstreet JD Petit P (2006) ESPaDOnS: The New Generation Stellar Spectropolarimeter. Performances and First Results. In: Casini R Lites BW (eds) Astronomical Society of the Pacific Conference Series, Astronomical Society of the Pacific Conference Series, vol 358, p 362
Donati JF, Gregory SG, Alencar SHP et al. (2012) Magnetometry of the classical T Tauri star GQ Lup: non-stationary dynamos and spin evolution of young Suns. MNRAS425:2948–2963
Donati JF, Gregory SG, Alencar SHP et al. (2013) Magnetospheric accretion on the fully convective classical T Tauri star DN Tau. MNRAS436:881–897
Donati JF, Hébrard E, Hussain G et al. (2014) Modelling the magnetic activity and filtering radial velocity curves of young Suns : the weak-line T Tauri star LkCa 4. MNRAS444:3220–3229
SPIRou: a nIR spectropolarimeter / velocimeter for the CFHT

Donati JF, Moutou C, Malo L et al. (2016) A hot Jupiter orbiting a 2-million-year-old solar-mass T Tauri star. Nature534:662–666

Donati JF, Yu L, Moutou C et al. (2017) The hot Jupiter of the magnetically active weak-line T Tauri star V830 Tau. MNRAS465:3343–3360

Dressing CD Charbonneau D (2015) The Occurrence of Potentially Habitable Planets Orbiting M Dwarfs Estimated from the Full Kepler Dataset and an Empirical Measurement of the Detection Sensitivity. ApJ807:45

Feiden GA (2016) Magnetic inhibition of convection and the fundamental properties of low-mass stars. III. A consistent 10 Myr age for the Upper Scorpius OB association. A&A593:A99

Gaidos E Selsis F (2007) From Protoplanets to ProtoLife: The Emergence and Maintenance of Life. Protostars and Planets V pp 929–944

Gaidos E, Mann AW, Kraus AL Ireland M (2016) They are small worlds after all: revised properties of Kepler M dwarf stars and their planets. MNRAS457:2877–2899

Gomes da Silva J, Santos NC, Bonfils X et al. (2012) Long-term magnetic activity of a sample of M-dwarf stars from the HARPS program. II. Activity and radial velocity. A&A541:A9

Gregory SG, Donati JF, Morin J et al. (2012) Can We Predict the Global Magnetic Topology of a Pre-main-sequence Star from Its Position in the Hertzsprung-Russell Diagram? ApJ755:97

Güdel M, Dvorak R, Erkaev N et al. (2014) Astrophysical Conditions for Planetary Habitability. Protostars and Planets VI pp 883–906

Hébrard EM, Donati JF, Delfosse X et al. (2016) Modelling the RV jitter of early-M dwarfs using tomographic imaging. MNRAS461:1465–1497

Johansen A (2009) The role of magnetic fields for planetary formation. In: Strassmeier KG, Kosovichev AG Beckman JE (eds) Cosmic Magnetic Fields: From Planets, to Stars and Galaxies, IAU Symposium, vol 259, pp 249–258. DOI 10.1017/S1743921309030592

Johns-Krull CM, Greene TF, Doppmann GW Covey KR (2009) First Magnetic Field Detection on a Class I Protostar. ApJ700:1440–1448

Lin DNC, Bodenheimer P Richardson DC (1996) Orbital migration of the planetary companion of 51 Pegasi to its present location. Nature380:606–607

Lissauer JJ, Dawson RI Tremaine S (2014) Advances in exoplanet science from Kepler. Nature513:336–344

Machado P, Widemann T, Luz D Peralta J (2014) Wind circulation regimes at Venus’ cloud tops: Ground-based Doppler velocimetry using CFHT/ESPaDOnS and comparison with simultaneous cloud tracking measurements using VEx/VIRTIS in February 2011. Icarus243:249–263

Machado P, Widemann T, Peralta J et al. (2017) Venus cloud-tracked and doppler velocimetry winds from CFHT/ESPaDOnS and Venus Express/VIRTIS in April 2014. Icarus285:8–26

Maury AJ, André P, Hennebelle P et al. (2010) Toward understanding the formation of multiple systems. A pilot IRAM-PdBI survey of Class 0 objects. A&A512:A40

Micheau Y, Bouchy F, Pepe F et al. (2012) SPIRou @ CFHT: fiber links and pupil slicer. In: Ground-based and Airborne Instrumentation for Astronomy IV, Proc SPIE, vol 8464, p 84642R, DOI 10.1117/12.926084

Micheau Y, Bouyé M, Parisot J Kouch D (2015) Fluoride fiber thermal emission study for SPIRou @ CFHT. In: Techniques and Instrumentation for Detection of Exoplanets VII, Proc SPIE, vol 9605, p 96051Q, DOI 10.1117/12.2185188

Morin J, Donati JF, Petit P et al. (2008) Large-scale magnetic topologies of mid M dwarfs. MNRAS409:567–581

Morin J, Donati JF, Petit P et al. (2010) Large-scale magnetic topologies of late M dwarfs. MNRAS407:2269–2286

Moutou C, Boisse I, Hébrard G et al. (2015) SPIRou: a spectropolarimeter for the CFHT. In: Martins F, Boissier S, Buat V, Cambresy L Petit P (eds) SF2A-2015: Proceedings of the Annual meeting of the French Society of Astronomy and Astrophysics, pp 205–212

Muirhead PS, Johnson JA, Apps K et al. (2012) Characterizing the Cool KOIs. III. KOI 961: A Small Star with Large Proper Motion and Three Small Planets. ApJ747:144

Muirhead PS, Mann AW, Vanderburg A et al. (2015) Kepler-445, Kepler-446 and the Occurrence of Compact Multiples Orbiting Mid-M Dwarf Stars. ApJ801:18
Newton ER, Irwin J, Charbonneau D, Berta-Thompson ZK Dittmann JA (2016) The Impact of Stellar Rotation on the Detectability of Habitable Planets around M Dwarfs. ApJ821:L19
Parès L, Donati JF, Dupieux M et al. (2012) Front end of the SPIRou spectropolarimeter for Canada-France Hawaii Telescope. In: Ground-based and Airborne Instrumentation for Astronomy IV, Proc SPIE, vol 8446, p 84462E, DOI 10.1117/12.925410
Passegger VM, Wende-von Berg S Reiners A (2016) Fundamental M-dwarf parameters from high-resolution spectra using PHOENIX ACES models. I. Parameter accuracy and benchmark stars. A&A587:A19
Pepe F, Rupprecht G, Avila G et al. (2003) Performance verification of HARPS: first laboratory results. In: Iye M Moorwood AFM (eds) Instrument Design and Performance for Optical/Infrared Ground-based Telescopes, Proc SPIE, vol 4841, pp 1045–1056, DOI 10.1117/12.460777
Rajpurohit AS, Reylé C, Allard F et al. (2013) The effective temperature scale of M dwarfs. A&A556:A15
Reggiani H, Meléndez J, Yong D, Ramirez I Asplund M (2016) First high-precision differential abundance analysis of extremely metal-poor stars. A&A586:A67
Reshetov V, Herriot G, Thibault S et al. (2012) Cryogenic mechanical design: SPIROU spectrograph. In: Ground-based and Airborne Instrumentation for Astronomy IV, Proc SPIE, vol 8446, p 84464E, DOI 10.1117/12.927442
Romanova MM Lovelace RVE (2006) The Magnetospheric Gap and the Accumulation of Giant Planets Close to a Star. ApJ645:L73–L76
Romanova MM, Ustyugova GV, Koldoba AV Lovelace RVE (2004) The Propeller Regime of Disk Accretion to a Rapidly Rotating Magnetized Star. ApJ616:L151–L154
Romanova MM, Kulkarni AK Lovelace RVE (2008) Unstable Disk Accretion onto Magnetized Stars: First Global Three-dimensional Magnetohydrodynamic Simulations. ApJ673:L171
Romanova MM, Long M, Lamb FK, Kulkarni AK Donati J (2011) Global 3D simulations of disc accretion on to the classical T Tauri star V2129 Oph. MNRAS411:915–928
Rupprecht G, Pepe F, Mayor M et al. (2004) The exoplanet hunter HARPS: performance and first results. In: Moorwood AFM Iye M (eds) Ground-based Instrumentation for Astronomy, Proc SPIE, vol 5492, pp 148–159, DOI 10.1117/12.551267
Santerne A, Donati JF, Doyon R et al. (2013) Charaterizing small planets transiting small stars with SPIROu. In: Cambresy L, Martins F, Nuss E Palacios A (eds) SF2A-2013: Proceedings of the Annual meeting of the French Society of Astronomy and Astrophysics, pp 509–514
Shu FH, Galli D, Lizano S, Glassgold AE Diamond PH (2007) Mean Field Magnetohydrodynamics of Accretion Disks. ApJ665:535–553
Skelly MB, Donati JF, Bouvier J et al. (2010) Dynamo processes in the T Tauri star V410 Tau. MNRAS403:159–169
Snellen IAG, de Kok RJ, de Mooij EFW Albrecht S (2010) The orbital motion, absolute mass and high-altitude winds of exoplanet HD209458b. Nature465:1049–1051
Sousa AP, Alencar SHP, Bouvier J et al. (2016) CSI 2264: Accretion process in classical T Tauri stars in the young cluster NGC 2264. A&A586:A47
Strugarek A, Brun AS, Matt SP Réville V (2015) Magnetic Games between a Planet and Its Host Star: The Key Role of Topology. ApJ815:111
Sullivan PW, Winn JN, Berta-Thompson ZK et al. (2015) The Transiting Exoplanet Survey Satellite: Simulations of Planet Detections and Astrophysical False Positives. ApJ809:77
Thibault S, Rabou P, Donati JF et al. (2012) SPIRou @ CFHT: spectrograph optical design. In: Ground-based and Airborne Instrumentation for Astronomy IV, Proc SPIE, vol 8446, p 844630, DOI 10.1117/12.926697
Vidotto AA Donati JF (2017) Predicting radio emission from the newborn hot Jupiter V830 Tau b. A&Asubmitted
Vidotto AA, Jardine M, Morin J et al. (2013) Effects of M dwarf magnetic fields on potentially habitable planets. A&A557:A67
Yu L, Donati JF, Hebrard EM et al. (2017) A hot Jupiter around the very active weak-line T Tauri star TAF 26. MNRAS
SPIRou: a nIR spectropolarimeter / velocimeter for the CFHT

Zanni C Ferreira J (2013) MHD simulations of accretion onto a dipolar magnetosphere. II. Magnetospheric ejections and stellar spin-down. A&A550:A99