SF2A 2013
L. Cambrésy, F. Martins, E. Nuss and A. Palacios (eds)

WORLD-LEADING SCIENCE WITH SPIROU - THE NIR SPECTROPOLARIMETER / HIGH-PRECISION VELOCIMETER FOR CFHT

X. Delfosse[1], J.-F. Donati[2], D. Kouach[2], G. Hébrard[3], R. Doyon[4], E. Artigau[4], F. Bouchy[5], I. Boisse[5], A.S. Brun[6], P. Hennebelle[6,7], T. Widemann[8], J. Bouvier[1], X. Bonfils[1], J. Morin[9], C. Moutou[10], F. Pepe[11], S. Udry[11], J.-D. do Nascimento[12], S.H.P. Alencar[13], B.V. Castilho[14], E. Martioli[14], S.Y. Wang[15], P. Figueira[16], N.C. Santos[16] and the SPIRou Science Team

Abstract.
SPIRou is a near-infrared (nIR) spectropolarimeter / velocimeter proposed as a new-generation instrument for CFHT. SPIRou aims in particular at becoming world-leader on two forefront science topics, (i) the quest for habitable Earth-like planets around very- low-mass stars, and (ii) the study of low-mass star and planet formation in the presence of magnetic fields. In addition to these two main goals, SPIRou will be able to tackle many key programs, from weather patterns on brown dwarf to solar-system planet atmospheres, to dynamo processes in fully-convective bodies and planet habitability. The science programs that SPIRou proposes to tackle are forefront (identified as first priorities by most research agencies worldwide), ambitious (competitive and complementary with science programs carried out on much larger facilities, such as ALMA and JWST) and timely (ideally phased with complementary space missions like TESS and CHEOPS).

SPIRou is designed to carry out its science mission with maximum efficiency and optimum precision. More specifically, SPIRou will be able to cover a very wide single-shot nIR spectral domain (0.98-2.35 μm) at a resolving power of 73.5K, providing unpolarized and polarized spectra of low-mass stars with a $\sim$15% average throughput and a radial velocity (RV) precision of 1 m/s.

Keywords: Extrasolar planets, Super-Earths in the habitable zone, Star / planet formation, Stellar magnetic fields, Velocimetry, Spectropolarimetry.

[1] UJF-Grenoble 1/CNRS-INSU, Institut de Planétologie et d'Astrophysique de Grenoble (IPAG) UMR 5274, 38041 Grenoble, France
[2] UPS-Toulouse / CNRS-INSU, Institut de Recherche en Astrophysique et Planétologie (IRAP) UMR 5277, Toulouse, F31400 France
[3] Institut dAstrophysique de Paris, CNRS, Université Pierre et Marie Curie, 98bis Bd. Arago, 75014 Paris, France
[4] Département de physique and Observatoire du Mont-Mégantic, Université de Montréal, C.P. 6128, Succursale Centre-Ville, Montréal, QC H3C 3J7, Canada
[5] Aix Marseille Université, CNRS, LAM (Laboratoire dAstrophysique de Marseille) UMR 7326, 13388, Marseille, France
[6] Laboratoire AIM Paris-Saclay, CEA/Irfu Université Paris-Diderot CNRS/INSU, 91191 Gif-sur-Yvette, France
[7] LERMA (UMR CNRS 8112), Ecole Normale Supérieure, 75231, Paris Cedex, France
[8] Paris Observatory, LESIA UMR 8109, Meudon, France
[9] LUPM, Université Montpellier II, CNRS, UMR 5299, Place E. Bataillon, 34095, Montpellier, France
[10] Canada-France-Hawaii Telescope Corporation, 65-1238 Mamalahoa Hwy., Kamuela, HI 96743, USA
[11] Observatoire Astronomique de l'Université de Genève, 51 Ch. des Maillettes, 1290 Sauverny, Versoix, Suisse
[12] Departamento de Física Teórica e Experimental (DFTE), Universidade Federal do Rio Grande do Norte (UFRN), CP 1641, 59072-970 Natal, RN, Brazil
[13] Departamento de Física - ICEx - UFMG, Av. Antnio Carlos, 6627, 30270-901 Belo Horizonte, MG, Brazil
[14] Laboratório Nacional de Astrofísica/MCT, Rua Estados Unidos 154, 37504-364 Itajubá, MG, Brazil
[15] Institute of Astronomy and Astrophysics, National Taiwan Univ., Taiwan
[16] Centro de Astrofísica, Universidade do Porto, Rua das Estrelas, 4150-762, Porto, Portugal

Requirement	Value
Simultaneous Spectral Range	full coverage from 0.98-2.35 m (YJHK bands)
Resolving Power	>70K (goal 75K)
RV Precision	<1 m/s (rms)
Polarimetric Performance	relative precision: better than 2% (goal 1%); sensitivity: 10 ppm
Instrument Sensitivity	S/N>100 per 2 km/s pixel in 1 hr at J=12 & K=11; bright limit: H<3.5 (goal H<1) - faint limit: H$\sim$14
Observational Efficiency	>70% & >90% for 15 min & 1 hr visit respectively
Sky Coverage	up to airmass 2.5 (zenithal distance 70°)

Table 1. Summary of SPIRou scientific requirements

1 Introduction

The science programs SPIRou proposes to tackle are forefront (first priorities for most research agencies worldwide), ambitious (competitive and complementary with science programs carried out on much larger facilities, e.g., ALMA/ESO and JWST/NASA) and timely (ideally phased with complementary instruments, e.g., TESS/NASA, CHEOPS/ESA and JWST/NASA). SPIRou plans to concentrate on two main scientific goals. The first one is to search for and characterize habitable exo-Earths orbiting very-low mass stars (vLMSs) using high-precision radial velocity (RV) measurements. This search will expand the initial, exploratory studies carried out with visible instruments (e.g., HARPS/ESO) and will survey in particular large samples of stars mostly out of reach of existing instruments. In particular, carrying out a new large- scale survey at nIR wavelengths will boost the sensitivity to habitable exo-Earths by typically an order of magnitude on planetary mass (with respect to existing instruments). SPIRou will also work in close collaboration with space- and ground- based photometric transit surveys like TESS/NASA, CHEOPS/ESA and ExTrA* to identify the true planets among the candidates they will discover.

The second main goal is to explore the impact of magnetic fields on star and planet formation, by detecting fields of various types of young stellar objects (e.g. class-I, -II and -III protostars, young FUor-like protostellar accretion discs) and by characterizing their large-scale topologies. SPIRou will also investigate the potential presence of giant planets around protostars and in the inner regions of accretion discs. In particular, this study will vastly amplify the initial exploration surveys carried out at optical wavelengths within the MaPP (Magnetic Protostars and Planets) and MaTYSSE (Magnetic Topologies of Young Stars and the Survival of close-in massive Exoplanets) CFHT Large Programs (LPs). It will also ideally complement the data that ALMA/ESO has just started collecting on outer accretion discs and dense prestellar cores. SPIRou will also be able to tackle many additional exciting research topics in stellar physics (e.g., dynamos of fully convective stars, weather patterns of brown dwarfs), in planetary physics (e.g., winds and chemistry of solar-system planets), galactic physics (e.g. stellar archeology) as well as in extragalactic astronomy. We detail these goals below, giving in the main cases the typical samples that need to be explored and their observational properties.

2 SPIRou

2.1 Science requirements and instrument concept

SPIRou is designed to carry out its science mission with maximum efficiency and optimum precision. More specifically, SPIRou will be able to cover a very wide single-shot nIR spectral domain (0.98-2.35μm) at a resolving power of 73.5K, providing unpolarized and polarized spectra of low-mass stars with a $\sim$15% average throughput and a RV precision of 1 m/s. Table 1 list the main scientific requirements of SPIRou, needed to carry out most science goals detailled in Sec 3 and 4.

The very-wide simultaneous spectral range, including in particular the K band, is crucial to SPIRou. It maximizes the instrument efficiency, both for the exoplanet programs - the K band totaling $\sim$40% of the RV content in a full YJHK spectrum for an average M dwarf (see Fig 1) - and for the magnetic fields and star/planet formation themes - the relative spectropolarimetric weight of the K band reaching 60-70% given the increase of

*ExTrA is a recently funded ERC project whose aim is to detect transiting Earth-like planets around M-dwarfs from the ground. As a low resolution multiple-object spectrograph, ExTrA will allow extremely accurate photometry in narrow wavelength bands the Zeeman effect with wavelength as λ^2. Moreover, the K band is the only window to access class I embedded protostars, a key stellar sample to be explored for the first time with SPIRou. The wide spectral coverage and spectropolarimetric capabilities are also unique to SPIRou; other nIR RV instruments currently under planning (Carmenes on Calar Alto, IRD on Subaru, HZPF on the HET) do not cover beyond the H band nor include a polarimeter. The spectral resolution is also very important, not only to maximize the velocimetric efficiency, but also to ensure high enough spectropolarimetric sensitivity to Zeeman signatures; with a spectral resolution of at least 73.5K, SPIRou is nearing optimal performances.

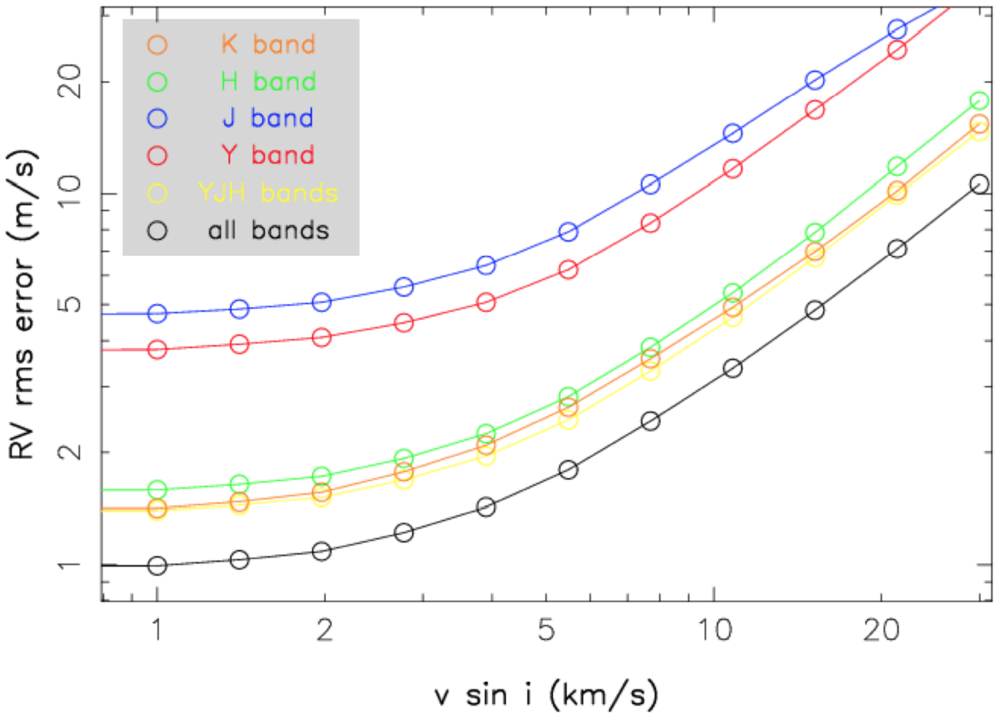

Fig. 1. RV rms photon-noise error (in m/s) vs rotational broadening ($v \sin i$) for a M7 dwarf (2,700 K) and for the different nIR bands (color curves), assuming a spectral resolution of 75K and a peak S/N of 160 per 2 km/s pixel. A RV precision of 1 m/s can be reached at low $v \sin i$'s. The K band (orange) is the main contributor to the RV precision and contributes almost as much as all other bands (yellow). Without the K band, a twice longer exposure time would be required to reach the same RV precision. Note that this estimate is likely pessimistic by potentially as much as a factor of 2, nIR synthetic spectra systematically under-estimating the strength of many molecular and even atomic features.

The resulting instrument concept proposed for SPIRou is a direct heritage from previous successful instruments built by various members of the SPIRou project team: HARPS at the 3.6-m ESO telescope (Mayor et al. 2003), ESPaDOnS at CFHT (Donati 2003) and SOPHIE at 1.93-m OHP telescope (Bouchy & Sophie Team 2006; Bouchy et al. 2013). More specifically, 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 the HARPS/SOPHIE velocimeters, and a Calibration/RV reference unit largely copied from those of SOPHIE and HARPS.

2.1.1 The Cassegrain unit

The Cassegrain unit consists of 2 modules mounted (on top of each other) at the Cassegrain focus of the telescope. The upper Cassegrain module includes an ADC correcting the entrance beam for the atmospheric refraction and a tip-tilt module stabilizing the entrance image to better than 0.05" rms; this module also includes a calibration wheel allowing to inject light from the calibration unit into the instrument. Beginning with a circular instrument aperture of diameter 1.3", the lower Cassegrain module mainly includes an achromatic polarimeter made of two 3/4-wave dual ZnSe Fresnel rhombs coupled to a Wollaston prism, splitting the beam into 2 orthogonal linear-polarization states. The 2 beams emerging from the beamsplitter are injected into 2 separate fibers at polarimeter output

2.1.2 The fiber link and pupil slicer

The fiber link conveys the light from the twin orthogonally polarized beams coming out of the Cassegrain polarimeter into the cryogenic spectrograph. This link consists of a dual 35-m circular fluoride fiber custom-made with purified material to ensure a throughput of >90% over the entire spectral range of SPIRou; this fiber link also includes a pupil-slicer at spectrograph entrance to minimize injection losses without affecting the spectrograph resolution. The last section of the fiber link includes a triple 90μm octogonal fiber (2 for the science fibers and 1 for a simultaneous RV reference) ensuring a high scrambling of the near-field image is at least 1000.

2.1.3 The cryogenic spectrograph

The high-resolution échelle spectrograph is bench-mounted, protected by one active and 3 passive thermal shields, and enclosed within a cryogenic dewar. Thanks to a dual-pupil design and an off-the-shelf commercial R2 échelle grating (w/ 23.2 gr/mm), the spectrograph can record the entire spectral range on a Hawaii 4RG detector (15μm square pixels). The pixel size translates into an average spectral bin of 2.28 km/s and the spectrograph features a non-Gaussian instrumental profile yielding a spectral resolving power of 73.5K. The optical design of the spectrograph ensure a high total average throughput of 45% (detector included). The spectrograph is cooled down to 80 K and thermally stabilized at a rms level of $\sim$2 mK; this thermal stability ensures in particular that the corresponding spectral drift at detector level is <0.70 m/s on timescales of 1 night. This drift can be monitored, and thus mostly corrected for, by recording the RV reference spectrum; in this case, the residual spectral drift at detector level reduces to <0.25 m/s.

2.1.4 The calibration and RV reference module

The calibration module and RV reference unit is used to provide the instrument with all the required laboratory lamps, and in particular halogen lamps (for flat fields, used to correct for the detector pixel-to-pixel sensitivity differences), hollow-cathode lamps (e.g., Th/U spectra, used to derive the pixel-to-wavelength calibration relation) and include an additional RV reference, in the form of a flat field lamp coupled to a Fabry-Perot (FP) etalon, thermally stabilized at a level of $\sim$10 mK rms to ensure that spectral lines do not drift by more than 0.25 m/s rms throughout one night. This thermalized FP unit (and possibly even the Th/U lamps) could be replaced in the future with a nIR tunable laser comb (stable to <0.10 m/s) to further improve the overall RV precision of the instrument.

2.2 The international project team

The SPIRou project team gathers a number of partners from different institutes and countries. More specifically, the team includes several institutes from France (IRAP and OMP in Toulouse, IPAG in Grenoble, OHP and LAM in Marseille, plus an extended science team from IAP / LESIA / CEA / LERMA / IAS / LUTH / LATMOS based in Paris and surroundings), from Canada (UdeM / UL in Montréal and Québec City, NRC in Victoria), from Switzerland (Geneva Observatory), from Taiwan (ASIAA in Taipei), from Brazil (LNA in Itajuba, plus additional science contribution from UFRN / UFMG in Natal and Belo Horizonte), from Portugal (CAUP in Porto) and from CFHT.

3 Main science goal #1 : exoplanets around very-low-mass stars

3.1 Scientific context

One of the 2 main goals of SPIRou is to search for, and to characterize, exo-Earths orbiting low-mass stars - with a particular interest for planets located in the habitable zone (HZ) of their host stars. The study of exoplanetary systems is one of the most exciting areas of astronomy today. Identifying habitable Earth-like planets and searching for biomarkers in their atmospheres is among the main objectives of this new century's astronomy, motivating ambitious space missions (e.g., JWST, TESS, CHEOPS, EChO, PLATO). Among the various techniques developed to detect exoplanets, two are very efficient and complementary. Whereas RV studies look for Doppler shifts induced by orbiting planets in the spectrum of their host stars, giving access to the planet mass, long-term photometric monitoring searches for regular occultations caused by planets transiting the visible stellar disc, yielding the planet radius. For exoplanets detected with both techniques, one can estimate their densities and thus constrain their bulk compositions. Provided host stars are bright enough, one can even probe the outer atmosphere of transiting planets using transit spectroscopy, opening the new research field of exoplanetology (Charbonneau et al. 2007).

In this context, much interest has recently been focused on low-mass M dwarfs, around which habitable super-Earths are much easier to detect. To be considered potentially habitable, planets must be within the proper range of orbital distances where liquid water can be stable on their surface. This constraint also imposes limits on the atmospheric pressure at the planet surface, and thus indirectly on the planet mass. The range of orbital distances for HZs also strongly depends on the mass (and thus on the temperature) of the host star, with lower temperatures moving HZs closer in. Habitable exo-Earths around M dwarfs are thus expected to produce much larger RV wobbles ($4\times$ to $8\times$ for M4 and M6 dwarfs, respectively) compared to the same planet orbiting a Sun-like star. A 1 m/s RV precision is sufficient to detect habitable telluric planets around M dwarfs - the much shorter orbital periods (of order of weeks) vastly decreasing the timescale over which observations must be collected; this is how the first likely- habitables super-Earths were discovered (Udry et al. 2007; Mayor et al. 2009; Delfosse et al. 2013; Bonfils et al. 2013b).

Photometric transits are also much deeper for M dwarfs as a result of their smaller radii - by $11\times$ and $45\times$ for M4 and M6 dwarfs, respectively. A prime goal of the coming years is to discover Earths or super-Earths whose atmosphere can be scrutinized and characterized with space missions (such as JWST and/or EChO) in the next decade. Since atmospheric characterization primarily requires as deep an atmospheric transit as possible on the one hand, and as bright a star as possible on the other hand (in the nIR, where absorption from atmospheric molecules mostly concentrates), M dwarfs are optimal targets for this quest (Rauer et al. 2011). Today, only a handful of very-bright transiting systems have been discovered up to now - most being giant gaseous planets - but many more are expected with forthcoming space missions like TESS or PLATO.

Last but not least, statistical properties of planets around M dwarfs (compared to those around Sun-like stars) can provide key information on planetary formation, and in particular on the sensitivity of planet formation to initial conditions in the protoplanetary disc (e.g., Ida & Lin 2005). That M dwarfs vastly dominate the stellar population in the solar neighborhood and are likely hosting most planets in our Galaxy only makes this study even more crucial.

3.2 The SPIRou planet search

Based on high-precision RV measurements, the SPIRou planet search we propose will greatly expand the current exploratory studies carried out with existing visible velocimeters (e.g., HARPS@ESO, SOPHIE@OHP) by giving access to a large sample of stars inaccessible with existing instrumentation. The SPIRou planet search will in particular build upon the success of the pioneering HARPS RV survey of M dwarfs (Bonfils et al. 2013a), which 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%; moreover, preliminary results suggest that about half of these super-Earths are located in the HZs of their host stars. With existing velocimeters such as HARPS, RV measurements with a precision of 1 m/s are possible for only the $\sim$100 brightest M dwarfs. This is clearly insufficient, either to have a realistic chance of detecting several transiting habitable super-Earths or to achieve a proper statistical survey of rocky exoplanets around M dwarfs. Given their low temperatures, red and brown dwarfs are much more accessible at nIR wavelengths (see Fig 2). In addition to a 1 m/s RV precision and a high throughput, SPIRou offers the widest simultaneous nIR spectral coverage (0.98-2.35 μm) yet available on any telescope, making it optimally suited for carrying out efficient, systematic RV exoplanet surveys of M dwarfs.

SPIRou will also crucially contribute to the forthcoming extensive photometric surveys of transiting planets around M dwarfs, either from space (e.g., TESS, CHEOPS, PLATO) or from the ground (e.g., ExTrA). Spectroscopy is indeed mandatory to discard false detections (e.g., background eclipsing binaries), to establish the planetary nature of all transiting objects detected around low-mass dwarfs through photometric monitoring and to measure their mass from RV measurements. A high-precision velocimeter working in the nIR will thus be essential to monitor all candidates detected with ground and space photometers around bright M dwarfs, and in particular around late-M ones, hardly accessible to velocimeters working in the visible. A nIR spectrograph will also usefully contribute to the quest for close-in transiting exo-Earths around bright M dwarfs through a systematic survey prior to any photometric observations.

More specifically, SPIRou will contribute to exoplanet science along 3 main avenues, that we foresee as the prime exoplanet themes of the SPIRou planet search.

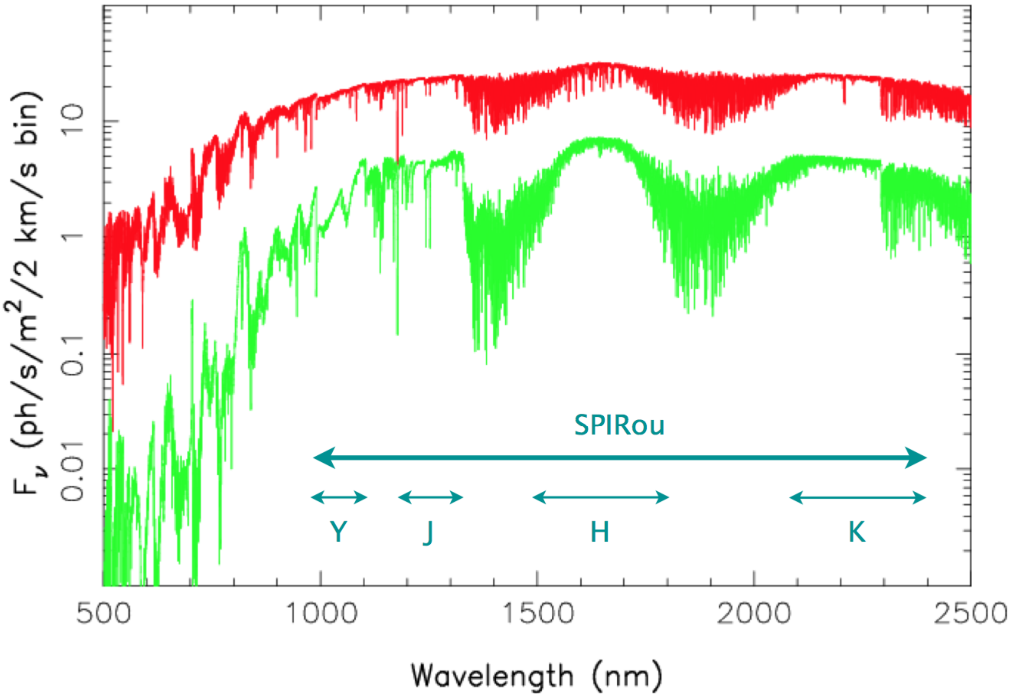

Fig. 2. Photon distribution (per 2 km/s velocity bin size) for a M6 (3,100 K, red) and M8 (2,300 K, green) dwarfs at 10 pc (derived from NextGen models (Allard et al. 1997). M6 and M8 dwarfs respectively produce ∼30 and ∼1000 times more photons (per velocity bin) in HK than in V.

3.2.1 Follow-up of transiting planet candidates uncovered by future photometric surveys

Among the 3,500+ planet candidates yet found by Kepler, only a few tens have been validated and characterized through RV measurements, the vast majority of candidates orbiting stars that are too faint for current RV surveys (see Santerne et al. 2013, for more details). The goal of future photometric surveys is to detect planet candidates around brighter stars, with a specific emphasis on nearby M dwarfs. Among them, the TESS space mission, to be launched in 2017 and predicted to detect ∼300 super-Earths, is certainly very promising. Since (i) most Earths and super-Earths detected with TESS will orbit around M dwarfs, and (ii) less than ∼30% of them will be accessible to optical RV follow-ups (Deming et al. 2009), SPIRou will be the best RV instrument to monitor in the nIR the ∼150 best candidates visible from CFHT, to confirm or reject their planetary nature and to determine their masses.

Monte Carlo simulation show that with ∼60 visits per star and with S/N∼160 spectra per visit SPIRou has the capacity to validate and characterize planets of Earth Mass, orbiting mid-M dwarfs with a period of ∼30 d. This observational effort requires a total of 150 CFHT nights.

3.2.2 RV survey of a large sample of M-dwarfs

As TESS will majoritarly operate on 27-d windows of continuous monitoring for most stars, the majority of planet candidates showing at least 2 transits will have periods <20 d and will not be located in the HZ of their host stars. For planets with longer periods, and in particular for those located in the HZ, RV-driven planet searches will be more efficient. Our Monte Carlo simulations demonstrate that (see Fig 3), with a survey focussing on ∼600 M dwarfs (requiring 600 CFHT nights for >60 visits per stars), SPIRou could potentially detect ∼450 new exoplanets, ∼300 being less massive than 5 $M_\oplus$; among the latter sample, ∼50 would be orbiting in the HZ and ∼15 would be transiting, while ∼2 would have both characteristics. This survey should allow to determine $\eta_\oplus$, the faction of habitable planets in the Solar neighborhood, with an accuracy of <10%. Photometric follow-ups of all planets detected with SPIRou will be achieved, e.g., with CHEOPS and ExTrA, to determine which ones are transiting, once their ephemeris and transit windows are well known. Identifying transiting habitable super Earths is crucial for all future attempts at detecting biomarkers in their atmospheres

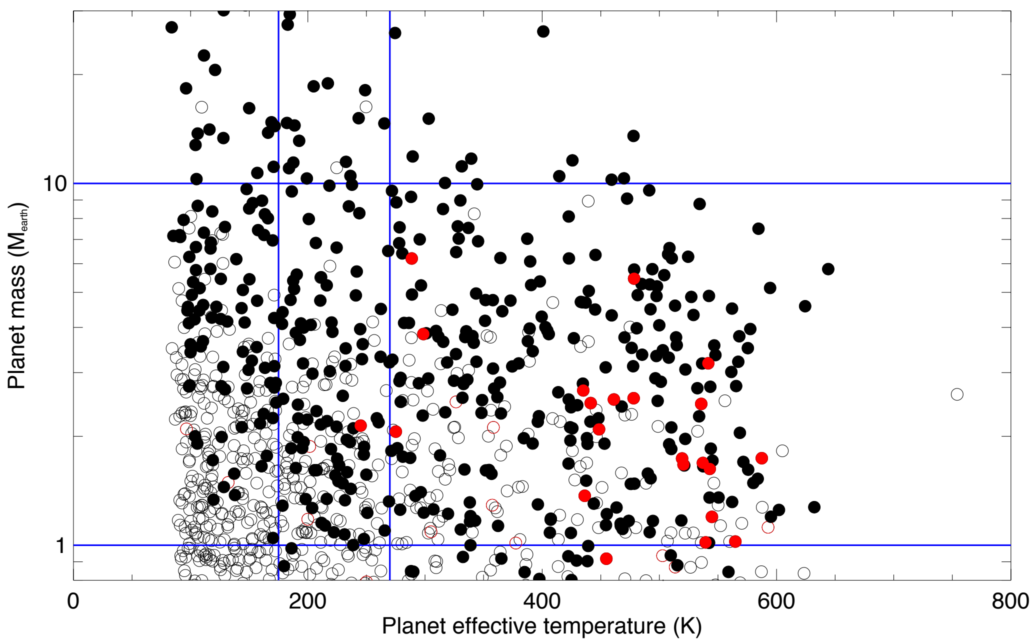

Fig. 3. Planets found with a 600-target survey according to our Monte Carlo simulation. Filled circled indicate detected planets, open circles undetected ones and red circles (both filled and open) represent transiting planets. Blue lines show notional limits for the habitable zone, both in mass and temperature. Most planets with >2 $M_\oplus$ in the habitable zone are detected, including one transiting. Interestingly, a sample of sub-$M_\oplus$ planets with T_{eq} >350 K is also detected.

with JWST or EChO.

3.2.3 Occurrence frequency of planets around M dwarfs

By expanding the sample by 10× (with respect to the existing optical surveys of M dwarfs) and thus by bringing a 3 fold improvement in the statistics of planet properties, the SPIRou observations outlined in the 2 first items of our planet search will provide much more reliable constraints on planet formation models. Moreover, by extending the RV monitoring on a selected sample of M dwarfs and on a larger time span, SPIRou will likely reveal additional bodies in most systems at larger period. This extended monitoring, not included in the first part of RV of our planet search, will be carried out on the ∼350 most interesting M dwarfs with detected planets / systems and will require an additional amount of 250 CFHT nights to achieve 40 more visits per star.

4 Main science goal #2 : magnetic fields and star / planet Formation

4.1 Scientific context

The other main goal of SPIRou is to explore the impact of magnetic fields on star and planet formation, by detecting and characterizing magnetic fields of various types of young stellar objects (e.g., classical T Tauri stars, embedded class-I protostars, young protostellar accretion discs). This quest will expand the pioneering surveys carried out in the framework of the study with optical spectropolarimeter, mainly ESPaDOnS@CFHT.

Studying how Sun-like stars and their planetary systems form comes as a logical addition to the direct observation of exoplanets. Within the last decades, this research field underwent major observational and theoretical advances, for instance by clarifying the crucial role of magnetic fields, not only on the gravitational collapse of giant molecular clouds (e.g., Hennebelle & Fromang 2008), but also on the formation of accretion discs and pre-stellar cores (e.g., Hennebelle & Teyssier 2008) from which stars and their planetary systems are born.

At an age of ∼1 Myr, low-mass protostars emerge from their dust cocoons, most often surrounded by a massive accretion disc in which planet form and migrate. This is the so-called "classical T Tauri" (cTTS or class-II protostar) stage - one of the best studied phase of stellar formation thanks to its relative accessibility to existing instruments. Observations suggest in particular that magnetic fields of cTTSs are strong enough (i) to disrupt the central regions of the surrounding accretion discs, thereby generating magnetospheric gaps at the heart of the discs, (ii) to guide the plasma from the discs to the stars along discrete magnetospheric accretion funnels, and (iii) to drastically slow-down their rotation rates by magnetically coupling stellar surfaces with the inner edges of the accretion discs (e.g., Bouvier et al. 2007).

Spectropolarimetric observations secured with ESPaDOnS@CFHT enabled to disclose, for a small sample of ∼15 cTTSs, the large-scale magnetic topologies that link low-mass protostars to their accretion discs, and to demonstrate that this topology strongly relates to the internal structure of the protostar, and thus to both its age and mass (e.g., Donati et al. 2010). When the protostar is young enough and has a low-enough mass to be fully-convective, its large-scale magnetic topology is dominated by a strong dipolar-like field roughly aligned with the stellar rotation axis - thereby providing a quantitative explanation of the physical star/disc coupling mechanism through which the protostar is strongly spun down (e.g., Zanni & Ferreira 2013). These observations are however still rather sparse as a result of the relative faintness of cTTSs (at optical wavelengths); moreover, younger class-I protostars (with ages <1 Myr), for which magnetic fields are expected to have an even bigger evolutionary impact, are still out of reach of existing instruments, their dust cocoon hiding them completely from view at optical wavelengths.

4.2 The SPIRou survey of magnetic protostars

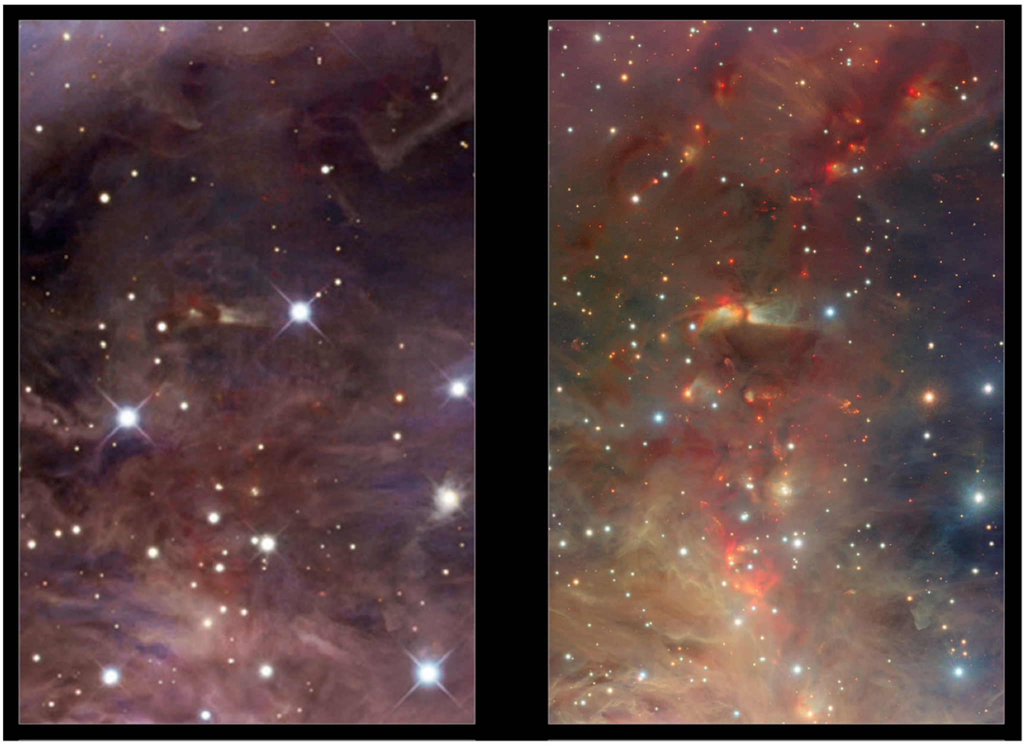

Fig. 4. The Orion nebula as seen in visible (left) and IR (right) light (ESO/VISTA). In the IR, dust cocoons around young stars are much more transparent.

With a much higher magnetic sensitivity than ESPaDOnS, thanks to both the increased nIR brightness of protostars (especially in K, see Fig 4) and the enhanced Zeeman effect at larger wavelengths, SPIRou will provide a much deeper and more systematic access to large-scale fields of class-I and -II protostars. More specifically, it will allow (i) to survey a 5-10× larger sample of cTTSs than the very limited one currently accessible with ESPaDOnS, and (ii) to extend for the first time this study to the brightest class-I protostars thanks to the K band coverage. The suggested SPIRou survey will ideally complement ALMA observations of pre-stellar (class-0) cores and of their magnetic fields, and will thus bring one of the key missing pieces in our understanding of star / planet formation.

SPIRou will also have the power to detect hot Jupiters orbiting around more-evolved class-III protostars (the so-called "weak-line T Tauri" stars or wTTSs) and thus to verify whether close-in giant planets are either much more or much less frequent around low-mass protostars than around mature, Gyr-old Sun-like stars. These observations will thus yield a direct observational test of the formation and migration of hot Jupiters, allowing to estimate the relative fraction produced through disc migration (acting during the formation stage) and that attributable to interactions / scattering (occurring much later). Finally, SPIRou will also be able to observe the innermost regions of protostellar accretion discs, out of reach of ALMA, to detect and characterize their magnetic fields and to identify the potential presence of migrating hot Jupiters (e.g., Donati et al. 2005; Powell et al. 2012).

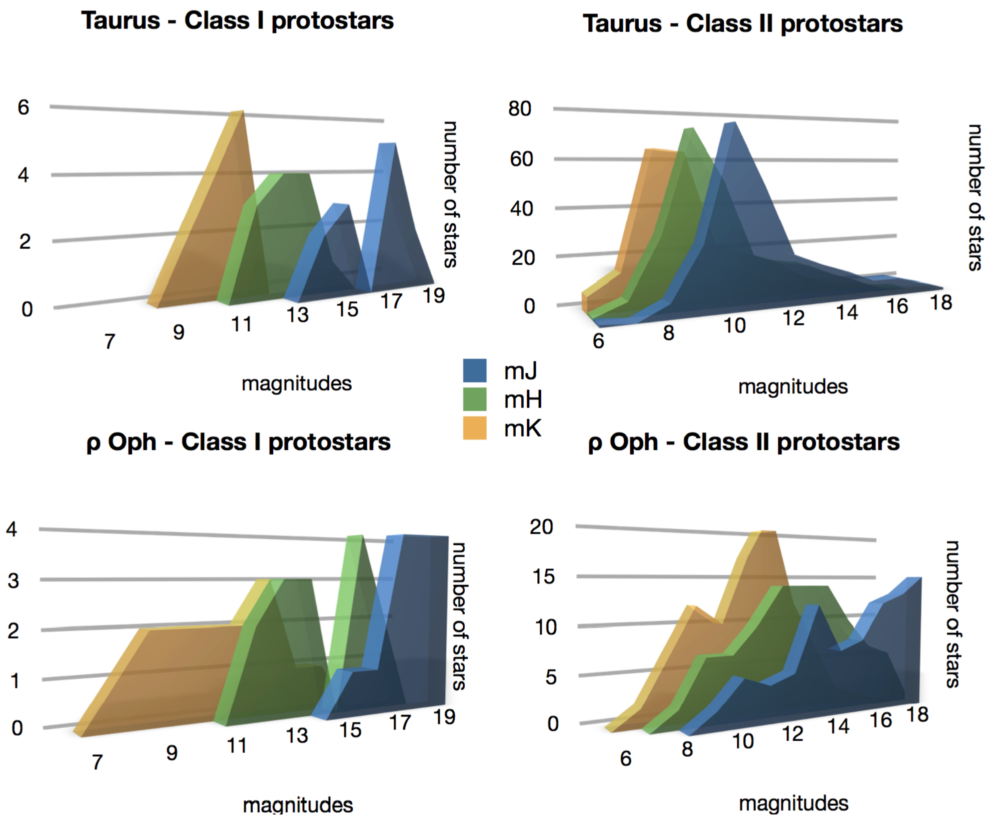

Fig. 5. JHK magnitude histograms of class-I (left) & -II (right) protostars in Taurus (up) and ρ Oph (bottom). Class-I protostars are mostly brighter than 12 in K only (as a result of obscuration, especially in ρ Oph), whereas a significant fraction of class-II protostars are accessible in all 3 bands.

With a survey carried out on 5 of the most accessible star forming regions (e.g., Taurus/Auriga, TW Hya Association, ρ Ophiuchius, Lupus, Orion Nebula Cluster; see Fig 5), SPIRou can detect for the first time the large-scale fields of ∼50 embedded class-I protostars, bringing yet unknown information on how magnetospheric accretion operates at so early a step in the formation process. In addition to this, SPIRou will be able to monitor ∼200 class-II and -III protostars (cTTSs and wTTSs), expanding the pioneering ESPaDOnS survey by 5-10× into full-scale surveys of magnetic protostars and their close-in giant planets. This survey will require a total of 250 CFHT nights; on top of this, monitoring a small sample of ∼10 protostellar accretion discs will require an additional 50 nights.

5 Additional science goals

In addition to the two main goals, SPIRou will be a very innovative and efficient instrument for tackling many more science themes. A few of them are briefly outlined below.

5.1 Large-scale dynamos of M-dwarfs

Using the spectropolarimetric data collected for the exoplanet survey of M dwarfs, SPIRou can also study the large-scale dynamo fields of fully convective dwarfs. These magnetic fields are indeed the main source of their activity and therefore a potential drawback for the habitability of their planets (Lecavelier des Etangs et al. 2012; Vidotto et al. 2013); studying dynamos of fully convective bodies can also be very informative on magnetic fields of Earth-like exoplanets (e.g., Christensen et al. 2009; Reiners & Christensen 2010) and usefully complement direct sensitive radio observations (e.g., LOFAR, Zarka 2010), with the ultimate aim of working out whether magnetic fields of exoplanets can improve their habitability.

Published studies of large-scale fields of fully-convective dwarfs have already demonstrated that these magnetic topologies are very sensitive to the aspect ratio of the convective zone and even suggest, for very-low mass dwarfs, a bistable behavior of the underlying dynamo processes potentially similar to that invoked for planetary dynamos (Morin et al. 2008, 2010, 2011). By comparing magnetic topologies of M dwarfs with theoretical predictions and results of numerical simulations, and by trying to generalize these results to planetary dynamos, one should ultimately be able to better understand the physical processes capable of amplifying and sustaining large-scale magnetic fields in both fully-convective dwarfs and planets (e.g., Schrinner et al. 2012). Using data from the exoplanet survey, SPIRou will provide a thorough census of magnetic topologies of M dwarfs (and in particular of fully-convective ones) that will usefully guide theorists towards more realistic, generalized dynamo models in better agreement with observations of both stellar and planetary large-scale fields.

5.2 Studies of planetary atmospheres

SPIRou can also very efficiently contribute to atmospheric studies of telluric or giant planets, whether or not they belong to the solar system.

In the case of the solar system, SPIRou will be able to carry out spatially-resolved, detailed spectroscopic studies of the chemical composition (at both low and high altitudes), of the wind dynamics and of the auroral emission of planetary atmospheres. These studies will allow in particular to better understand the complex interactions between atmospheric volatiles, planetary interiors, surfaces and climates (e.g., Bézard et al. 2009); they can also accurately estimate wind velocities at different atmospheric locations and altitudes, as well as their temporal variability (e.g., Widemann et al. 2008). Finally, auroral emission (and polarization) can inform on potential links between planetary atmospheres and magnetospheres. Thanks to its wide spectral domain (including the K band), to its high RV precision and to its spectropolarimetric capabilities, SPIRou will be able to very significantly contribute to chemical and dynamical studies of solar-system planet atmospheres.

Exoplanet atmospheres are obviously much more elusive and tricky to detect and to characterize. In the particular case of transiting exoplanets, atmospheres can be scrutinized either by transmission during a planetary transit, or by occultation during a planetary eclipse. For close-in planets (and in particular hot Jupiters), it could be possible to detect from the ground the spectral contribution of the star-lit side of the planet, by monitoring the Doppler shift (induced by the planet orbital motion) of specific atmospheric species (e.g., CO, Snellen et al. 2010). SPIRou will thus be able to contribute to this quest in a original way, thanks to its wide spectral domain and to the K band in particular (that includes a number of key atmospheric markers).

5.3 Weather patterns of brown dwarfs

Studying the atmospheres of ultra-cool L and T brown dwarfs (BDs) is yet another obvious research field for SPIRou. Despite huge modeling efforts invested since the discovery of BDs, many questions remain open - likely related to the complex physics of BDs atmospheres and in particular to mechanisms of dust clearing through specific weather patterns occurring in their atmospheres (e.g., Radigan et al. 2012). The disc-averaged spectral energy distribution (SED) of ultra-cool BDs may indeed not be representative of any single region, and thus cannot be modeled using a unique set of physical parameters (e.g., temperature, dust-settling, grain properties). Evidence that this is likely the case comes from the fact that ultra-cool BDs often exhibit photometric variability at a level of a few % up to a remarkable 25% (Artigau et al. 2009). This variability is apparently due to a combination of rotational modulation and intrinsic evolution on short timescales, likely caused by weather-like clearings in the dust- cloud deck (e.g., Littlefair et al. 2006). Unravelling the physics of these weather patterns and distinguishing between the several theoretical scenarios requires observations capable of localizing the dust clouds in BD atmospheres and following their rapid evolution with time.

Doppler imaging through high-resolution nIR spectroscopy is a very attractive and viable approach to map weather patterns of BDs; most BDs are indeed rapid rotators and often exhibit rotational modulation, both photometrically and spectroscopically, providing ideal conditions for Doppler imaging. Though not yet applied to stars cooler than mid-M due to their intrinsic faintness at optical wavelengths, Doppler imaging of BDs in the nIR is perfectly feasible with SPIRou, opening a new window for studying chemical inhomogeneities in their atmospheres. SPIRou will be able to monitor $\sim$10 L and T BDs among the best suited for this experiment, for a total amount of 30 nights.

6 The SPIRou Legacy Survey

The amount of observing time required to complete the two main science goal is large (1300 nights). In this context, SPIRou only makes sense if coupled to a SPIRou Legacy Survey of 500 CFHT nights on a timescale of $\sim$5 yr focussed mostly on both main science goals. The current plan is to divide the SPIRou Legacy Survey into three main components, two of them being dedicated to exoplanets around M dwarfs, while one will be concentrating on large-scale magnetic fields and young hot Jupiters of class-I-III protostars.

7 Calendar

SPIRou has successfully passed the preliminary design phase (PDR) in October 2012 and is now in the final design phase. Provided SPIRou is selected by CFHT and succeeds the upcoming final design review (FDR), it should be installed on the 3.6-m CFH telescope in early 2017 after the following phases :

- early 2014: design validation (FDR)
- 2014-2015: construction and acceptance tests of all individual SPIRou subsystems
- 2016: instrument integration and acceptance tests at IRAP
- 2017: installation at CFHT, first light, technical commissioning and science verification

We further stress that, with this schedule, SPIRou is ideally phased with the predicted launch times of both TESS and CHEOPS (2017) as well as that of JWST (2018).

References

Allard, F., Hauschildt, P. H., Alexander, D. R., & Starrfield, S. 1997, ARA&A, 35, 137

Artigau, É., Bouchard, S., Doyon, R., & Lafrenière, D. 2009, ApJ, 701, 1534

Bézard, B., Tsang, C. C. C., Carlson, R. W., et al. 2009, Journal of Geophysical Research (Planets), 114, 0

Bonfils, X., Delfosse, X., Udry, S., et al. 2013a, A&A, 549, A109

Bonfils, X., Lo Curto, G., Correia, A. C. M., et al. 2013b, A&A, 556, A110

Bouchy, F., Díaz, R. F., Hébrard, G., et al. 2013, A&A, 549, A49

Bouchy, F. & Sophie Team. 2006, in Tenth Anniversary of 51 Peg-b: Status of and prospects for hot Jupiter studies, ed. L. Arnold, F. Bouchy, & C. Moutou, 319–325

Bouvier, J., Alencar, S. H. P., Harries, T. J., Johns-Krull, C. M., & Romanova, M. M. 2007, Protostars and Planets V, 479

Charbonneau, D., Brown, T. M., Burrows, A., & Laughlin, G. 2007, Protostars and Planets V, 701

Christensen, U. R., Holzwarth, V., & Reiners, A. 2009, Nature, 457, 167

Delfosse, X., Bonfils, X., Forveille, T., et al. 2013, A&A, 553, A8

Deming, D., Seager, S., Winn, J., et al. 2009, PASP, 121, 952

Donati, J.-F. 2003, in Astronomical Society of the Pacific Conference Series, Vol. 307, Solar Polarization, ed. J. Trujillo-Bueno & J. Sanchez Almeida, 41

Donati, J.-F., Paletou, F., Bouvier, J., & Ferreira, J. 2005, Nature, 438, 466

Donati, J.-F., Skelly, M. B., Bouvier, J., et al. 2010, MNRAS, 409, 1347

Hennebelle, P. & Fromang, S. 2008, A&A, 477, 9

Hennebelle, P. & Teyssier, R. 2008, A&A, 477, 25

Ida, S. & Lin, D. N. C. 2005, ApJ, 626, 1045

Lecavelier des Etangs, A., Bourrier, V., Wheatley, P. J., et al. 2012, A&A, 543, L4
Littlefair, S. P., Dhillon, V. S., Marsh, T. R., Shahbaz, T., & Martín, E. L. 2006, MNRAS, 370, 1208
Mayor, M., Bonfils, X., Forveille, T., et al. 2009, A&A, 507, 487
Mayor, M., Pepe, F., Queloz, D., et al. 2003, The Messenger, 114, 20
Morin, J., Donati, J.-F., Petit, P., et al. 2008, MNRAS, 390, 567
Morin, J., Donati, J.-F., Petit, P., et al. 2010, MNRAS, 407, 2269
Morin, J., Dormy, E., Schrinner, M., & Donati, J.-F. 2011, MNRAS, 418, L133
Powell, S. L., Irwin, M., Bouvier, J., & Clarke, C. J. 2012, MNRAS, 426, 3315
Radigan, J., Jayawardhana, R., Lafrenière, D., et al. 2012, ApJ, 750, 105
Rauer, H., Gebauer, S., Paris, P. V., et al. 2011, A&A, 529, A8
Reiners, A. & Christensen, U. R. 2010, A&A, 522, A13
Santerne, A., Donati, J. F., Doyon, R., et al. 2013, These Proceedings
Schrinner, M., Petitdemange, L., & Dormy, E. 2012, ApJ, 752, 121
Snellen, I. A. G., de Kok, R. J., de Mooij, E. J. W., & Albrecht, S. 2010, Nature, 465, 1049
Udry, S., Bonfils, X., Delfosse, X., et al. 2007, A&A, 469, L43
Vidotto, A. A., Jardine, M., Morin, J., et al. 2013, A&A, 557, A67
Widemann, T., Lellouch, E., & Donati, J.-F. 2008, Planet. Space Sci., 56, 1320
Zanni, C. & Ferreira, J. 2013, A&A, 550, A99
Zarka, P. 2010, in Astronomical Society of the Pacific Conference Series, Vol. 430, Pathways Towards Habitable Planets, ed. V. Coudé du Foresto, D. M. Gelino, & I. Ribas, 175