# CFHT [2013A - 2016B] Large Programs

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| **Title** | **MaTYSSE : Magnetic Topologies of Young Stars & the Survival of close-in massive Exoplanets** |
| **Abstract** | MaTYSSE is a large program addressing major unsolved issues regarding the formation of Sun-like stars and their planetary systems, and in particular about the strong impact of magnetic fields on these initial steps so critical for our understanding of the early life of a star like our Sun.<br>More specifically, MaTYSSE aims at studying the **large-scale magnetic topologies of a sample of low-mass protostars** that have mostly dissipated their accretion disc already (called weak-line T Tauri stars / wTTSs or transitional T Tauri stars / tTTSs) to investigate **how different they are from those of protostars that are still surrounded by their accretion discs** (called classical T Tauri stars / cTTSs), **and from those of mature main-sequence stars**; being the missing link in our knowledge of magnetic topologies of low-mass stars, tTTSs/wTTSs should reveal the kind of magnetospheres with which Sun-like stars initiate their unleashed spin-up as they contract towards the main-sequence. Through this survey, MaTYSSE will also be able to assess **whether close-in giant planets** (called hot Jupiters / hJs) **are significantly more frequent around low-mass protostars than around mature stars** and **whether magnetospheric gaps can explain the survival of hJs around Sun-like stars**. MaTYSSE also aims at monitoring a few selected cTTSs to **document the long-term variation of their magnetic large-scale topologies** and **investigate how these variations are likely to affect magnetospheric gaps and the survival of hJs**.<br>By coupling together studies of magnetic fields of protostars and searches for young exoplanets, MaTYSSE should also ensure that scientists from the CFHT community are well prepared for exploiting SPIRou when the instrument comes on-line. MaTYSSE will also contribute to the MagIcS spectropolarimetric LEGACY survey. |
| **PI Name** | JF Donati |
| **PI Institute** | IRAP / Observatoire Midi-Pyrenees, 31400 Toulouse France |
| **Co-Is (Name, Institute)**<br><br>(obs / theory) | **France**: F Ménard, C Dougados, J Bouvier, J Ferreira, X Delfosse, X Bonfils, T Forveille (IPAG, Grenoble), L Jouve, C Baruteau (IRAP, Toulouse), G Chabrier (ENS, Lyon), S Brun, S Matt, N Bessolaz (CEA, Saclay), C Moutou, G Hébrard (Pytheas, Marseille), A Morbidelli, A Crida (OCA, Nice)<br><br>**Canada**: R Doyon, E Artigau, D Lafreniere (UdM, Montreal), D Bohlender, C Marois (HIA, Victoria)<br><br>**Brazil**: SHP Alencar, G Franco (UFMG, Belo Horizonte), J Gregorio-Hetem (Sao Paulo)<br><br>**Taiwan**: H Takami, SY Wang, H Shang (ASIAA, Taipei), SP Lai (NTHU, Hsinchu)<br><br>**China**: G Herczeg (NAO, Beijing), SH Gu (NAO, Kunming)<br><br>**Other**: SG Gregory, L Rebull, L Hillenbrand (Caltech, USA), J Morin (Göttingen, Germany), G Hussain (ESO, Germany), M Jardine, A Vidotto, R Fares, A Cameron (StAndrews, UK), K Rice (Edinburgh, UK), M Romanova (Cornell, USA), I Baraffe, M Browning (Exeter, UK), S Mohanty, Y Unruh (Imperial, UK), K Grankin (CAO, Ukraine), A Dupree, N Brickhouse (CfA, USA), C Argiroffi, E Flaccomio (Palermo, Italy), F Pepe, F Bouchy, C Lovis (Geneve, Suisse), P Figueira, I Boisse (CAUP, Portugal)<br><br>MaTYSSE will be open to all (remaining) members of the SPIRou science team interested in joining. |

**Total** number of **hours** requested : **510**

| **Hours per agency:** | **France: 270** | **Canada: 110** | **Brazil: 60** | **Taiwan: 40** | **China: 30** | **Hawaii: 0** |
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| **Hours per semester :** | 13A: 50 | 13B: 94 | 14A: 30 | 14B: 76 | 15A: 52 | 15B: 96 | 16A: 40 | 16B: 72 |
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| **Proprietary period for participating community access is zero by *default* (free immediate access).**<br>**If you want this proprietary period to be set to a specific time, provide below the time period and justify it in the proposal.** |
|---|
| 0 yr |
| **Proprietary period for World Access is by default one year after the end of each semester for the duration of the survey.**<br>**If you want this proprietary period to be changed, provide below a data release schedule and justify it in your proposal.** |
| 1 yr |

## 2. Science Justification (5 pages)

### A. General context and open questions

Magnetic fields are known to play a significant role throughout the life of low-mass stars, from the cradle to the grave (eg Donati & Landstreet 2009 for a recent review on this topic); for instance, they are very efficient at spinning down young Sun-like stars by dissipating a large amount of angular momentum through magnetic braking, via mass loss in large-scale field topologies (winds, coronal mass ejection). Yet, **magnetic fields have an even bigger impact during the early phases of stellar evolution**, when stars and their planetary systems form from collapsing parsec-sized molecular clouds, progressively flattening into large-scale magnetized accretion discs and finally settling as protostars surrounded by protoplanetary discs. Throughout this formation process, magnetic fields have a critical role in many different steps, eg by dissipating the excess angular momentum and mass (through magnetic braking, winds & jets) and by drastically scaling up the amount of turbulence (through various instabilities, eg MRI) and inhibiting the fragmentation process within the disc (see, eg, André et al 2009 for a review).

At a typical age of 1-10 Myr, low-mass protostars have emerged from their surrounding dust cocoons (enough to be visible at optical wavelengths) and are still in a phase of gravitational contraction towards the main-sequence (MS). They are either **classical T Tauri stars** (cTTSs) when still surrounded by a massive (and presumably planet-forming) accretion disc or **weak-line T Tauri stars** (wTTSs) when their disc has mostly dissipated; they can also be caught in the short intermediate stage between cTTS & wTTS, hence **called transitional TTSs** (tTTs, eg Cieza et al 2010), with optically thin inner discs and optically thick outer discs. Yet, ages of cTTSs, tTTSs and wTTSs are not statistically very different, these populations mostly reflecting differences in the lifetime of their accretion discs. TTSs have been the subject of intense scrutiny at all wavelengths in the last few decades given their obvious interest for benchmarking the scenarios currently invoked to explain low-mass star and planet formation (eg Bouvier et al 2007 for a review).

**Magnetic fields of TTSs also play a key role in the formation process**. In particular, large-scale fields of cTTSs are strong enough to evacuate the central regions of the accretion disc, to funnel the disc material from the inner disc rim onto the stellar surface, and even to enforce corotation between the protostar and the Keplerian flow just outside of the magnetosphere, forcing cTTSs to rotate much slower than expected from the cloud contraction. Magnetic fields of TTSs are also crucial to generate a hot corona and thus to boost the leakage of angular momentum (through magnetized winds and coronal mass ejections) that will eventually slow down the star within the first few 100 Myrs of its MS life. Last but not least, magnetospheric gaps and winds of cTTSs may also be vital for the survival of hot Jupiters (hJs), stopping their inward migration within the accretion disc at distances of ~0.05 AU (typical to hJs and compatible with observed magnetospheric gaps of cTTSs) avoiding their falling into their host star (eg Lin et al 1996).

Although first detected about 2 decades ago (eg Johns-Krull 2007 for an overview), magnetic fields of TTSs remained elusive for a long time; more specifically, the large-scale magnetic topologies of cTTSs were unclear until recently revealed thanks to the MaPP Large Program (LP) carried out with ESPaDOnS @ CFHT between semesters 2008b and 2012b onto a sample of about 15 cTTSs. **This first survey revealed in particular that the magnetic topologies of cTTSs are usually significantly more complex than pure dipoles** and include a significant (and sometimes often dominant) octupolar component, depending mostly on the internal structure of the protostar (and in particular the existence of a radiative core and its relative size, see Fig 1); it also demonstrated that these large-scale fields are similar to those of mature stars of similar internal structure (Gregory et al 2012) and are variable on timescales of a few yrs (Donati et al 2011, 2012), strongly suggesting that they are of dynamo origin. These new results also stimulated more realistic models of magnetospheric accretion (eg Romanova et al 2011).

However, a number of hot questions remain unsolved. The 3 main issues on which we propose to focus this new LP are as follows:

- **are large-scale magnetic fields of tTTSs/wTTSs similar to those of cTTSs?** In particular, are the magnetic topologies of cTTSs typical initial magnetic conditions of tTTSs/wTTSs as they start their unleashed acceleration towards the MS, as a combined result of the radius contraction and of the vanishing magnetic brake from the disc (mostly dissipated at the tTTSs/wTTS stage)? Or are they significantly different, eg as a result of accretion and of the star/disc coupling torque modifying dynamo processes in accreting stars and consequently the large-scale field topology? This is essential information for consistently explaining the rotational history of low-mass stars once on the MS, usually invoking magnetic braking as the main cause of their later spin down;

- **is disc migration the main process for producing hJs and are magnetospheric gaps & winds key factors for their survival?** If this is the case, one can expect to find at least as many hJs in TTSs than in mature stars, and possibly significantly more if we account for all those that did not resist the subsequent tidal-induced forces from the disc-less protostar over the whole contraction phase. Although technically very difficult for cTTSs (given their very high level of intrinsic accretion-induced variability), detecting hJs is potentially feasible for tTTSs/wTTSs whose spectral variability (mostly due to magnetic activity) is much easier to model and thus subtract from radial velocity (RV) curves; detecting even one single hJ around a TTS would be a major observational step forward for our understanding of the formation / migration of hJs;
- **by how much do magnetospheric gaps & winds vary with time** as a result of the non-stationary dynamos operating in cTTSs? Magnetospheric gaps / winds are expected to vary in size / strength with time, reflecting changes in the large-scale magnetic topologies of cTTSs on timescales of a few yr. By monitoring selected cTTSs (those that already showed time-variable large-scale fields in particular) over the whole LP, we can work out how variable magnetospheric gaps / winds are and whether this variability is compatible with the survival of hJs.

**We thus propose a new LP, called MaTYSSE** (for Magnetic Topologies of Young Stars & the Survival of close-in massive Exoplanets), **to address these major unsolved issues** through a detailed survey of ~40 wTTSs/tTTSs as well as a regular monitoring of ~5 cTTSs.

## B. Specific goals of MaTYSSE

MaTYSSE will thus concentrate on the 3 hot questions mentioned above & detailed below, on which we aim at providing clear answers by the completion of the LP.

### (a) Large-scale magnetic topologies of wTTSs/tTTSs

We plan to investigate the large-scale magnetic topologies of wTTSs/tTTSs in the same way as those of M dwarfs (eg Morin et al 2008, 2010, Donati et al 2008) and cTTSs (eg Donati et al 2010, 2011, 2012). More specifically, we will **observe ~40 wTTSs/tTTSs with different masses** (bracketing the mass of the Sun), **ages and rotation periods**, in order to produce 3 different Fig 1-like diagrams (with 10-15 points each) respectively corresponding to rotation rate bins of <2d, 2-5d & >5d; this will give us the opportunity not only to investigate how magnetic topologies change with mass & age (as in Fig 1), but also to find out whether they depend on rotation rate. For each target, we will collect ~16 circularly polarized & unpolarized spectra across the rotation cycle and derive from these data **images of the surface brightness distributions & large-scale magnetic topologies**. To achieve this goal, we will be using the latest version of Zeeman-Doppler imaging (ZDI, eg Donati et al 2006, 2010), where magnetic fields are decomposed into their elementary poloidal and toroidal components, each being described using spherical harmonics decomposition, which proved very successful at recovering the large-scale properties of magnetic topologies of MS and pre-main-sequence (PMS) low-mass stars. Only 1 wTTS (namely V410 Tau, Skelly et al 2010) has been studied in such a way up to now (at 2 different epochs), but this first example clearly demonstrates that the proposed program is straightforwardly feasible (see Fig 2).

In a second step, we will examine **how the large-scale field properties of these protostars** (and in particular the intensity of the large-scale field, the relative fraction of magnetic energy stored into the poloidal component, and the degree of axisymmetry of the poloidal component, see Fig 1, see also Fig 3 in Donati & Landstreet 2009) **vary with mass, age and rotation period**. (Specifically for this task, we developed an automatic spectral classification tool that can accurately estimate the effective temperature and surface gravity from the observed spectra, to ensure that all of our surveyed targets are properly located in the HR diagram.) Up to now, these parameters have shown to closely reflect changes in the internal structure of low-mass stars (be it MS or PMS); stars with relative convective depths larger than about 50% (in radius) are apparently capable of triggering strong, mainly poloidal and axisymmetric magnetic fields, whereas stars with shallower convective zones exhibit more complex fields (with a significant toroidal component and a moderate, mostly non-axisymmetric poloidal component). In cTTSs, fully convective stars are observed to host mainly aligned dipolar fields while dominantly (but non-fully) convective ones all harbor mainly aligned (and time variable) octupolar fields (see Fig 1). In addition to suggesting an obvious observational way of testing theoretical models of the internal structure and evolution of PMS low-mass stars (eg Gregory et al 2012), these results demonstrate that **magnetic fields of PMS stars are produced by non-stationary dynamo processes** (similar to those of MS stars) rather than being fossil remnants of the interstellar field; they provide a direct method for observing astrophysical dynamos in a much more general context than that of the Sun or the Earth, and should ultimately guide us towards modern dynamo theories applicable to a wide range of astrophysical objects (from planets to stars, eg Christensen et al 2009, Morin et al 2011).

The survey of wTTSs/tTTSs we propose should bridge an obvious gap between what we already know about the large-scale fields of accreting cTTSs (from MaPP) and those of MS low-mass stars; wTTSs/tTTSs are indeed the missing link between these two stellar populations, and our survey should thus clarify **what are the typical large-scale magnetic topologies with which protostars of different masses begin their complex rotation history towards MS and later**. We will also be able to work out whether accretion processes and star/disc coupling torques can significantly impact dynamos and consequently large-scale field topologies of protostars (and in particular their toroidal components), eg by comparing Fig 1-like diagrams derived for cTTSs (MaPP) and wTTSs/tTTSs (this survey); the first results obtained on V410 Tau suggest that the **magnetic topologies of wTTSs may indeed significantly differ from that those of cTTSs** (see Fig 2). This definitely requires confirmation with an observational survey of a sample of wTTSs/tTTSs like the one we propose here.

### (b) Looking for hot Jupiters around wTTSs/tTTSs

Our survey of wTTSs/tTTSs can also be used to attempt detecting hJs around stars younger than 10 Myr. Since their initial discovery ~15 yrs ago, hJs are a real challenge to theorists on planet formation and are thus very interesting despite their relative sparseness. Obviously, hJs cannot be formed in situ given the limited & hot disc material at so short distances from the host star (eg Lin et al 1996). The most plausible scenario to explain hJs is thus that they form much further out in the protoplanetary disc and migrate inwards, either under the non-zero gravitational torque from the accretion disc (Goldreich & Tremaine 1980, Alibert et al 2005) or through planet-planet interaction / scattering (eg Rasio & Ford 1996, Eggenberger et al 2004). While the second scenario may explain the (small) fraction of hJs with highly inclined orbits, **disc migration remains the most likely option for the majority of hJs**; in this case, both the formation & migration processes must occur on a timescale significantly shorter than the lifetime of the disc (ie 5-10 Myr) to allow hJs to end up so close to their host star. Moreover, hJs (at least a fraction of them) can survive the migration, stop at a distance of ~0.05 AU and avoid falling into their host star; having typical radii of 0.1 AU, **magnetospheric gaps may be the most natural way to achieve this** (Lin et al 1996, Romanova & Lovelace 2006, see also Fig 3, Rice et al 2008). If this is confirmed, it would imply that magnetic fields of low-mass protostars are the key parameter of this survival.

We propose to investigate this idea by looking, among our wTTS/tTTS survey, for periodic RV changes that may reveal the presence of hJs (producing typical peak-to-peak RV amplitudes of 0.1-1 km/s on periods of a few d). This is non-trivial given the high level of activity that wTTSs/tTTSs are subject to, generating RV changes comparable to or even larger than those induced by the reflex motion of potential hJs; however, by accurately modeling the activity of wTTSs with the imaging methods indicated above (see above, see also Queloz et al 2009, Boisse et al 2011 for alternate methods), one can succeed at **filtering most of the activity-induced RV changes down to the level at which hJs should become detectable**. In particular, this technique should be much more successful on wTTSs/tTTSs than on cTTSs, as their intrinsic variability (drastically limiting the power of filtering techniques, mostly efficient at removing the rotationally modulated component of the activity) is significantly lower.

On extremely active stars with rotation periods < 2d (like the young Sun AB Dor or the wTTS V410 Tau, whose unfiltered RV curves reach peak-to-peak amplitudes of several km/s), this method yields rms RV residuals of ~100 m/s, ie a factor of ~20 smaller than the original peak-to-peak RV fluctuations; on less active stars (eg the young M2 dwarf GJ 182, whose unfiltered RV curve reaches peak-to-peak amplitudes of ~400 m/s, see also Morin et al 2008), the rms RV residual we obtain after activity filtering is ~30 m/s (ie the RV precision of ESPaDOnS). **We can thus realistically assume that RV precisions of ~30 m/s can be obtained for most of our wTTSs/tTTSs** (ie w/ rotation periods of 2-5d & >5d), around which we should be able to detect hJs; for our most active wTTSs/tTTSs (with rotation periods <2d), only massive (tauBooB-like) hJs will be detectable. **Our strategy will consist in flagging the few targets whose residual RV dispersion** (once activity is filtered) **exceeds 50 m/s, and in re-observing them at 16 more epochs** (~32 altogether) **to firmly establish the planetary nature of the RV variations**, work out the period on which they occur and derive the properties of the corresponding hJ. Additional observations on these candidates will also be collected with companion high-precision velocimeters (eg SOPHIE @ Observatoire de Haute Provence and/or HARPS @ ESO).

The predicted number of hJs orbiting wTTSs/tTTSs is unclear as of today. Since slightly less than 1% of mature Solar-like stars host hJs (eg Mayor et al 2012, the exact frequency likely depending both on mass & metallicity), one can expect that wTTSs/tTTSs should also host hJs with at least the same frequency if these hJs are generated through disc migration; if we further account for all hJs that did not survive the stages following formation, eg as a result of the strong tidal forces from the host protostar as it contracts towards the MS, one may argue that hJs should actually be far more numerous around cTTSs and wTTSs than around MS low-mass stars. If the fraction of hJs around wTTSs/tTTSs reaches up to ~5%, we may expect to find ~2 of them in our sample of ~40; **detecting even 1 such hJ would yield the most stringent upper limit to date on the frequency of hJs around wTTSs/tTTSs and would bring the first observational confirmation that disc migration is the main mechanism for generating hJs.** By itself, this result would represent a major observational achievement and would be a significant step forward in our understanding of how hJs form.

### (c) Secular changes in the magnetospheric gaps & winds of cTTSs

We also propose to carry-out a magnetic monitoring of a few cTTSs to investigate on a longer timescale the changes in their large-scale magnetic fields, and work out from this the expected changes in their magnetospheric gaps. In particular, for demonstrating that magnetospheric gaps can indeed save hJs from falling into their host star, one needs to firmly establish that **the large-scale magnetic dipole** (ie the key parameter ensuring disruption in the central regions of the accretion disc, see Fig 3) **remains strong enough at all times**, or at least over a time long enough to ensure that inward migration is in average too slow or too episodic to have fatal consequences on the fate of potential hJs.

Previous observations obtained within MaPP demonstrated already that large-scale fields of cTTSs are strongly variable with time, with the dipole or octupole components varying by a factor of ~2 on timescales as short as a few years (eg Donati et al 2011, 2012), establishing at the same time that large-scale fields of cTTSs are generated through non-stationary dynamos. The long-term variation of the dynamo fields of cTTSs is however still unclear. Are such dynamos cyclic, with the large-scale dipole component regularly switching sign every half-cycle like that of the Sun (every 11 yr) or that of the few other stars in which magnetic cycles have been detected (eg tauBoo, whose large-scale field flips polarity every single yr, Fares et al 2009)? In such a case, accretion onto cTTSs, and hence the size of their magnetospheric gaps, would fluctuate across magnetic cycles (eg Clarke et al 1995). For instance, the large-scale dipole could vanish for a while before being replaced by a copy of opposite polarity; as a result, the disc would respond by filling in most of the magnetospheric gap (with only higher orders of the magnetic expansion, eg the octupole, achieving disc disruption, albeit over a much smaller radius). **What would happen to hJs potentially present in the magnetospheric gap as the large-scale dipole reverses?** Similarly, what would happen if dynamos of cTTSs were chaotic rather than cyclic? And how does the changing stellar wind impact the migration (eg Lovelace et al 2008, Vidotto et al 2009, 2010)?

The answers to these questions likely depend again on the internal structure of the protostar, ie on its mass. For low-mass protostars, expected to undergo key structural changes (and in particular the step from fully convective to largely convective, and that from largely convective to largely radiative, respectively occurring at ~2.5 Myr and 10 Myr for a 1.0 $M_\odot$ star, see Fig 2) and therefore to operate the corresponding magnetic topological changes within the lifetime of the disc, one can wonder **whether magnetospheric gaps & winds can still prevent hJs from falling into their host protostars**. For answering these questions in a quantitative way, **we propose to carry out a regular magnetic monitoring of a few cTTSs of different masses and ages**, in particular those on which temporal variations of the large-scale field have been detected already (namely the partly radiative cTTSs V2129 Oph and GQ Lup, see Fig 1). We propose to include as well the fully convective cTTSs AA Tau (particularly well studied & prototypical) and BP Tau (on which very recent MaPP data from 2012 January indicate that the field is also varying on a similar timescale) as well as the partly convective cTTS TW Hya (sampling low masses at a more advanced stage of evolution) to our sample. By doing so, and coupling the new data with the existing MaPP data, we will **extend up to ~1 decade the timescale on which these cTTSs have been monitored spectropolarimetrically**, making it comparable to that of the solar cycle.

We will also complement this observational program by **numerical simulations of planet migration within magnetospheric gaps of cTTS**; in particular, we will focus on how the varying large-scale field can impact the size of the magnetosphere, and how the varying magnetospheric gap will affect the survival of hJs. We will also study, from a theoretical point of view, **the impact of magnetic winds of cTTSs and wTTSs** (as derived from the observed magnetic topologies, eg Vidotto et al 2011) **on the migration and the survival of hot Jupiters** (eg following Lovelace et al 2008, Vidotto et al 2009, 2010).

## C. Surveying wTTSs/tTTSs and monitoring selected cTTSs

To achieve the above listed science goals, we propose to carry out (a) **the first spectropolarimetric survey of ~40 wTTSs/tTTSs** and (b) a **regular monitoring of ~5 cTTSs**.

### a) the wTTS survey & cTTS monitoring

This survey will be carried out mostly at CFHT, with ~20 wTTSs/tTTSs to be observed with ESPaDOnS; we will complete the survey by using NARVAL on the 2m Telescope Bernard Lyot (TBL) for the ~10 northern brightest stars, and HARPS-Pol on the ESO 3.6m (whose sensitivity is comparable to NARVAL@TBL) for the ~10 southern brightest stars. Targets for this survey are selected mostly from the published literature, keeping only those with well determined spectral types and rotation periods, and sampling as evenly as possible masses, ages and rotation rates (see Sec 3). With a typical monitoring of 16 visits per star (to densely cover the rotation cycle), **the complete survey of 20 stars requires a total of 370 hr @ CFHT** (see Sec 3 for more details). Those exhibiting excess RV scatter (after correcting the activity jitter) will be re-observed for another 16 visits (thus sacrificing 1 star in the sample for collecting the additional spectra). Additional time will be requested on NARVAL@TBL (mostly conditioned to CFHT allocation) & HARPS-Pol@ESO to survey the brightest stars of our sample.

Regarding cTTSs, our monitoring requires to observe all 5 selected stars at 2 different epochs over the whole LP. For all stars, we typically need ~16 visits to cover 2 complete rotation cycles and properly disentangle intrinsic variability (strong in cTTSs) from rotational modulation. To achieve this, **we need a total of 140 hr to complete our monitoring of the whole sample at 2 different epochs** (see Sec 3). For this monitoring, NARVAL@TBL & HARPS-Pol@ESO will collaborate to improve sampling (though obviously with spectra of twice lower quality) and collect useful complementary data during (short) episodes of bad weather at CFHT.

### b) multi-site, multi-wavelengths campaigns

We will also organize / participate to multi-wavelength multi-site observing campaigns similar to those arranged within MaPP and involving, eg, **Chandra & CRIRES@VLT**. Such campaigns proved extremely fruitful in terms of science return (eg Donati et al 2011, Argiroffi et al 2012, Alencar et al 2012). Simultaneous photometry will also be collected (eg w/ CAO, SuperWasp).

### c) the MagIcS spectropolarimetric LEGACY survey

All data collected with MaTYSSE will feed the MagIcS spectropolarimetric LEGACY survey, and will be made available to the whole CFHT community as soon as collected.

## D. Innovation & expertise

**MaTYSSE is a new ambitious observing program, addressing front-line questions of today's research: the formation of Sun-like stars & their planets**. MaTYSSE is building up on the success of MaPP, which gave the CFHT community a strong leadership in the field of magnetic imaging of protostars and allowed a breakthrough in understanding magnetospheric accretion processes and their impact on the formation of low-mass stars. MaTYSSE is both feasible and timely, and should allow the CFHT community to further strengthen their leadership in the field.

Gathering observers & theorists from the whole CFHT community & beyond, **MaTYSSE is well set to efficiently tackle all issues addressed by this program**. More specifically, our team include specialists of all domains involved in this program, ie stellar magnetic imaging & activity (Toulouse, Göttingen, ESO, CAUP, Geneva, StAndrews, Grenoble), magnetospheric accretion processes (Brazil, Grenoble, Toulouse, Cornell, Caltech, StAndrews, Imperial, Caltech), formation & evolution of low-mass stars (Lyon, Exeter, Grenoble), exoplanets & planet migration (eg Grenoble, Marseille, Geneva, StAndrews, Porto, Toulouse, Nice, Edinburgh, Cornell), dynamos (Exeter, Saclay, Toulouse) & stellar winds (StAndrews, Grenoble, Saclay, Imperial).

By coupling together studies of magnetic fields of protostars and searches for young exoplanets, MaTYSSE will also significantly contribute to the 2 main science topics of SPIRou, the next generation high-precision velocimeter / spectropolarimeter presently in construction at CFHT. **MaTYSSE should thus give scientists from the CFHT community** (including France and Canada, but also Taiwan, Brazil and China) **the opportunity to be well prepared when SPIRou comes on-line** in ~2015, putting the team on the front line for carrying out a much more ambitious survey of the same kind with SPIRou, yielding in particular improved statistics of hJs around TTSs. MaTYSSE should also give the team expertise on techniques such as activity filtering of RV curves, that are now critical for top-level exoplanet science.

## Magnetic topologies of cTTSs

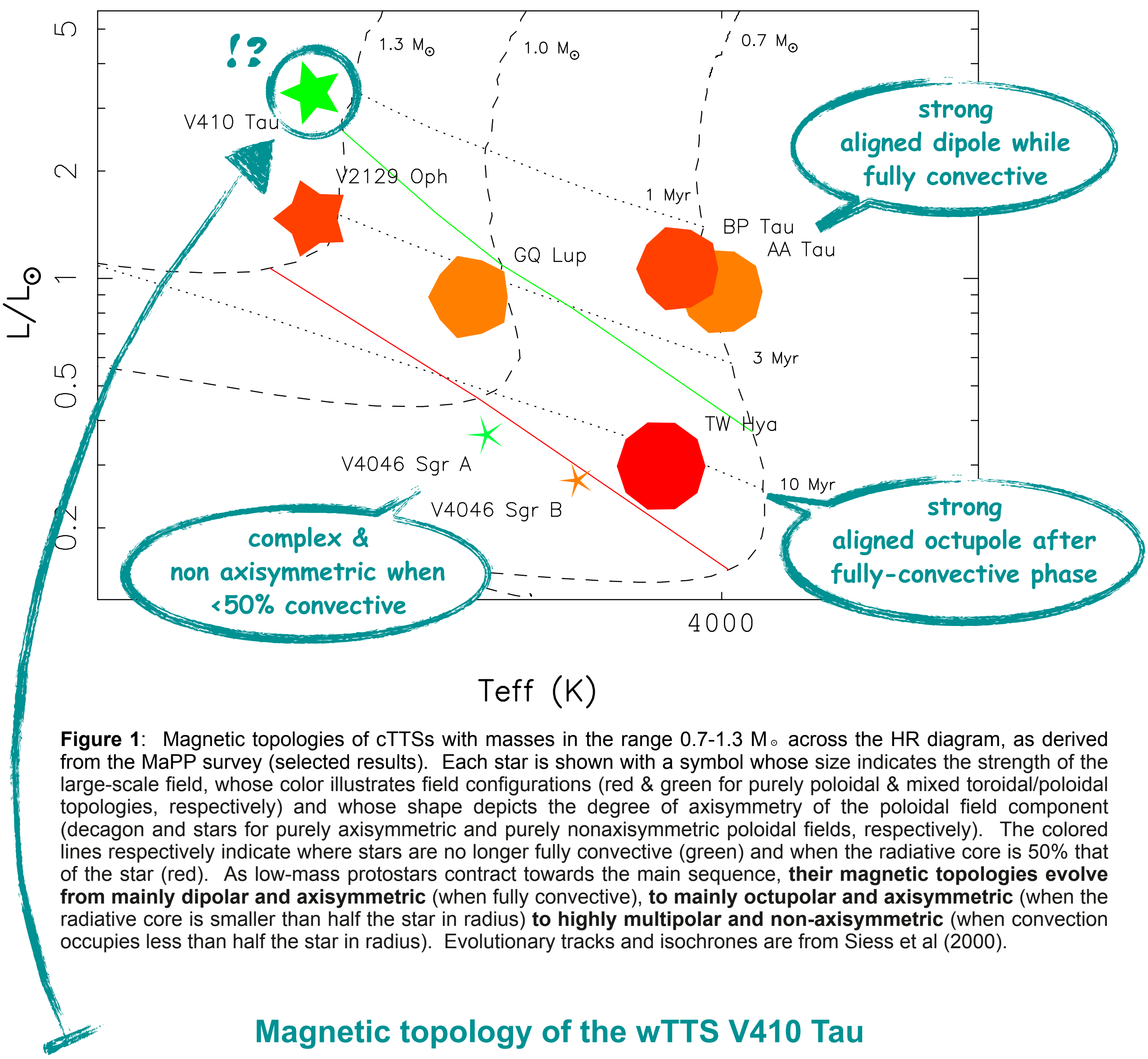


**Figure 1**: Magnetic topologies of cTTSs with masses in the range 0.7-1.3 $M_\odot$ across the HR diagram, as derived from the MaPP survey (selected results). Each star is shown with a symbol whose size indicates the strength of the large-scale field, whose color illustrates field configurations (red & green for purely poloidal & mixed toroidal/poloidal topologies, respectively) and whose shape depicts the degree of axisymmetry of the poloidal field component (decagon and stars for purely axisymmetric and purely nonaxisymmetric poloidal fields, respectively). The colored lines respectively indicate where stars are no longer fully convective (green) and when the radiative core is 50% that of the star (red). As low-mass protostars contract towards the main sequence, **their magnetic topologies evolve from mainly dipolar and axisymmetric** (when fully convective), **to mainly octupolar and axisymmetric** (when the radiative core is smaller than half the star in radius) **to highly multipolar and non-axisymmetric** (when convection occupies less than half the star in radius). Evolutionary tracks and isochrones are from Siess et al (2000).

## Magnetic topology of the wTTS V410 Tau

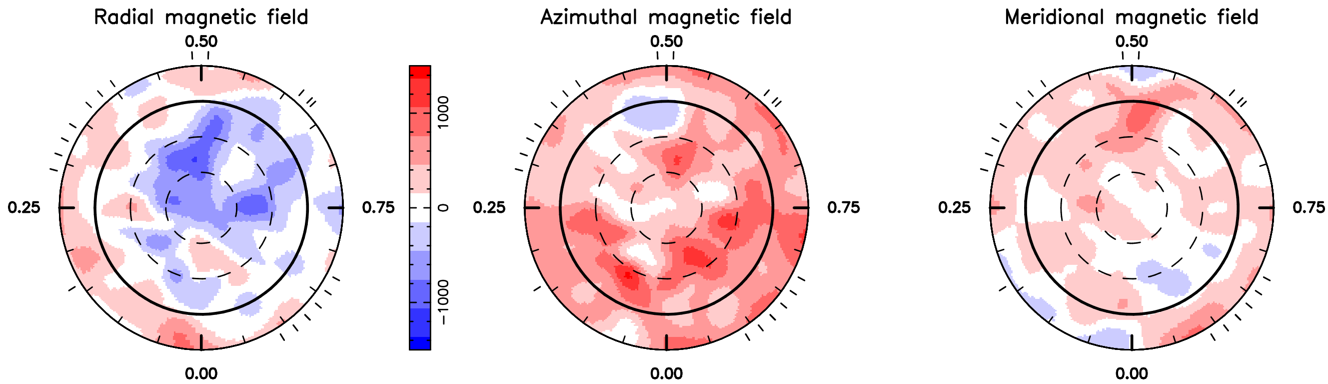


**Figure 2:** Surface magnetic maps of the wTTSs V410 Tau reconstructed from data collected in 2011 January using the latest version of Zeeman Doppler Imaging. The map shows the 3 components of the field in spherical coordinate with magnetic fluxes labeled in G. The star is shown in flattened polar projection down to a latitude of $-30^\circ$. Radial ticks around each plot indicate phases of observations. This map demonstrates that **V410 Tau includes a significant toroidal component and that non-axisymmetric terms dominate the poloidal component**, in agreement with previous results (Skelly et al 2010). Given the effective temperature and relative luminosity (with respect to the Sun) of V410 Tau (4500 K and 3.3), this would place V410 Tau in a region of Fig 1 where a star is predicted to have a mostly poloidal and axisymmetric field - **suggesting that wTTSs/tTTSs and cTTSs may differ significantly regarding their magnetic topologies**.

## MHD simulation of a magnetospheric gap

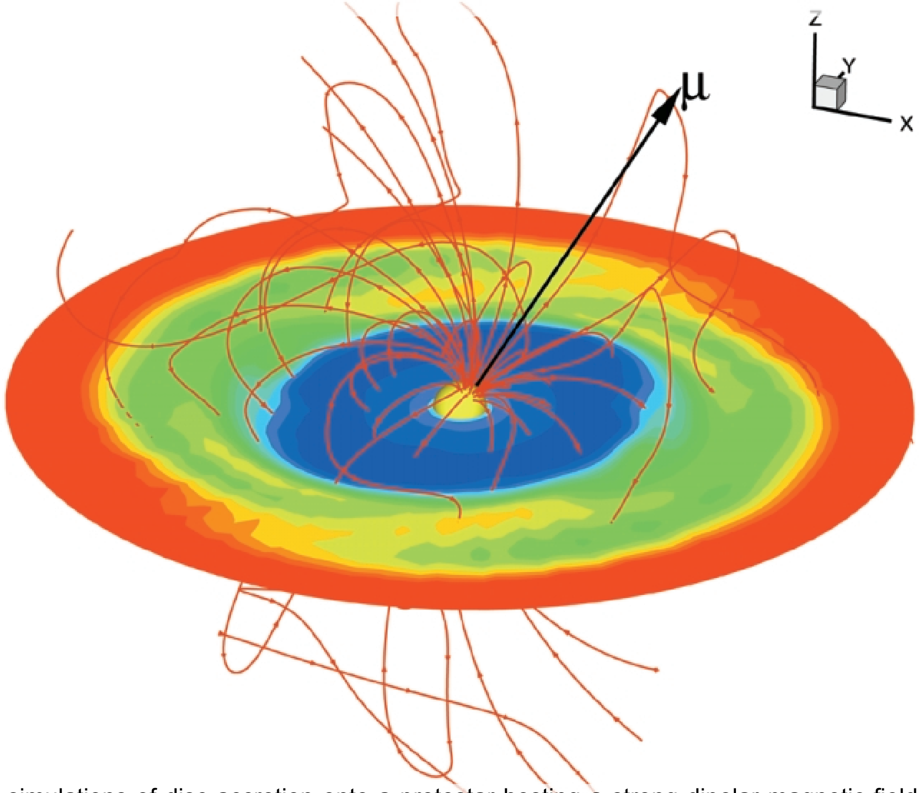


**Figure 3:** 3D MHD simulations of disc accretion onto a protostar hosting a strong dipolar magnetic field (tilted by 30° with respect to the rotation axis). The color background show the density distribution in the central regions of the accretion disc varying by a factor of >300 between the centre (blue) and the edges (red). This simulation suggests in particular that **magnetospheric gaps could be a viable mechanism for stopping the inward disc migration of hJs at orbital distances of ~0.05 AU and for preventing them from falling into their host star** (from Romanova & Lovelace 2006).

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## 3. Technical Justification

### A. The selected samples

As mentioned above, our wTTS/tTTS sample (see Table 1) includes ~40 targets with different masses (0.7-1.3 $M_\odot$, bracketing the mass of the Sun), ages (1-10 Myr) and rotation periods (0.5-10 d). This sample will allow us to study how magnetic topologies depend on mass and age (as in Fig 1) but also to find out whether they depend on rotation rate (with 10-15 stars for each of our 3 bins in rotation rate). This sample will also allow us to test whether wTTSs/tTTSs can host as much as 2.5-5% of hJs, which would correspond to 1-2 positive detections.

The stars we selected are among the best known wTTSs/tTTSs; in particular, their spectral type and rotation periods are well known from previous spectroscopic observations and photometric monitorings (eg G08, R01, L01, L05, P10, N07). All known spectroscopic binaries were removed from our sample; visual binarity (frequent for wTTSs) should not impact our study providing that the contrast between the components is large enough (eg, V2129 Oph, D11).

The survey will be carried out mostly at CFHT, with ~20 wTTSs/tTTSs to be observed with ESPaDOnS; we will complete the survey by using NARVAL on the 2m Telescope Bernard Lyot (TBL) for the ~10 northern brightest stars, and HARPS-Pol on the ESO 3.6m (whose sensitivity is comparable to NARVAL@TBL) for the ~10 southern brightest stars.

Although slightly less massive than the Sun in average (and hence slightly less prone to host hJs given trends derived from MS stars), wTTSs/tTTSs in the CFHT sample (see Table1) are also slightly more metallic than stars in the solar neighborhood ([Fe/H]~0 in Taurus against -0.2 for the solar neighborhood) and hence slightly more likely to host hJs (again, given trends derived from MS stars). Both effects should more or less compensate each other, hence not significantly degrading our potential chances of detecting hJs.

Regarding cTTSs, our sample includes the 5 targets best observed with MaPP, 3 of them (namely V2129 Oph, GQ Lup & BP Tau) having shown clear temporal variations of their large-scale magnetic topology and the 2 others (AA Tau & TW Hya, focusing the interest of the whole community) being by far the best candidates for this extended monitoring.

### B. Feasibility

Observations will consist in recording circular polarization spectra, following a specific procedure designed for suppressing all systematic errors to first order and reach photon noise limited polarimetric accuracies down to a relative level of about $10^{-5}$ (Donati et al 1997). This procedure has proved very efficient and is now used with most spectropolarimeters worldwide.

Using NARVAL@TBL, the Zeeman signatures of the wTTS V410 Tau (V=10.9) were easily detected at 2 different epochs (2009 January and 2011 January) in spectra with peak S/Ns of ~130 (per 2.3 km/s pixel) in exposure times of 0.7 hr (Skelly et al 2010). To detect such signatures (whose peak-to-peak amplitude is ~0.25%), we are using a multiline technique (called Least-Squares Deconvolution / LSD, Donati et al 1997) to extract the polarization information from 1000s of spectral lines simultaneously, allowing to decrease noise levels by a factor of ~30 and thus to detect Zeeman signatures with average S/Ns of 10:1. From sets of such Zeeman signatures, the parent large-scale magnetic field was mapped using the latest version of our magnetic imaging code (see Skelly et al 2010 and Fig 2 for the resulting images). Since V410 Tau has broader spectral lines (v sin i = 75 km/s) than the vast majority of our survey stars, it can be considered as a pessimistic case regarding detectability (as Zeeman signatures decrease in amplitude with increasing v sin i's, for v sin i > 15 km/s for a given magnetic topology).

Assuming that the selected wTTSs/tTTSs host similarly intense & complex large-scale fields than those of V410 Tau (which looks reasonable given Fig 1), we conclude that their large-scale fields are easily detectable with NARVAL@TBL at V=11 provided S/N>130 (per 2.3 km/s pixel). Scaling up to the sensitivity of ESPaDOnS@CFHT (1.5mag more efficient than NARVAL@TBL, given the larger photon collecting power of CFHT), it implies that large-scale fields of wTTS/tTTSs are detectable at V=12.5 provided S/N>130 (per 2.3 km/s pixel).

We propose to be conservative and aim for S/N=150 for all stars of our sample (see Table 1), ensuring that **Zeeman signatures of all wTTS/tTTSs will be detected with S/Ns of at least 10:1**. In practice, we will concentrate at CFHT on the faintest targets, with V ranging from 12 up to 13.5; we also include 2 stars with V~11.5 and rotation periods <0.8 d (namely TWA 6 & V642 Mon) that will be hard to reach with either NARVAL or HARPS given the short exposure times needed to freeze the rotation phase.

Regarding the cTTSs selected for our survey (see Table 2), the large-scale field has already been detected and mapped (see Table 2), thus **demonstrating the feasibility of our program**.

**Table 1:** selected wTTSs/tTTSs with well known spectral types (STs) and rotation periods. Colors outline the CFHT/TBL/ESO subsamples, while black indicate replacement targets @ CFHT.

| name | ST | mass (M☉) | age (Myr) | Prot (d) | V | SFR | references |
|---|---|---|---|---|---|---|---|
| LkCa 1 | M4 | <0.5 | 3-5 | 2.5 | 13.7 | Taurus | G08 |
| LkCa 21 | M3 | <0.5 | 3-5 | 8.6 | 13.5 | Taurus | P10 + G08 |
| LkCa 11 | M2 | 0.5 | 3-5 | 1.5 | 13.2 | Taurus | G08 |
| Sz 116 | M2 | 0.5 | 3-5 | 2.1 | 13.2 | Lupus | C07 + SuperWASP |
| VY Tau | M1 | 0.6 | 3-5 | 5.4 | 13.5 | Taurus | G08 |
| LkCa 3 | M1 | 0.6 | <1 | 7.4 | 11.7 | Taurus | G08 |
| RXJ1608.0-3857 | M1 | 0.6 | 1-3 | 2.4 | 12.7 | Lupus | C07 + SuperWASP |
| RXJ1609.5-3850 | M1 | 0.6 | 1-3 | 3.9 | 12.5 | Lupus | C07 + SuperWASP |
| LkCa 4 | K7 | 0.8 | 3-5 | 3.4 | 12.6 | Taurus | G08 + P10 |
| V827 Tau | K7 | 0.8 | 3-5 | 3.8 | 12.5 | Taurus | G08 + P10 |
| V819 Tau | K7 | 0.8 | 5-10 | 5.5 | 13.1 | Taurus | G08 + P10 |
| TaP 45 | K7 | 0.8 | 5-10 | 9.9 | 13.2 | Taurus | G08 |
| ROXs 45F | K7 | 0.8 | 5-10 | 2.5 | 13.0 | rho Oph | C07 + SuperWASP |
| TaP 26 | K7 | 0.8 | 3-5 | 0.7 | 12.3 | Taurus | G08 + P10 |
| LkCa 2 | K7 | 0.8 | 3-5 | 1.4 | 12.3 | Taurus | G08 |
| TaP 41 | K7 | 0.8 | 3-5 | 2.4 | 12.2 | Taurus | G08 |
| V830 Tau | K7 | 0.8 | 3-5 | 2.7 | 12.2 | Taurus | G08 + P10 |
| V826 Tau | K7 | 0.8 | 3-5 | 3.9 | 12.1 | Taurus | P10 + G08 |
| LkCa7 | K7 | 0.8 | 3-5 | 5.7 | 12.4 | Taurus | G08 + P10 |
| Hubble I 4 | K7 | 0.8 | 3-5 | 1.5 | 12.6 | Taurus | N07 |
| V1207 Tau | K7 | 0.8 | 1-3 | 7.7 | 11.9 | Taurus | G08 |
| TaP 57 | K7 | 0.8 | 1-3 | 9.3 | 11.5 | Taurus | G08 + P10 |
| TWA 6 | K7 | 0.8 | 10 | 0.54 | 11.6 | TWA | L05 |
| Par 2244 | K6 | 0.9 | <1 | 2.8 | 12.3 | Orion | R01 |
| TaP 40 | K5 | 1.0 | 5-10 | 1.6 | 12.6 | Taurus | G08 |
| TWA 9a | K5 | 1.0 | 10 | 5.1 | 11.3 | TWA | L05 |
| ROX 39 | K5 | 1.0 | 5-10 | 0.88 | 12.9 | rho Oph | C07 + SuperWASP |
| RXJ1609.7-3854 | K5 | 1.0 | 3-5 | 2.9 | 11.6 | Lupus | C07 + SuperWASP |
| RXJ1612.0-3840 | K5 | 1.0 | 3-5 | 2.8 | 11.7 | Lupus | C07 + SuperWASP |
| RECX 1 | K5 | 1.0 | 5-10 | 2.2 | 10.5 | eta Cha | L01 |
| RECX 7 | K5 | 1.0 | 5-10 | 2.6 | 10.8 | eta Cha | L01 |
| RECX 11 | K5 | 1.0 | 5-10 | 3.9 | 11.1 | eta Cha | L01 |
| RXJ1539.7-3450 | K4 | 1.1 | 1-3 | 7.1 | 10.6 | Lupus | C07 + SuperWASP |
| Par 1379 | K4 | 1.1 | <1 | 5.6 | 12.8 | Orion | R01 |
| ROXs 35a | K3 | 1.2 | 3-5 | 1.8 | 12.4 | rho Oph | C07 + SuperWASP |
| V410 Tau | K3 | 1.2 | 1-3 | 1.8 | 10.9 | Taurus | G08 + P10 |
| Wa Oph 1 | K2 | 1.3 | 3-5 | 3.8 | 12.0 | rho Oph | G08 |
| RXJ1608.9-3905 | K2 | 1.3 | 1-3 | 2.0 | 10.9 | Lupus | C07 + SuperWASP |
| TaP 35 | K1 | 1.4 | 1-3 | 2.7 | 10.3 | Taurus | G08 + P10 |
| TaP 4 | K1 | 1.4 | 3-5 | 0.48 | 12.1 | Taurus | G08 |
| 2MASS J06410688+0923213 | K1 | 1.4 | 1-3 | 11.0 | 12.5 | NGC 2264 | Corot |
| V642 Mon | K1 | 1.4 | 1-3 | 0.74 | 11.5 | NGC 2264 | Corot |
| 2MASS J06410025+0958496 | K1 | 1.4 | 1-3 | 3.0 | 13.5 | NGC 2264 | Corot |
| V1197 Tau | K0 | 1.5 | 1-3 | 2.7 | 10.3 | Taurus | G08 |
| LkCa 19 | K0 | 1.5 | 1-3 | 2.2 | 10.9 | Auriga | G08 + P10 |
| Wa Oph 3 | K0 | 1.5 | 1-3 | 1.5 | 10.8 | rho Oph | G08 |

**Table 2:** list of cTTSs for which we will carry out monitoring from CFHT (plus additional lower quality spectra from TBL & ESO) at 2 different epochs.

| name | ST | mass (M☉) | age (Myr) | Prot (d) | V | SFR | references |
|---|---|---|---|---|---|---|---|
| BP Tau | K7 | 0.8 | 1-3 | 7.6 | 12.5 | Taurus | D08 |
| AA Tau | K7 | 0.8 | 1-3 | 8.4 | 12.8 | Taurus | D10 |
| V2129 Oph | K3 | 1.3 | 3 | 6.5 | 11.4 | rho Ohp | D11 |
| GQ Lup | K5 | 1.0 | 3 | 8.4 | 11.4 | Lupus | D12 |
| TW Hya | K7 | 0.8 | 8 | 3.6 | 11.1 | TWA | D11b |

| V | stars | exposure times for 16 visits (hr) |
|---|---|---|
| 11.0-11.9 | V642 Mon, TWA 6, TW Hya, GQ Lup, V2129 Oph | 10 |
| 12.0-12.4 | ROXs 35a, TaP 4, Par 2244, LkCa7, V830 Tau, LkCa 2, TaP 26, | 14 |
| 12.5-12.9 | 2MASS J06410688+0923213, Par 1379, ROX 39, TaP 40, RXJ1608.0-3857, RXJ1609.5-3850, LkCa 4, AA Tau, BP Tau | 20 |
| 13.0-13.5 | ROXs 45F, TaP 45, LkCa 21, V819 Tau | 28 |

**Table 3:** exposure times for the wTTSs/tTTSs and cTTSs of the proposed CFHT survey.

## C. Requested time

Given the V magnitudes of our stars (ranging from 11.6 to 13.5, see Table 1), we find that the time needed for obtaining the 16 spectra of each star varies from 10 to 28 hr per target (depending on the magnitude, see Table 3). Summing up the time needed for all stars, we obtain that **the total time required to complete the survey of the 20 selected wTTSs/tTTSs at S/N~150 is 370 hr**.

For cTTSs, we propose to use observing times similar to those used during MaPP, ie 20 hr per epoch (ie for one group of 16 visits) and per star for AA Tau & BP Tau (V~12.8), and 10 hr per epoch and per star for TW Hya, V2129 Oph and GQ Lup (V~11.4), as recalled in Table 3. The **full amount of time needed for the whole monitoring of our 5 cTTSs at 2 different epochs is thus 140 hr**.

## D. Observing plan

Regarding wTTSs/tTTSs, our observing plan will consist in observing systematically all targets of our sample, trying to mix fainter and brighter ones to minimize disparities between semesters. We also try to mix stars with short and long rotating periods to avoid conflicting scheduling constraints (strongest for short period stars). The resulting observing plan is given in Table 4.

For cTTSs, we will simply observe one star per semester (coming back on each star after four semesters), with the exception of GQ Lup & TW Hya that will be observed on the same semesters (2014A & 2016A). Merging this new set with the existing MaPP data on V2129 Oph (epochs 2005, 2009, 2012), TW Hya (epochs 2008, 2010, 2012), GQ Lup (epochs 2009, 2011, 2012), AA Tau (epochs 2007, 2008, 2010, 2012), BP Tau (2006, 2011), the proposed observing plan (see Table 4) ensures that the 5 selected cTTS will have been monitored on timescales ranging from 7 to 10 yr.

**Table 4:** proposed observation plan for our survey

| Semester | stars | time needed (hr) |
|---|---|---|
| 2013A | RXJ1609.5-3850, RXJ1608.0-3857, V2129 Oph | 20+20+10 = 50 |
| 2013B | LkCa 4, TaP 40, Par 1379, TaP 4, AA Tau | 20+20+20+14+20 = 94 |
| 2014A | TWA 6, GQ Lup, TW Hya | 10+10+10 = 30 |
| 2014B | V819 Tau, Par 2244, V830 Tau, BP Tau | 28+14+14+20 = 76 |
| 2015A | ROXs 45F, ROXs 35a, V2129 Oph | 28+14+10 = 52 |
| 2015B | TaP 26, TaP 45, LkCa 7, 2MASS J06410688+0923213, AA Tau | 14+28+14+20+20 = 96 |
| 2016A | ROX 39, GQ Lup, TW Hya | 20+10+10 = 40 |
| 2016B | LkCa 2, LkCa 21, V642 Mon, BP Tau | 14+28+10+20 = 72 |
| | | **total = 510 hr** |

## 4. Observing strategy (1 page)

Following the observing plan detailed in Sec 3, we end up with the following right-ascension distribution of observations across semesters 2013A to 2016B:

| 2013 A | |
|---|---|
| RA | Hours |
| 00-04 | |
| 04-08 | |
| 08-12 | |
| 12-16 | |
| 16-20 | 50 |
| 20-24 | |

| 2013 B | |
|---|---|
| RA | Hours |
| 00-04 | |
| 04-08 | 94 |
| 08-12 | |
| 12-16 | |
| 16-20 | |
| 20-24 | |

| 2014 A | |
|---|---|
| RA | Hours |
| 00-04 | |
| 04-08 | |
| 08-12 | 20 |
| 12-16 | |
| 16-20 | 10 |
| 20-24 | |

| 2014 B | |
|---|---|
| RA | Hours |
| 00-04 | |
| 04-08 | 76 |
| 08-12 | |
| 12-16 | |
| 16-20 | |
| 20-24 | |

| 2015 A | |
|---|---|
| RA | Hours |
| 00-04 | |
| 04-08 | |
| 08-12 | |
| 12-16 | |
| 16-20 | 52 |
| 20-24 | |

| 2015 B | |
|---|---|
| RA | Hours |
| 00-04 | |
| 04-08 | 96 |
| 08-12 | |
| 12-16 | |
| 16-20 | |
| 20-24 | |

| 2016 A | |
|---|---|
| RA | Hours |
| 00-04 | |
| 04-08 | |
| 08-12 | 10 |
| 12-16 | |
| 16-20 | 30 |
| 20-24 | |

| 2016 B | |
|---|---|
| RA | Hours |
| 00-04 | |
| 04-08 | 72 |
| 08-12 | |
| 12-16 | |
| 16-20 | |
| 20-24 | |

## 5. Data management plan (1 page)

**A. Data collection & reduction**

1. **Core data:** ESPaDOnS data (collected in QSO mode) will be downloaded as soon as available, reprocessed locally in Toulouse with a dedicated version of Libre_ESpRIT (optimized for young stars) and analyzed with our new spectral classification tool (which we will try to make publicly available, eg through a web-based interface), hence contributing to the MagIcS spectropolarimetric LEGACY survey. Zeeman signatures and raw RVs will be derived on the fly within the reduction process.
2. **Complementary data:** Companion LPs will be setup both for NARVAL@TBL and for HARPS-Pol@ESO. We will also organize coordinated multi-wavelengths multi-site campaigns (eg with Chandra and/or CRIRES/VLT) and setup simultaneous photometric observations (eg from CAO and/or SuperWASP), in the same way as fruitfully achieved for MaPP.

**B. Data modeling**

1. **Tomographic imaging:** Stellar surface imaging from spectropolarimetric data sets will be carried out with different codes (eg Toulouse, ESO), allowing us to derive brightness and magnetic maps of the observed stars and to double check the consistency of all results. The global analysis of all magnetic results will be achieved collectively, eg through regular workshops that we will organize during the LP.
2. **Activity filtering / RV analyses:** Several groups (eg Geneva, Grenoble, Porto, Toulouse) will work together on optimizing existing techniques for filtering the activity jitter from RV curves, using in particular output from tomographic imaging of spectropolarimetric data and/or complementary data (eg from CRIRES/VLT) and techniques (eg Boisse et al 2011). For candidates showing excess RV dispersion, renewed and extended observations will be organized to attempt confirming the planetary origin of the detected RV fluctuations.

**C. Simulations**

1. **Dynamos**: Through dynamo simulations (eg Saclay, Toulouse, Exeter), we will investigate how the large-scale field is expected to respond to changes in convective depths and rotation rates, especially in regions of the HR diagram where drastic changes are observed to occur (see Fig 1). In a second step, we will attempt working out how accretion is susceptible of modifying dynamo processes and large-scale magnetic topologies.
2. **Impact of dynamo processes on magnetospheric gaps**: In addition, we also plan to investigate how secular changes in large-scale magnetic fields of protostars are likely to affect the sizes and density contrasts of magnetospheric gaps (eg Cornell, Toulouse, Grenoble).
3. **Planet migration:** We plan as well to simulate how hJs will react to changes in the sizes of magnetospheric gaps (eg StAndrews, Toulouse), reassess in more details (by using MaTYSSE data) the potential impact of the stellar wind on stopping the migration (eg St Andrews, Saclay, Cornell) and finally re-evaluate the chances for hJs to survive this phase.
4. **PMS evolution & internal stellar structure:** Following Gregory et al (2012), we plan to see how our results can be used to improve our knowledge of the PMS evolution and internal stellar structure of Sun-like stars.

**D. Coordination, scheduling & publications**

As for MaPP, a dedicated wiki site will be setup and regular workshops will be organized for sharing data, discussing and distributing preliminary results from both observations and simulations as the project goes on, and to work out the presentation / publication strategy that will maximize the science return and widely publicize the LP results.