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SPIROU: A SPECTROPOLARIMETER FOR THE CFHT

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Abstract. SPIRou is a near-infrared spectropolarimeter and high-precision radial-velocity instrument, to be mounted on the 3.6m Canada-France-Hawaii telescope ontop Maunakea and to be offered to the CFHT community from 2018. It focuses on two main scientific objectives : (i) the search and study of Earth-like planets around M dwarfs, especially in their habitable zone and (ii) the study of stellar and planetary formation in the presence of stellar magnetic field. The SPIRou characteristics (complete coverage of the near infrared wavelengths, high resolution, high stability and efficiency, polarimetry) also allow many other programs, e.g., magnetic fields and atmospheres of M dwarfs and brown dwarfs, star-planet interactions, formation and characterization of massive stars, dynamics and atmospheric chemistry of planets in the solar system.

Keywords: spectrograph, exoplanets, stellar formation, spectropolarimetry

1 Introduction

SPIRou is a near-infrared spectropolarimeter designed for the detection of exoplanets around low-mass stars and for the detection of magnetic fields of young stellar objects. It is currently under construction with a first light foreseen in fall 2017. SPIRou will then be available to the community in 2018. An overview of the key aspects of SPIRou's design is given in Artigau et al. (2014). Delfosse et al. (2013) and Santerne et al. (2013a) detailed several aspects of the science cases. In this article, we will recall the science goals and challenges (Section 2), present the status of the instrument development (Section 3) and describe the SPIRou Legacy Survey (Section 4) as presently foreseen for the Canada-France-Hawaii Telescope (CFHT).

2 The SPIRou science

2.1 *The Quest for Earth-like planets around M dwarfs*

One objective of the current exoplanet science is to find and characterise habitable Earths and Super Earths. Among the 1600 planets detected (and many more candidates), very few are in the habitable zone (sphere around a star where liquid water can be stable of the surface) of their host stars, and none is equivalent to Earth. On

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another hand, very few planets are known around M dwarfs. Finally, observing the planetary architecture as a function of the stellar host mass is important to constrain planet formation models.

The long-term goal of exploring the atmospheric composition of the telluric, potentially habitable exoplanets starts with the discovery of such objects in the solar neighbourhood and the statistical description of their properties. Ideally, one would need to complete a catalog of habitable terrestrial planets, allowing future space missions to concentrate on planet characterization without wasting time on their detection. In addition, statistical properties of planets around M dwarfs can provide key information on planetary formation, and in particular on the sensitivity of planet formation to initial conditions in the protoplanetary disc. Recent simulations indeed suggest that planet populations change very significantly for M dwarfs of increasing masses (Alibert et al in preparation). M dwarfs also vastly dominate the stellar population in the Solar neighborhood and are likely hosting most planets in our Galaxy; this makes such studies even more crucial. Finally, pioneering studies with HARPS at the ESO 3.6m telescope demonstrated that super-Earths with orbital periods ¡100 d are more numerous around M dwarfs than around Sun-like stars, with an occurrence frequency close to 90% (Bonfils et al. 2013); moreover, about half of these super-Earths are potentially located in the habitable zones of their host stars.

The exoplanetary scientists have several reasons to focus on low-mass M dwarfs around which small/low-mass planets are easier to detect. Indeed, the radial-velocity signal of a planet is inversely proportional to $M_\star^{2/3}$, so the method is more favorable to the coolest dwarf stars. It is also faster and easier to detect planets in the habitable zone of low-mass stars since it is located at a distance where planets orbital periods are in the range 10 to 50 days, thanks to a lower stellar temperature and to the fact that the radial-velocity semi-amplitude is proportional to $P_{orb}^{-1/3}$.

Since M dwarfs are faint in the visible, we designed the SPIRou spectropolarimeter in the infrared, so that it is optimised for accurate radial-velocity measurements on M dwarfs. Two challenges will have yet to be faced when pursuing the search for telluric planets in the habitable zones of M dwarfs with SPIRou. First, numerous telluric lines are present in the near-infrared part of the spectra. These lines do not have an equal contribution on each observation depending on time and weather conditions. One should carefully mask or remove them, before deriving the radial-velocity of the star. The second limitation is the level of activity of low-mass M dwarfs. We are currently investigating several reseach directions to mitigate this problem (see Sect. 2.3).

The quest for low-mass planets around very low mass stars is a major science goal that requires large amounts of time.

2.2 Characterization of transiting exoplanets

Numerous ground- and space-based photometric surveys have been used to detect new transiting planets and several others are in project. Exoplanets transiting in front of their host stars are particularly interesting objects as they allow numerous key studies to be performed. This includes accurate radius, mass, and density measurements, atmospheric studies in absorption through transits and in emission through occultations, dynamic analyses from possible timing variations or obliquity measurements.

With precise masses of transiting exoplanets, the atmospheric models can be efficiently tested. For instance, the presence of an atmosphere and its composition strongly depend on these fundamental parameters, as shown by the difference between CoRoT-7b and GJ 1214b (larger radius for a similar mass for the latter): the atmosphere can be dominated by water or by hydrogen, leading to different chemistry and various densities. The diversity of mass or density in the regime of Earth-like exoplanets and super-earthes is striking, and requires a greater sample, and accurate mass measurements, to become useful constraints for the theory (Valencia et al. 2010; Lopez & Fortney 2014; Valencia et al. 2013).

M dwarfs are advantageous hosts for transiting planets studies, as for the radial-velocity method. Their small radii make deeper the transits of telluric planets, and the reduced size of their habitable zone makes more frequent and probable the transits of a potentially habitable planet. SPIRou is thus well optimized to perform the radial velocity follow up of photometric surveys observing M dwarfs to detect transiting planets. Since the rate of false positives could be significant, in particular those due to blended or unblended binaries, the first goal of this follow up is to establish the planetary nature of the transiting candidates. For such validated transiting planets, the radial velocities are then used to characterize the systems and in particular to measure the mass, eccentricity, and obliquity of the planets. They are also used to characterize the host stars and to search for possible extra companions. SPIRou is expected to play an important role in the follow up of planetary candidates transiting in front of M dwarfs detected by photometric surveys, including ExTra, NGTS, K2, TESS, or PLATO.

Finally, as the magnetic field of the host stars will also be obtained by SPIRou for each planet detection, it will be possible to investigate the role of the magnetic field to shape the evolution of planets, through evaporation or stellar wind interactions. Such studies in transiting systems, where the relative inclinations are better constrained and the planet masses are well known, are particularly interesting.

2.3 *Filtering out the radial-velocity activity jitter using the spectropolarimetry*

To diagnose the radial velocity jitter, several complementary approaches are commonly used, mostly making use of chromospheric activity indicators like excess flux in the cores of the Hα and Ca II H&K, or measurements of spectral line asymmetries. For the use of SPIRou, we investigate how we can use spectropolarimetry to better characterize and ultimately model the radial-velocity jitter. This new method aims at studying both the radial-velocity jitter caused by activity and Zeeman signatures reflecting the large-scale magnetic field at the origin of activity. To model the radial-velocity jitter due to rotational modulations, we take advantage of the distortions of the Stokes I profiles that are caused by brightness inhomogeneities at the stellar surface (Hébrard et al., 2015, in prep).

As an example, we outline the results obtained for GJ 358, a moderately active M2-dwarf. From the Stokes V signatures we infer a rotational period of $\sim$25.4 days; using Zeeman Doppler Imaging, we then recover the parent large scale magnetic field. This star exhibits a poloidal component with a polar intensity of -110 G inclined at 45°to the line of sight. We observe that the radial velocities and the longitudinal field vary in quadrature, which suggest that spots cluster at phase $\sim$0.7 (see right panel Fig. 1). By modeling the tiny distortions in Stokes I profile using a modified version of Zeeman Doppler Imaging (Hébrard et al. 2015 in prep.), we obtain a map representing the statistical distribution of spots at the stellar surface. As expected, we find a cluster of spots lying close to the same longitude. The radial velocity jitter of full amplitude of $\sim$ 15 $\mathrm{m\,s^{-1}}$ can be filtered out at a rms precision of 2.8 $\mathrm{m\,s^{-1}}$ close to the intrinsic precision of the data set (see right panel of Fig. 1). In the Lomb-Scargle periodogram of the radial velocities, the periods $P_{\rm rot}$, $P_{\rm rot}/2$ and $P_{\rm rot}/3$ have been filtered, and there is no more prevailing peaks in the periodogram of the residuals.

A similar method has been used the analysis of V830 Tau (Donati et al. 2015) and it will be generalized to the planet search programs in the SPIRou data. In the near-infrared, profile distortions induced by cool spots are smaller than in the visible (Huélamo et al. 2008, e.g.), but the Zeeman broadening is larger, so filtering needs to be adjusted accordingly (Hébrard et al. 2014).

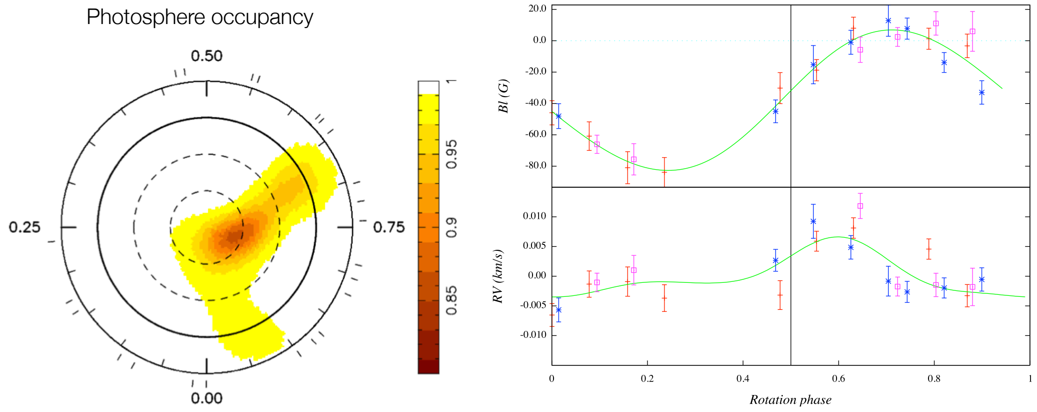

Fig. 1. *Left:* Map of the photosphere occupancy (white for quiet photosphere, brown for spot). The star is viewed in flattened polar projection. The pole is in the center, the bold circle depicts the stellar equator and the outer line represents the -30° latitude. *Right:* Longitudinal field (in G) and radial velocities (in $\mathrm{km\,s^{-1}}$) as a function of the rotation phase, collected with HARPSPol Each color symbol represents a stellar rotation phase. The green curves represent the predicted values.

2.4 *Magnetic fields of protostars and cool stars*

Our second main scientific goal is to characterise the impact of magnetic fields on the formation of stars and planets. Magnetic fields in the inner disc regions or at protostar surfaces can only be investigated through nIR spectroscopy (Johns-Krull 2007, e.g.) or optical spectropolarimetry (Donati et al. 2005, e.g.). In both cases, magnetic fields are detected through the Zeeman effect on spectral lines, and more specifically through the additional broadening (with respect to non magnetically-sensitive lines of otherwise similar properties) and the polarization structures they generate within line profiles. With SPIRou, we will measure and characterise the structure of the magnetic field of young protostars thanks to the polarimetric capability of SPIRou. The near infrared is needed since these targets are faint in the visible. Moreover the Zeeman effect increases with wavelength.

The questions that SPIRou will be able to handle include: (i) what is the origin of their magnetic fields (e.g. fossil or dynamo), (ii) how do these magnetic fields connect the protostars to their accretion discs, (iii) how do these fields control accretion from the discs and how can they slow down the rotation of the protostars, (iv) how do they participate (along with accretion disc fields) in launching collimated jets, (v) how importantly do they contribute to the photo-evaporation of the disk through the coronal X-rays they indirectly produce, (vi) to what extent do magnetism and magnetospheric accretion modify the internal structure of protostars, and (vii) with which magnetic topologies do protostars start their unleashed spin-up towards the main sequence once they dissipated their accretion discs?

At ages of 0.1-0.5 Myr, low-mass pre-main-sequence stars (class-I protostars) are surrounded by massive accretion discs from which they actively feed, and are embedded in dust cocoons hiding them from view at optical wavelengths. As a result, the large-scale magnetic topology at the surface of a class-I protostars has never been observed and will be assessed for the first time with SPIRou.

With SPIRou data, quantitative studies of how protostars accrete material from their accretion discs and how this process impacts their structure and rotation evolution can be carried out and the corresponding models can be directly confronted to observations. One can for instance retrieve the location and geometry of accretion funnels (Romanova et al. 2011, e.g.), investigate how the resulting accretion shock affects the atmosphere of the star and evaluate the impact of accretion on structure and angular momentum content (Zanni & Ferreira 2013) of the newly born star. In particular, class-I protostars should be well suited for investigating magnetospheric accretion at higher accretion-rate regimes.

With SPIRou, we will be estimating the gaseous content in the inner regions of different types of protostellar accretion discs, investigating their magnetic field strengths and topologies and looking for potential correlations between the disc and field properties to find out whether and how fields can impact discs. Magnetic fields in discs are potentially important since fields are expected to impact significantly the formation, disc-induced migration and orbital inclination of protoplanets. More specifically, discs fields and associated MHD turbulence can potentially inhibit fragmentation through gravitational instabilities and modify the subsequent formation of giant planets. Thanks to our first study on filtering out activity jitter on rotating stars (Petit et al. 2015; Donati et al. 2015), we could also search for hot Jupiters around these targets. Detecting hot Jupiters at the early stage would constrain the theory on the formation and migration of planetary systems.

3 The instrument development status

SPIRou is being developed by seven countries: Canada, France, Switzerland, Taiwan, Brazil, Portugal, Hawaii and 12 institutes in these countries. The consortium is led by IRAP (Toulouse, France).

The science requirements and technical specifications of SPIRou can be summarized as follows:

- Acquire a single-shot spectral domain covering the YJHK domain (0.98-2.35 μm), to benefit the very high spectral radial velocity content in the H and K-band for M-dwarfs and to allow observing the magnetic field of embedded young stars in their early phase.

- Get a spectral resolution of 70K to 75K, in order to optimize the radial-velocity accuracy for lines of slowly rotating M dwarfs.

- Achieve the radial velocity stability of 1m/s, to allow the detection of Earth and Super-Earth exoplanets in the habitable zone of M-dwarfs.

- Provide the linear and circular polarimetric capacity, with maximum 1-2 % crosstalk and down to a sensitivity of 10 ppm (similar to CFHT/ESPaDOnS). This will allow the observations of stellar magnetic fields and the disentangling of the stellar activity and the keplerian signal.

- Obtain a signal-to-noise ratio of 100 per 2km/s pixel for a star of magnitude J=12.0 or K=11; this implies a requirement on the throughput of 15 % and on the thermal background at 2.35 μm of maximum 50 ph/s/Å. This efficiency is required for a large radial-velocity and polarimetric survey.

SPIRou is made of several sub-systems, each of them being simultaneously developed in different institutes of the consortium. The first sub-system is the Cassegrain unit, mounted in the dome at the Cassegrain focus of the 3.6m CFH telescope. It is composed of an atmospheric dispersion corrector, the guide camera with an image stabilisation system and an achromatic polarimeter. The Cassegrain unit is being developed and tested at IRAP, Toulouse. The second sub-system contains the fibers and the pupil slicer. The spectral range requires the use of fluoride fibers; high transmission fibers are chosen to maximize thoughput. The near-field scrambling is obtained with a section of octogonal fibers. The pupil is split into four slices for each science fiber, with 4 pixels separating each fiber. The main piece of SPIRou is the cryogenic spectrograph, located in the coudé room at the third floor of the telescope building. Its thermal control has a specification of 2 mK over a day. The spectrograph design contains a large parabolic mirror, a double-pass prism-train cross-disperser with an R2 diffraction grating, and a fully dioptric camera with a Hawaii 4RG 4kx4k detector array. The spectrograph cryostat, currently being mounted in Victoria (Canada), is shown on Fig. 2. Essential to the radial-velocity accuracy is the calibration & super-stable radial-velocity reference module, also located in the coudé room and fiber linked to the spectrograph; this calibration module is being assembled between Geneva and Observatoire de Haute Provence.

The data reduction pipeline is being developed by the consortium (effort led by LAM, Marseille) and will be delivered to CFHT with the instrument, aiming at a complete extraction of spectra as well as radial-velocity and polarisation signatures available a few minutes after the observations.

The last project review was held in June 2015 at IRAP, Toulouse. The funding process is now finalised, and should be secured at the end of 2015. The integration / validation of the full instrument will be at IRAP, Toulouse and should last 7 months. The integration at system level is expected to start on March 2016, followed by the validation phase on November 2016. The system Acceptance at IRAP will be in April 2017. We expect the final integration on CFHT site to be in summer 2017 for a first light in the last semester of 2017.

Stay tuned by consulting the SPIRou web page `http://spirou.irap.omp.eu/`.

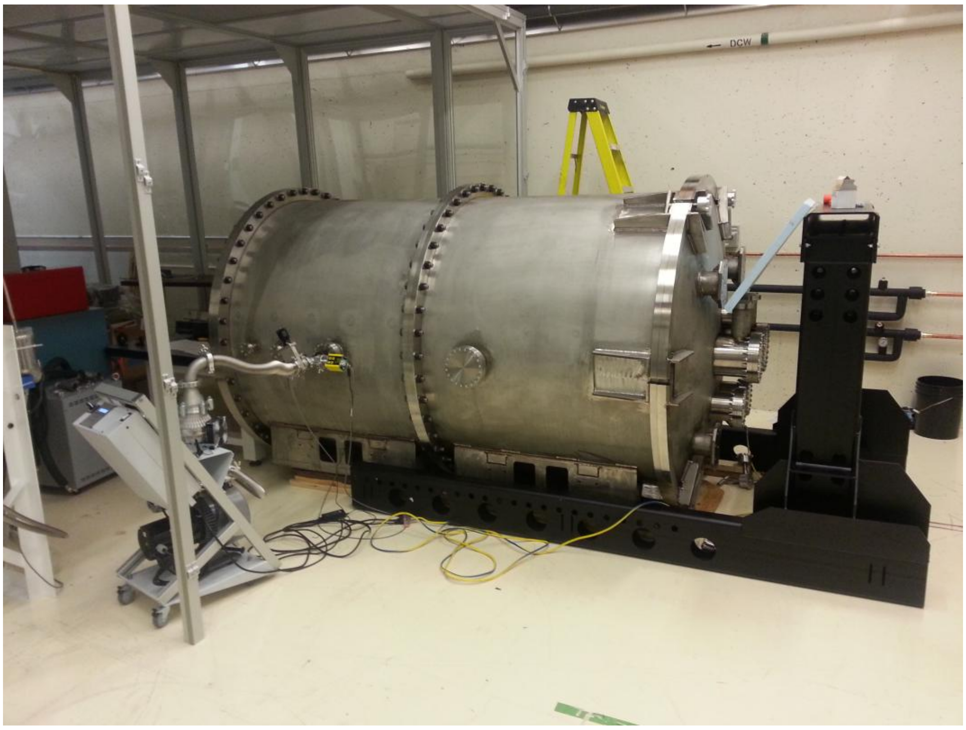

Fig. 2. The SPIRou cryostat, being integrated at NRC Herzberg, Victoria, Canada.

4 The SPIRou Legacy Survey (SLS)

Shortly after its installation on the CFHT, SPIRou will start a series of Legacy Surveys, for a minimum of 300 nights over the first 3 years of operations of the instrument -as approved by the CFHT Board in 2015. The objectives of the surveys are threefold:

- identify several tens of habitable-zone Earth-like planets orbiting M dwarfs in the immediate neighborhood of the Solar System, as well as more than 100 exoplanets with orbital periods ranging from 1 day to 1 year, to derive accurate planet statistics,
- characterize the internal structure of several dozens of telluric planets with moderate equilibrium temperature, by providing mass measurements to the transit candidates discovered by K2, TESS and PLATO,
- explore the impact of magnetic fields on star / planet formation, by detecting and characterizing magnetic fields of various types of young stellar objects.

These three observing programs require large input catalogs of targets for statistical relevance, and a large number of visits per target. With its queue operation mode, the CFHT is well adapted and flexible to handle large surveys, get homogeneous data sets and optimize temporal sampling and critical scheduling. Specific tools are being developed at the observatory to support SPIRou surveys operations.

The radial-velocity **planet-search survey (SLS-PS)** will focus on an input catalog of 330 nearby M dwarfs. They are selected from the catalog by Lépine & Gaidos (2011) and cover a range in mass from 0.08 to 0.5 M_{sun}. Monte Carlo simulations suggest that the SLS-PS should detect $\sim$ 250 new exoplanets, including $\sim$180 with masses less than 5 Earth masses and $\sim$30 of them lying in the habitable zone. Breaking down the full stellar sample in 0.5-dex bins in orbital period and mass, the SLS-PS will provide occurrence rates of Earth-like planets in each mass / period bin with a $\sim$20% accuracy. In particular, the SLS-PS will determine the frequency η_E of habitable-zone Earth-like planets around M dwarfs to an accuracy of $\sim$5%. Extensions of this program are possible and can be carried out after the completion of SLS-PS. The required number of visits per star averages to $\sim$ 50 per star during the survey duration, but this parameter may have to be increased at the expanse of decreasing the sample size, especially if multi-planet systems are frequently found or/and if the stellar jitter remains an issue.

The total time required for the SLS-PS is of the order of 275 nights, counting on $\sim$ 10 min per visits to achieve the required 1 m/s precision on individual radial velocity measurements. As SPIRou observations are done in the spectropolarimetric mode, the magnetic field of the host stars will be monitored at the same frequency than the planetary orbits, offering a unique view on the evolution of magnetic topologies of evolved and quiet fully convective stars. Other activity proxies will also be monitored.

With the future collection of planetary systems to be found by SPIRou, we will be able to bring unprecedented constraints on the formation of planets around low-mass stars, their dynamical evolution and interactions between planets and with the host star. Consequences for further studies are expected to be huge, as tidal locking, orbital properties and stellar wind may be limits to planet habitability and presently require additional observational constraints.

The radial-velocity follow-up observations of transiting planetary candidates is the best way to get rid of false positives (Santerne et al. 2013b) and to measure the mass of the confirmed planets. With mass and radius, the bulk density and global properties of the planetary internal structure can be inferred. In the continuation of successful missions like CoRoT and *Kepler*, NASA is currently operating the K2 mission and is going to launch TESS in 2017. By targeting bright stars, TESS will provide Earth-like planet candidates which radial-velocity follow-up will be possible on ground-based telescopes -unlike most of the *Kepler* candidates. SPIRou at CFHT will be unique to secure radial-velocity measurements on the coolest part of the stellar hosts. Using statistics based on Kepler results, 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. The list of planet candidates discovered by TESS and their light curves will be made available to the community for complementary observations. Most super-Earth candidates detected by TESS will orbit M dwarfs - with less than 30% of them accessible to optical radial-velocity follow-ups; nIR velocimeters like SPIRou will thus be essential to validate planet candidates.

In the meantime, ground-based transit surveys of M stars are ongoing (e.g., MEarth) or about to start (e.g., ExTrA), with many candidate planets known by 2017. With a first light scheduled in 2016, ExTrA targets stars of late spectral types (M4 to L0) and aims at the smallest planets around the smallest stars. ExTrA should detect a few tens of very-low-mass transiting planet candidates, again to be validated with nIR velocimetry. Expected to even outperform ESPRESSO on the VLT for most types of M dwarfs, SPIRou will be the best and most efficient radial-velocity instrument to monitor in the nIR the candidates visible from CFHT, to confirm or reject their planetary nature and to determine their masses.

The second component of the SLS - **the SLS-TF for Transit Follow-up**, will carry out radial-velocity follow-up observations of the 50 most interesting transiting planet candidates uncovered by future photometry surveys including TESS and ExTrA - for a total of 100 CFHT nights. We will focus on candidates with orbits closest to their habitable zones and/or around the brightest stars for a given spectral type - to select the best ones to be scrutinized in the future by the JWST or the E-ELT for spectral signatures of biomarkers in their atmospheres. The observing strategy includes an estimated number of 70 visits per candidate.

The third component of the SPIRou Legacy Survey is the study of class-I,-II and -III protostars (**SLS-MP: Magnetic Protostar / Planet**). We aim at detecting and mapping the magnetic topologies of young stars and their accretion discs and to explore the origins and evolution of the magnetic field of stars. In this survey, it will also be possible to unveil giant planets in short orbits and put constraints on the formation versus migration timescales for hot-Jupiter like planets - as they survive the system formation processes.

Magnetic fields play a major role in the early evolution of stellar systems. By affecting and often controlling accretion processes, triggering and channeling outflows, and producing intense X-rays, magnetic fields critically impact the physics and largely dictate the angular momentum evolution of pre-main-sequence stars and their accretion discs. Magnetic fields link accreting pre-main-sequence stars to their discs and evacuate the central disc regions; they funnel the disc material onto the stars, generate powerful winds and force classical T Tauri stars to rotate much more slowly than expected from contraction and accretion. Fields of accretion discs trigger instabilities, enhance accretion rates and extract angular momentum through magnetic braking and outflows; they also produce X-rays through flares and shocks, ionizing the disc gas and impacting disc dynamics and planet formation.

The targets are brighter in the nIR than in the optical, whereas the Zeeman effect is stronger at longer wavelengths. Spectropolarimetric observations with SPIRou will thus allow us to survey much larger samples of pre-main-sequence stars than accessible presently, as well as to access younger embedded class-I protostars and their discs on which very little information is yet available.

The SLS-MP survey will consist in collecting spectropolarimetric observations of about 140 young protostars in various stages of evolution, selected in the close star-forming regions of Taurus/Auriga, TW Hya and ρ Ophiuchius. It will, in particular, explore for the first time the magnetic topologies of class-I protostars. The survey will extend over 125 nights as each target requires multiple visits (about 20) to sample the rotation cycle over a couple of cycles. As previously, the MP survey can be extended towards other young systems.

With these three axes, the SPIRou Legacy Survey will gather a large community of scientists interested in the formation, evolution and characteristics of exoplanets and stars. The SPIRou science group is open to any proposal of legacy-type science that would not yet be covered but accessible with the survey observations. Out of these surveys, SPIRou will be able and available to explore many more science topics via open time proposals.

5 Conclusions

The SPIRou near-infrared velocimeter and spectropolarimeter, soon to be installed at the Maunakea CFHT observatory, mainly aims at the specific tasks of investigating planet formation and properties around cool stars and young stars, while describing the magnetic properties of these stars. The polarimetric capability is unique and will widen the future diagnostics of stellar variability for planet search. SPIRou has the potential of finding the telluric exoplanets that space telescopes like JWST will focus on, for atmospheric studies and further habitability explorations. Other near-infrared velocimeters are being built in the world, e.g. CARMENES (Quirrenbach et al. 2010), IRD (Kotani et al. 2014), HPF (Hearty et al. 2014). None of these instruments, however, includes the spectropolarimetric capability (required for stellar activity corrections) nor the essential K band (with a large radial-velocity content for low mass stars and a large flux for embedded sources).

The SPIRou science group is open to any interested member of the CFHT community, especially in the context of the large surveys which will use SPIRou for $\sim 70\%$ of the time and at least 300 nights over the 3 first years.

The community is now structured around five main work packages; three focussing on the three components of the SPIRou Legacy Survey. The other two explore topics that are common to all science goals, like radial-velocity optimization, stellar jitter correction or stellar spectroscopic and magnetic characterisation.

The first sub-systems of SPIRou are being delivered to Toulouse, and the integration and tests will take place at IRAP until mid 2017, when the instrument will be shipped to Hawaii. SPIRou should be on the sky at the end of 2017, and probably open to the community in 2018A.

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