1. Cover page (1 page)

Title: MaPP (Magnetic Protostars and Planets) - studying the impact of magnetic fields on the formation of low-mass stars and planets

Abstract: MaPP aims at studying the impact of magnetic fields on the physics of protostars and accretion discs, and thus on the formation of stars and planetary systems. Youth is indeed the period in the life of non-degenerate stars at which magnetic fields play a key role, through the accretion/ejection processes involved in the collapse of the protostellar cloud. In particular, our study will focus on the core regions of protostellar accretion discs, the newly born star and their potential close-in giant planets. We propose to carry-out **the first spectropolarimetric survey on a significant sample of low-mass protostars, including a few bright protostellar accretion discs;** From this survey, we will study the large-scale magnetic field topologies of protostellar objects using tomographic imaging techniques. By comparing these results to the predictions of new theoretical models and MHD simulations, **MaPP will answer several major open questions on star formation and produce updated models incorporating the effect of magnetic fields**.

MaPP is part of the international **MagIcS** initiative; all data collected with MaPP will thus directly feed the **MagIcS LEGACY database**.

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Instrument required: ESPaDOnS (polarimetric mode)
Total number of hours requested: 690
Hours per agency: C: 150 (21%) - F: 480 (70%) - T: 60 (9%)

Proprietary period for participating community access: 0 yr (default)
Proprietary period for participating community access: 1 yr (default)

2. Science Justification (5 pages)

A. General context and open questions

Whereas the understanding of most phases of stellar evolution made considerable progress throughout the twentieth century, stellar formation remained poorly constrained by observations until the last few decades ago. One major discovery obtained at this time is that protostellar accretion discs are often associated with bipolar flows (eg Snell et al, 1980), now known to be powerful, highly-collimated jets escaping the disc along its rotation axis. These jets (and in particular their collimation) have been attributed to the presence of magnetic fields and to the so-called magneto-centrifugal processes (eg Blandford & Payne 1982; Pudritz & Norman 1983). Another important discovery is that low-mass magnetic protostars are rotating significantly slower than predicted by a non magnetized collapse (eg Bertout 1989); this is likely due to the large-scale magnetic field coupling the protostar to its accretion disc (eg Königl 1991). Both results suggest that **magnetic fields play a central role throughout stellar formation**.

Since then, strong magnetic fields have been detected at the surface of several low-mass protostars (eg Johns-Krull et al 1999a,b; Valenti & Johns-Krull 2004; Symington et al 2005; Bouvier et al 2007; Donati et al 2007, 2008), in a protostellar accretion disc (Donati et al 2005) and within molecular clouds (eg Crutcher 2004); observations suggest that most stars, including very-low-mass stars and brown dwarfs, may share the same magnetic formation process, featuring in particular accretion, discs and jets (eg Jayawardhana et al 2006). Numerous models and numerical simulations illustrated the effect of magnetic fields on the cloud collapse with increased sophistication (eg Mouschovias & Spitzer 1976; Machida et al 2004; Banerjee & Pudritz 2006, see Fig 1; Machida et al 2007; Hennebelle & Fromang 2008; Hennebelle & Teyssier 2008). Theoretical models and simulations also described the subsequent central clearing of the accretion disc by the large-scale magnetic field of the newly-born protostar, the magnetic coupling between the protostar and the inner edge of the accretion disc (eg Shu et al 1987, Cameron & Cambell 1993; Romanova et al 2004, see Fig 2; Long et al 2005; Bouvier et al 2007; Bessolaz et al 2008; Mohanty & Shu 2008) and the impact of magnetized accretion onto the mechanical and thermal structure of the protostar (eg Hartmann et al 1997; Chabrier et al 2007).

Despite significant progress, **several major issues remain unresolved**:

(a) **what is the origin of the disc field? how much angular momentum and magnetic flux is dissipated during the cloud collapse?** We can address these issues by unveiling the strength and orientation of the magnetic fields that managed to survive the collapse and the associated angular rotation velocities, in particular within the central regions of the protostellar accretion discs from which the jets are fired;

(b) **how does magnetospheric accretion control the angular momentum and how much does it modify the internal structure of the protostar?** This can be studied by measuring the intensity and complexity of the magnetic fields that protostars host and weave with their accretion disc to funnel the disc material towards the stellar surface.

(c) **why are some discs/protostars showing jets while some others are not?** By using input from (a) and (b), we can investigate how jets relate to the magnetic fields in accretion discs and to those on protostars;

(d) **how do close-in giant planets form and stop their inward migration?** Results from (a) and (b) will show whether (and where) close-in giant planets are present in the central regions of protostellar accretion discs or around more evolved protostars.

To answer these questions, we thus propose to carry out ***the first spectropolarimetric survey on a significant sample of young stellar objects****, including in particular several young low-mass stars (classical T Tauri stars or cTTSs) and a few bright protostellar accretion discs (FUOrs), and study how the magnetic properties vary with the object characteristics (eg accretion rate, outflow properties, protostar's mass and rotation rate); this new body of observations will allow us to select among the various existing theoretical models and provide an updated description of magnetized stellar formation. We describe below the various aspects of this project - called* ***MaPP*** *(Magnetic Protostars and Planets).*

B. Specific goals of MaPP - confronting observations & simulations

As described above, MaPP will concentrate on four specific fronts to provide new answers to several major unresolved issues in stellar formation.

a) magnetised collapse of the molecular cloud and structure of protostellar accretion discs:
We first aim at deriving the topology and strength of large-scale magnetic fields as well as the density and angular rotation profile in the central regions of protostellar accretion discs, when the

pre-stellar core had just started to form (ie at an age of about 0.1 Myr). From this we will (i) determine the disc structure and field topology where jets are launched and (ii) ascertain the origin of the disc field and constrain the amount of angular momentum and magnetic flux dissipated throughout the cloud collapse.

Using ESPaDOnS, Zeeman signatures tracing the disc magnetic fields have already been detected in the particular case of the protostellar accretion disc FU Ori (Donati et al 2005, see Fig 3), demonstrating that **kG poloidal fields and weaker toroidal fields are present in the central regions of the disc**. Additional observations indicate that both the unpolarized profiles produced in the disc plasma and the Zeeman signatures tracing the parent magnetic field are variable with time (see Fig 4), suggesting that the magnetic field is not purely axisymmetric.

With MaPP, we will observe protostellar accretion discs, both very young (about 0.1 Myr) yet luminous enough (ie the brightest FUOrs: FU Ori, V1057 Cyg and V1515 Cyg) to be visible (and produce line profiles) at optical wavelengths. Using ESPaDOnS, we will repeat the observations first carried out on FU Ori on V1057 Cyg and V1515 Cyg to confirm that they host similar magnetic topologies. We will also densely monitor one accretion disc (eg FU Ori) over 2 weeks (ie the Keplerian period at a disc radius of 0.1 AU) to track how the intensity profiles and Zeeman signatures of absorption lines formed in the inner regions of the accretion disc are modulated with time. Applying Doppler tomography (eg Marsh & Horne 1988) on the collected ESPaDOnS data sets will enable us to retrieve the **density, angular rotation and magnetic field distribution in the central regions of the accretion disc** (within 0.1 AU). ALMA observations on the magnetic field in the outer disc (at tens of AU) will nicely complement the ESPaDOnS data and bring a broader description of the magnetic field throughout the disc.

On the theoretical front, we will compare with recent models (eg Shu et al 2007) and run numerical simulations of the **first and second collapse in the presence of magnetic fields** (eg Banerjee & Pudritz 2006; Machida et al 2007; Hennebelle & Fromang 2008) up to the formation of a pre-stellar core with its surrounding accretion disc (ie about 0.1 Myr) using 3D adaptive mesh refinement MHD codes such as FLASH or RAMSES (eg Fromang et al 2006) and adding the best possible input physics (eg ohmic and ambipolar diffusion, dust cooling, H2 dissociation, magnetic instabilities). From these simulations, we will produce updated collapse calculations and magnetic disc models, and specify how density, temperature and magnetic field are expected to vary with radius, especially in the disc core. We will also couple these simulations with upgraded radiative transfer tools, in order to produce quantities from disc models that can be directly compared with observations, such as spectral line profiles, Zeeman signatures and Doppler maps. Comparing the observed and predicted density and angular rotation profile, as well as the vertical and azimuthal field distribution, within the innermost disc region will tell us about the amount of angular momentum and magnetic field that survived the collapse (eg Machida et al 2007), about the origin of the observed disc field (eg advection from a larger-scale interstellar field vs dynamo action, von Rekowski et al 2003), and about the physical conditions prevailing in the disc at the base of jets.

b) magnetic coupling and magnetospheric accretion between the disc and the protostar: *We also aim at investigating the large-scale magnetic field topologies in young low-mass stars (cTTS), to examine (i) how such fields succeed at clearing the central regions of the accretion disc, how they couple the inner disc to the surface of the protostar and how they control the accretion process, and (ii) how they influence the angular momentum and internal structure of the protostar.*

Both observations (eg Alencar et al 2005) and simulations (eg Jardine et al 2006; Gregory et al 2006; Long et al 2007) indicate that magnetospheric accretion is expected to depend strongly on the field geometry and thus potentially on the mass and rotation rate of the protostars, as well as on the ability of the star/disc system to drive a large-scale outflow. The magnetospheric topology of cTTS is however still unclear; while spectropolarimetric estimates of magnetic fields at footpoints of accretion funnels (as measured from emission lines produced in the accretion postshock region, Johns-Krull et al 1999a, Symington et al 2005) suggest highly-ordered large-scale magnetic structures, repeated failures at detecting dipolar-like photospheric fields (eg Valenti & Johns-Krull 2004) did not confirm this view. Recent ESPaDOnS observations of 2 cTTS allowed (i) to detect magnetic fields both at the surface of the protostar and at the footpoints of accretion funnels, (ii) to monitor their signatures over the full rotation cycle, and (iii) to produce (through tomographic imaging) consistent magnetospheric models reproducing all detected Zeeman signatures (Donati et al 2007, 2008, see Fig 5). The reconstructed field features **complex multipolar structures close to the stellar surface** and a simpler (though not dipolar) large-scale topology with accretion spots coinciding with high-latitude regions hosting multi kG magnetic fields. Tracing the path of accretion streams from the inner disc rim to the surface of the star indicates that the central magnetospheric gap extends to at least 5 stellar radii to ensure that accretion footpoints are located close to the pole as observed.

With MaPP, we aim at exploring observationally **how magnetospheric topologies depend on the mass and rotation rate of the protostars**, as well as on the ability of the system to drive a large-scale outflow. First estimates from fragmentary data sets (eg on SU Aur) indicate that the magnetosphere is getting more complex for high-mass, rapidly-rotating protostars. We will then be able to investigate how well the size of the central magnetospheric gaps in cTTSs accretion discs correlate with the properties of the large-scale field, mass accretion and rotation rate, and check whether magnetic coupling between the protostar and its accretion disc is indeed responsible for the slow rotation of cTTSs. We will collect ESPaDOnS spectropolarimetric data for 15 cTTSs with various masses, ages, accretion and rotation rates, and jet properties, repeating this effort >4 yrs later for the 8 most important ones to disclose the origin of the large-scale magnetic fields of cTTSs through their long-term evolution (indirectly traced by the long-term photometric variability, eg Grankin et al 2007, Bouvier et al 2007). From these data, we will retrieve, for all stars, both the magnetic topologies and a simultaneous estimate of their mass accretion rates at the time of our observations (to achieve maximum internal consistency in our data set).

We will then compare our observations to **new theoretical models of magnetospheric accretion** (eg Mohanty & Shu 2008) and will run dedicated **3D MHD numerical simulations** with multipolar non-axisymmetric fields akin to those revealed by observations, and including resistivity and viscosity needed to model properly the transport phenomena within the disc. Numerical modeling of the star/disc magnetospheric interaction is carried out at Cornell (eg Romanova et al 2004; Long et al 2005, 2007) and at Grenoble (eg Bessolaz et al 2008). These simulations will essentially aim at exploring how the observed correlations between the magnetospheric topologies and stellar parameters / accretion properties can be quantitatively explained; in particular, we will focus on clarifying whether and how magnetic coupling between the inner disc region and the surface of the star is indeed able to slow down the rotation of the protostar.

We also aim at developing **new theoretical models** describing the very early phases of evolution of low mass stars, taking explicitely into account the prior history of the pre-stellar core gravitational collapse and the magnetospheric accretion processes. Preliminary investigations based on a phenomenological approach show that the accretion process (eg fraction of the radiating surface covered by accretion, accretion rate, fraction of the accretion shock energy transferred to the protostar's internal heat content) can strongly impact the internal structure of very young low mass objects and affect their evolution over up to a few Myr (Chabrier et al 2007). From the updated constraints derived from this project and using the Lyon expertise, we will propose new models describing consistently the internal structure and evolution of contracting pre-main sequence stars with their gravitational collapse and accretion phase history taken into account. These models will also be used to reevaluate the **angular momentum evolution of young protostars** once their accretion disc is dissipated (eg Bouvier et al 1997).

c) magnetized mass loss from low-mass young stars and/or their accretion discs:

Through the results of (a) and (b), MaPP can also study the physical processes producing the collimated jets and winds frequently observed in association with protostellar accretion discs and known to participate actively in dissipating the angular momentum and magnetic flux originally present in the cloud. By looking at how the outflow properties correlate with the magnetic topologies in the inner regions of accretion discs and at the protostars' surfaces, we can determine which parameters are triggering and controlling the launching of winds and jets.

It is now widely accepted that **protostellar outflows are produced by magneto-centrifugal processes** propelling the in-falling disc material outwards and along the rotation axis at high speeds into a wind or a jet (eg Pudrtiz & Norman 1983; Ferreira et al 2006; Pudritz et al 2006). Numerous key points about these outflows however remain unclear. Does the jet originate from the central protostar, the surrounding accretion disc or both? Is the jet an intrinsically steady or time-variable process? Why are some protostars firing jets while others are not? Which field topologies are most efficient at launching outflows? Is the relative orientation of the protostar's and/or disc's magnetic field with respect to that of the parent molecular cloud of any relevance for this problem (eg Ménard & Duchène 2004)?

Using the spectropolarimetric data collected with MaPP on accretion discs and low-mass protostars, **we will determine which magnetic characteristics of the accretion discs and the protostars correlate best with outflow properties**. Observing discs and protostars with and without jets (eg FU Ori vs V1057 Cyg and V1515 Cyg for accretion discs, RY Tau vs T Tau, or DG Tau vs V2129 Oph for protostars) is particularly important in this respect. These observations will be compared to predictions from existing semi-analytical disk wind models and numerical simulations of jets from both magnetized accretion discs or star/disc magnetospheres.

d) impact of magnetic fields on the formation & migration of planets:
We will also use the results of (a) and (b) to diagnose the presence of close-in giant planets in the central regions of protostellar accretion discs; in particular, this will tell us how close-in giant planets can stop their migration and settle in the immediate neighborhood of their host star.

While giant planets are unlikely to form by disc fragmentation within 0.1 AU of their host star, observations show that lots of them, often more massive than Jupiter, are actually observed there (eg Bouchy et al 2005). The standard explanation is that giant planets begin their life in the outer accretion disc and migrate inwards as a result of tidal interactions within the protostellar disc until their migration stops. What stops this migration is still a matter of speculation - possibly a magnetic torque within the accretion disc (eg Terquem 2003) or the planet entering the central magnetospheric gap surrounding the protostar (eg Romanova & Lovelace 2006).

Observations collected in (a) and (b) can be used to test these scenarios. Clumps, gaps and magnetic field concentrations at specific radii in the inner disc (eg induced by potential close-in giant protoplanets, Clarke & Armitage 2003; Vittone & Errico 2006) can be detected in the data through the profile modulation they generate at the associated Keplerian period[1] and will show up as localized features in the reconstructed disc maps. Radial velocity measurements from spectropolarimetric data (eg Moutou et al 2007) on cTTSs can also directly reveal the presence of close-in giant planets such as that very recently discovered around TW Hya - the first such planet detected around a pre-main-sequence star (Setiawan et al 2008). Correlating the location of close-in giant protoplanets at the centre of an accretion disc (eg those reported for FU Ori, Clarke & Armitage 2003, Vittone & Errico 2006) with the reconstructed disc magnetic fields can validate the idea of Terquem (2003); alternatively, measuring the size of the magnetospheric gap at the centre of protostellar accretion discs (see b) provides a test for the idea of Romanova & Lovelace (2006). The planet found around TW Hya, located just within the inner disc rim, suggests that the second option is more likely; more data are and simulations are required to study this issue thoroughly.

C. A new ESPaDOnS spectropolarimetric survey of low-mass protostars

*To achieve the scientific goals outlined in (B), we propose to carry out **the first spectropolarimetric survey on a significant sample of low-mass protostars**, including a few bright protostellar accretion discs. In particular, this coordinated survey must be carried out globally to ensure that (i) relevant data are collected for enough stars to allow correlated searches between the magnetic properties and the stellar parameters, (ii) all polarized spectra are obtained with similar polarization sensitivities and rotational phase sampling, (iii) the efficiency of data collection is maximized, eg by concentrating observations on the most promising objects as results progressively build up, and (iv) simultaneous coverage from other observatories (Chandra, ALMA) can be organized and coordinated well in advance.*

Our sample includes 15 cTTSs (V2129 Oph, V2247 Oph, BP Tau, AA Tau, DF Tau, DG Tau, DK Tau, DN Tau, T Tau, RY Tau, SU Aur, COUP 932, TW Hya, RY Lup, GQ Lup, featuring different masses, ages, accretion and rotation rates, and jet properties, see Sec 4) and 3 bright protostellar accretion discs (FU Ori, V1057 Cyg, V1515 Cyg). Seven of the 15 cTTSs (V2129 Oph, BP Tau, AA Tau, DG Tau, T Tau, RY Tau, COUP 932) will be observed twice to study the long term evolution of the field topology, with 2 of them (V2129 Oph, BP Tau) already observed once (Donati et al 2007, 2008); TW Hya and its recently discovered close-in giant planet will be observed 3 times (including the already allocated 08a slot) given the obvious interest for our program.

We thus need to carry out the following operations:

i) densely monitor each of the 12 cTTSs not yet monitored with ESPaDOnS at an average rate of 1.2 hr/n and per star over 16 n (about twice the longest rotation period) to cover the rotation cycle of each star and disclose rotational modulation from intrinsic variability - requiring **226 hr;**

ii) detect the field at 3 epochs for V1057 Cyg and V1515 Cyg and carry-out the same analysis as in Donati et al (2005) - requiring **48 hr**;

iii) densely monitor the field of FU Ori over 16 n (ie the Keplerian period at 0.1 AU) at a rate of 8 hr/n) to allow tomographic imaging of the inner accretion disc (within 0.1 AU) - requiring **128 hr**;

iv) densely monitor again the 7 cTTS for which we need observations at a second epoch and TW Hya for which we need 2 additional epochs - requiring **160 hr**;

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[1]Line profile modulation on timescales of 3.5, 7 and 14.8d (corresponding to Keplerian radii of 0.03, 0.05 and 0.09 AU) has already been reported in the particular case of FU Ori, showing that such features are likely to be often present in protostellar accretion discs.

v) densely monitor the field of V1057 Cyg or V1515 Cyg (which ever turns out most interesting) over 16 n to attempt tomographic imaging of the central disc regions - requiring **128 hr**;

The full observing program therefore requires a total of 690 hr.

The ESPaDOnS observations already collected on FU Ori (Donati et al 2005), on V2129 Oph (Donati et al 2007) and on BP Tau (Donati et al 2008) demonstrate that our program is entirely feasible. **ESPaDOnS@CFHT is the only instrument worldwide that can achieve this survey; our program thus appears as timely and mature to qualify as a Large Program.**

To further enhance the overall return of the MaPP ESPaDOnS observations, we will arrange coordinated observations whenever possible. We will try to obtain **Chandra/XMM observations** for a few cTTS of the sample (those that have not yet been observed at Xray wavelengths, eg V2129 Oph), from which we will model the properties of the hot plasma in the small-scale coronal loops and the larger-scale accretion funnels (Jardine et al 2006; Gregory et al 2006). **ALMA radio observations** of the selected FUOrs protostellar accretion discs, informing us on the magnetic field in the outer disc, will nicely complement the ESPaDOnS data tracing the inner disc; with ALMA high-angular-resolution observations of molecular clouds, we can also estimate the spatial scale at which ambipolar diffusion impacts the cloud collapse, and use it to improve the physical realism of our collapse simulations.

We will also arrange **simultaneous spectrolarimetric monitoring with NARVAL** (the ESPaDOnS twin) at Télescope Bernard Lyot (TBL) atop Pic du Midi to improve phase coverage - as a result of the smaller collecting power (TBL is a 2m telescope only), NARVAL will record Zeeman signatures with much smaller precision (eg Donati et al 2008); such data will nevertheless be helpful to improve phase sampling, especially on northern stars with rotation periods of only a few days (eg T Tau, SU Aur, RY Tau). Finally, we will also try to carry out simultaneous observations of cTTSs at IR wavelengths, eg with **Phoenix/Gemini**, to obtain additional constraints on the magnetic fluxes by looking at the magnetic broadening of atomic spectral lines at about 2 microns (Johns-Krull et al 1999b) and will organize simultaneous **photometric monitoring** of all stars (eg WASP, Uzbekistan) before, during and after ESPaDOnS observations (eg to obtain additional information about the surface spots for tomographic imaging).

MaPP is carried out within the broader context of the **MagIcS initiative**[2] and shares links with several other MagIcS themes (eg dynamos of low-mass stars). As a result, **all data collected for this survey will directly feed the MagIcS LEGACY database** (beta version to come online in Spring 2008, see technical justification for more details on the database) and will thus be quickly accessible to the CFHT community for further complementary studies.

D. Innovation & expertise

MaPP is very **innovative, ambitious, unique and timely**. Dealing with the issue of Origins, this research is a very hot topic in the international community. It was recently selected by the French Agence National pour la Recherche (ANR) for funding and support.

Gathering an even proportion of observers and theorists from the Canadian, French, Opticon, Taiwan and USA communities, our team includes most world experts (and the French and Canadian leaders) on all aspects tackled within MaPP. The **Grenoble group** is well known for its forefront contributions on stellar and planetary formation (the IAU Symposium 243 on Star/Disc Interactions in Young Stars was organized in Grenoble and chaired by J Bouvier); the **McMaster/Toronto group** has pioneered the field of stellar formation, with R Pudritz being one of the conceptors of the magneto-centrifugal models for protostars; the **Toulouse group** has extensive experience in spectropolarimetry, has developed both ESPaDOnS@CFHT and NARVAL@TBL and initiated tomographic imaging for investigating the large-scale magnetic topologies of active stars; the **St Andrews group** is widely known for its expertise in modeling magnetospheres and corona of active stars. Our team also includes world-wide experts on most topics relevant to our study, eg on the magnetized cloud collapse and the internal structure of low-mass stars (the ENS group), on stellar magnetic fields (at Rice University & STScI), on 3D numerical simulations of star/disc interactions (eg the Cornell group), on simulating accretion discs and planet migration (the IAP group), on Xray observations of pre-main-sequence objects (at Penn State & ESO).

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[2] MagIcS is an international project aimed at studying the magnetic fields of various classes of stars throughout the HR diagram. The main goal is to produce up-to-date models of magnetic stars, by (i) investigating the origin of such fields and identifying the physical processes producing them, and (ii) documenting the impact of magnetic fields on the physical processes at work within and around stars and thereby on the long-term evolution of stars. MagIcS also supports several current and future space missions and includes a LEGACY database of all collected spectropolarimetric data. More information about MagIcS on http://www.ast.obs-mip.fr/users/donati/magics/

Figures (2 pages)

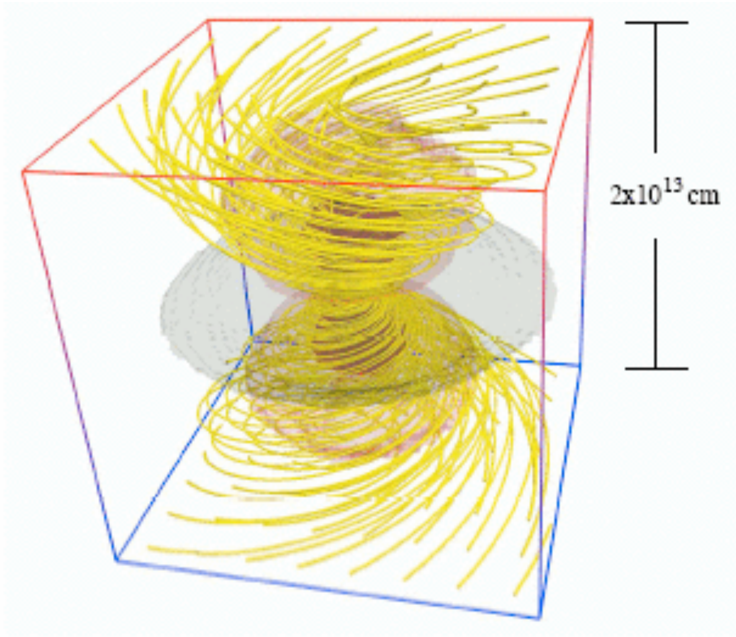

Figure 1: magnetic field structure, outflow and disc as obtained from the 3D MHD collapse simulation of Banerjee & Pudritz (2006).

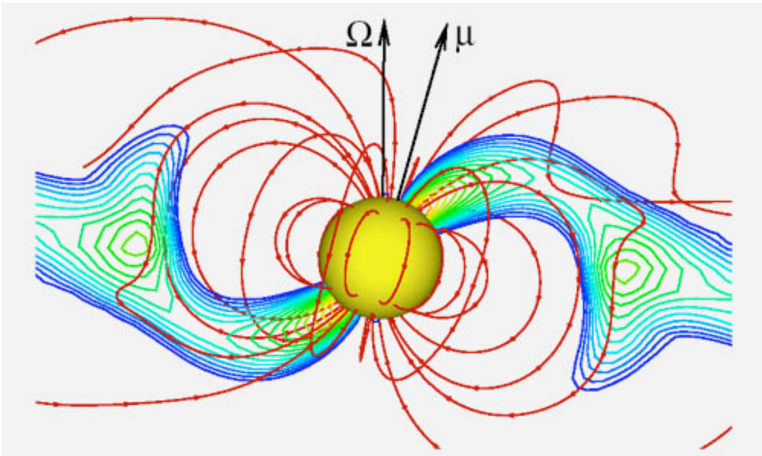

Figure 2: 3D MHD simulations of disc accretion to an inclined dipole from Romanova et al (2004). The material from the inner disc (shown as green/blue density contours) regions flows along the field lines (in red) onto the magnetic poles at the surface of the star, producing funnel streams linking the disc to the star and hot accretion spots at the funnel footpoints.

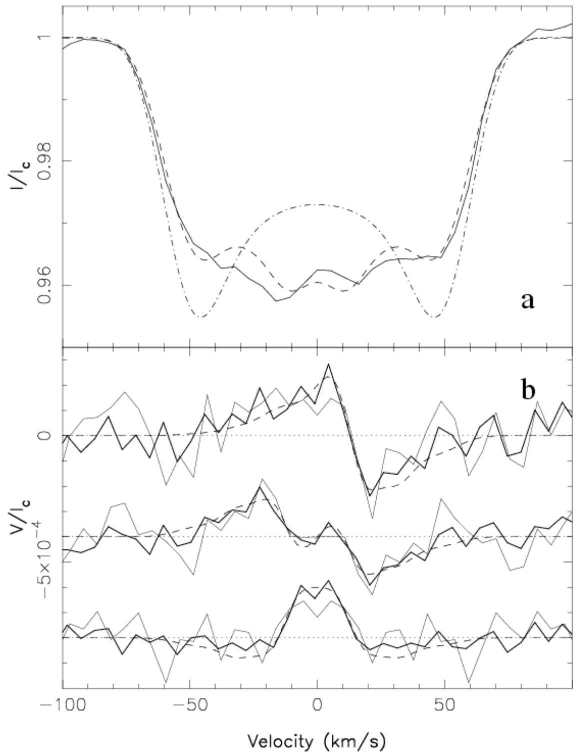

Figure 3a: Unpolarized line profile of FU Ori as observed ESPaDOnS (full line) with a standard (dot-dash) and modified (dash) disc model featuring a slowly rotating disc component.
3b: Zeeman signature of FU Ori as observed with ESPaDOnS (top), with antisymmetric (middle) and symmetric (bottom) components. Observations (full line) indicate the presence of a 1 kG vertical field plus a 0.5 kG azimuthal field in a slowly rotating disc plasma (from Donati et al 2005).

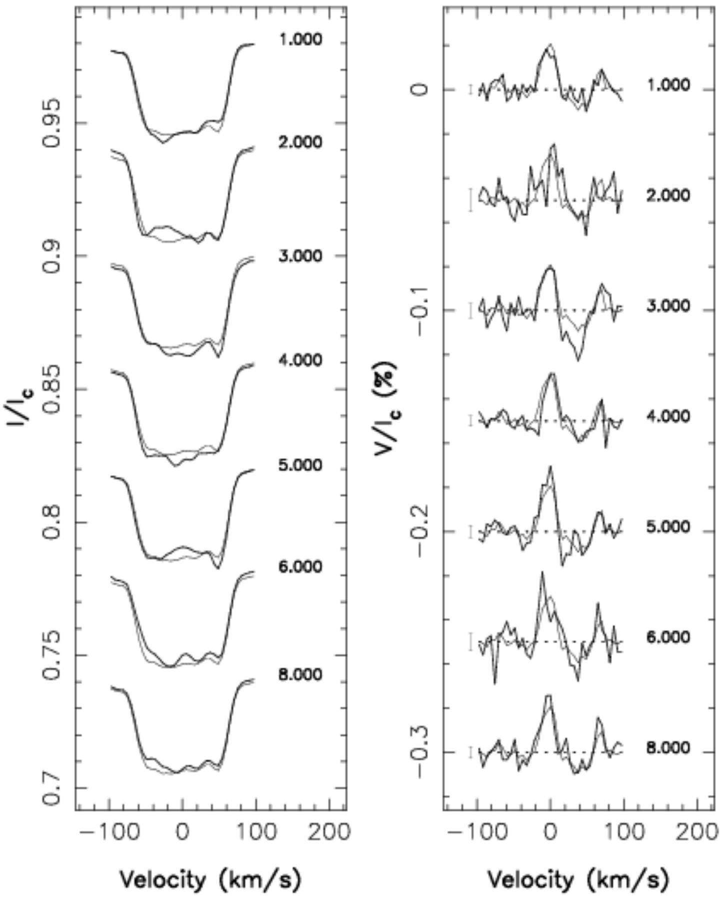

Figure 4: Unpolarized (left) and polarized (right) signatures of FU Ori in 2006 Feb (ESPaDOnS observations). The night number (1-8) is indicated next to each observed profile (thick line). The thin line depicts the mean profile. A 1sigma error bar is shown left to each Zeeman signature. On night 3, the observed Zeeman signature departs significantly from the mean, suggesting that variability is present.

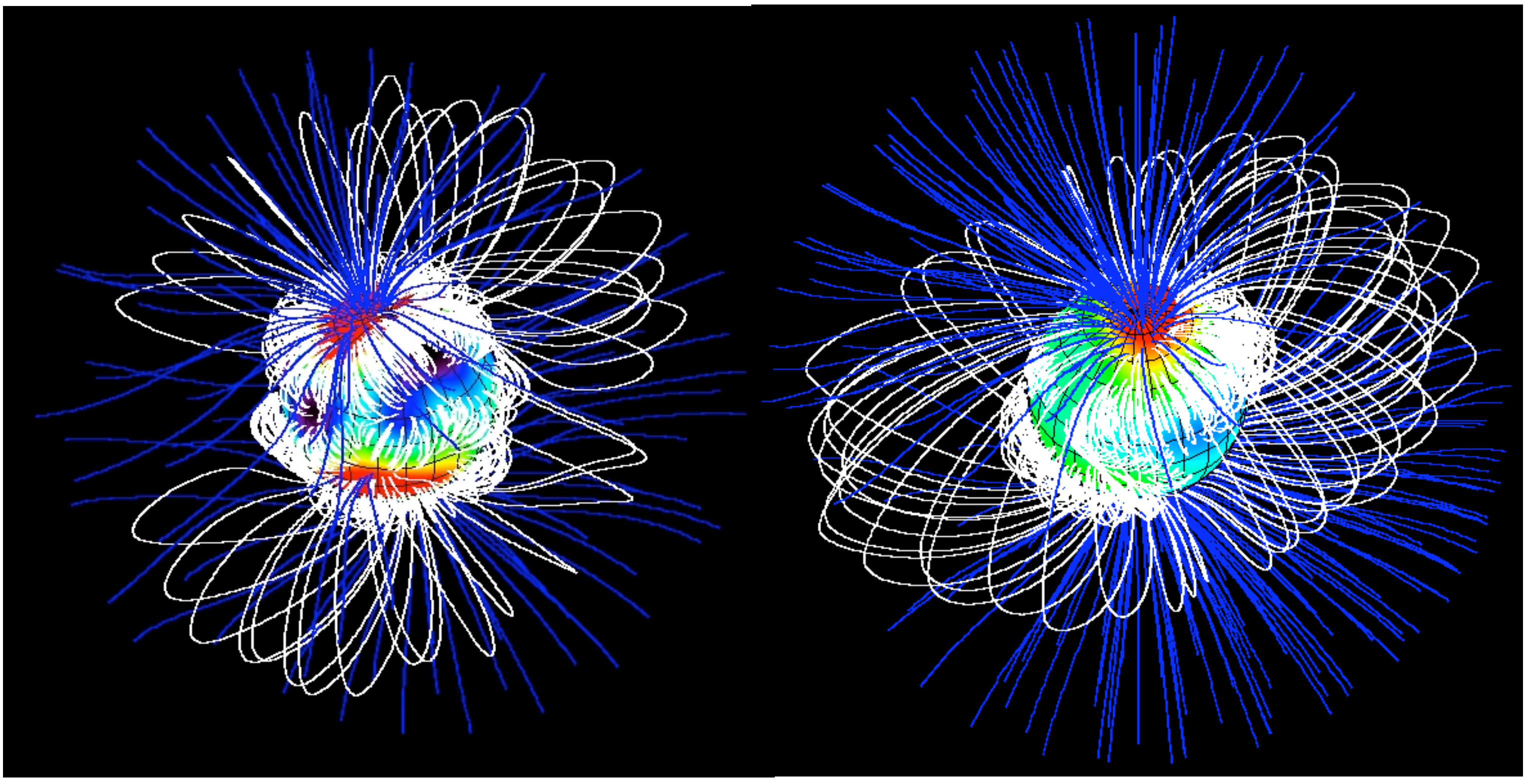

Figure 5: Simulated magnetospheres of the cTTSs V2129 Oph (left panel) and BP Tau (right panel) derived from the time-resolved data sets of Zeeman signatures collected with the ESPaDOnS (from Donati et al 2007, 2008). These magnetospheric maps are extrapolated from the surface magnetic map derived with tomographic imaging. Closed field lines are shown in white and open field lines are shown in blue. While the large-scale field is rather simple in both cases, the surface field shows complex multipolar structures associated with smaller field loops. Accretion funnels are anchored in the strongly magnetic regions close to the pole. **This image is best viewed in full color.**

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3. Technical Justification (3 pages)

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 in the first 3yrs of ESPaDOnS operation.

The ESPaDOnS observations already collected on FU Ori (Donati et al 2005), on V2129 Oph (Donati et al 2007) and on BP Tau (Donati et al 2008) demonstrate that the Zeeman signatures of FUOrs and cTTSs are detectable, demonstrating that our program is entirely feasible. More information on individual targets is given below.

Requested time:

For **FU Ori**, ESPaDOnS yields a peak S/N ratio of about 500 per 2.6 km/s velocity bin in Stokes V and I spectra for a 4x600s-exposure polarization sequence. Using cross-correlation routines such as Least-Squares Deconvolution (LSD, Donati et al 1997), we will extract the polarization information through some 5,000 line profiles simultaneously and improve the S/N ratio in V spectra by a factor of about 30 with respect to a single line with average magnetic sensitivity, yielding polarization accuracies of order 6×10^{-5} per 2.6 km/s velocity bin in the resulting LSD Stokes V profiles. This ensures that the small Zeeman signatures of FU Ori (full size of about 0.04% peak to peak, see Figs 3 & 4) are detected at 7 sigmas. We will then collect such signatures during the whole visibility period of the star (about 8 hr/n) during 16 consecutive nights (corresponding to the Keplerian period at a distance of 0.1 AU) to monitor the line profile changes at timescales ranging from a 1 hr to 16 d - this monitoring will be used to extract the density and field distribution within the disc using tomographic imaging (eg Marsh & Horne 1988). **The complete magnetic monitoring of FU Ori thus requires a total of 128 hr**.

For **V1057 Cyg** and **V1515 Cyg**, we will start by collecting 6 polarization sequences of 4x1200s, ie accumulate photons during the whole visibility period of each object (8 hr). Combining all spectra will yield a peak S/N ratio of about 500 in the spectrum of each object, and should allow the detection the Zeeman signatures with the same accuracy as for FU Ori (using LSD). We will first collect 3 such profiles (for each star) to confirm the detection and look for potential variability, then carry out the same analysis as Donati et al (2005) and will determine the strength and orientation of the (presumably) dominant axisymmetric field component within the inner regions of both accretion discs. **The field detections on V1057 Cyg and V1515 Cyg thus requires a total of 48 hr**.

For the most interesting/accessible of either V1057 Cyg and V1515 Cyg, we will carry out the same extensive monitoring as that of FU Ori, consisting in following the temporal variations of the Zeeman signature over a timescale of 16d. While variations on timescales of a few hrs will likely be out of reach (given the relative faintness of V1057 Cyg and V1515 Cyg with respect to FU Ori), we will still be able to monitor the longer timescales and map the main non-axisymmetric features within the disc (in addition to the dominant axisymmetric component). As for FU Ori, **this monitoring requires a total of 128 hr.**

The complete monitoring of all FUOrs at all epochs thus requires a total of 304 hr.

For **AA Tau**, **BP Tau**, **DG Tau, DK Tau and DN Tau and V2247 Oph** (ie the cTTSs of our sample with lowest brightnesses and longest periods), we will collect 1 polarization sequence of 4x1200s per night and per star, yielding a peak S/N ratio of 160 in average (ranging from 130 for V2247 Oph to 200 for BP Tau) per 2.6 km/s velocity bin. Using LSD, we will obtain polarization accuracies of order 3×10^{-4} in the resulting LSD Stokes V profiles. This is enough to detect the large Zeeman signatures both in photospheric line profiles and emission lines formed at the footpoints of accretion funnels (Donati et al 2008). We will monitor the variability of such signatures at a rate of about 1 per night over a complete time span of 16 n, ie twice the rotation period of the most slowly rotating cTTS of our sample (8.5d) to be able to disclose rotational modulation from intrinsic variability (usually significant in the spectra of cTTSs) in the observed profile variations. With a (shorter) period of 3.5 d, the rotation cycle of V2247 Oph can be covered with enough phase density in 7 n only, with observations covering 16 n ensuring that the surface of the star is covered twice (within 4 rotation cycles). Such data sets are perfectly adequate for carrying tomographic imaging of magnetic fields over stellar surfaces, as demonstrated in Donati et al (2008). **For each of these stars, the full monitoring requires 24 hr for 1 epoch** (including slewing, pointing, guiding and readout).

For **DF Tau, V2129 Oph, COUP 932, TW Hya, RY Lup, GQ Lup** (ie the cTTSs of our sample with intermediate magnitudes), we will carry out the same strategy except that the exposure time is decreased to 4x600s (to compensate for the higher brightness); this should yield an average peak S/N ratio of about 220 per 2.6 km/s velocity bin, enough to detect the large Zeeman signatures both in photospheric line profiles and emission lines formed at the footpoints of accretion funnels (Donati et al 2007). The (shorter) rotation period of TW Hya (2.8 d) and RY Lup (3.8 d) respectively require at least 12 and 16 n to provide both a dense enough phase coverage (with phase gaps smaller than 0.1 cycle) over successive rotation cycles (to disclose rotational modulation from intrinsic variability). **For each of these stars, the full monitoring requires 13 hr for 1 epoch** (including slewing, pointing, guiding and readout).

For **T Tau, RY Tau, SU Aur** (ie the brightest cTTSs of our sample, with relatively short periods), we will further decrease the exposure time to 4x400s ensuring an average peak S/N ratio of about 300 per 2.6 km/s velocity bin. This is adequate to detect the Zeeman signatures, in particular for SU Aur and RY Tau in which the larger rotation velocities generate smaller amplitude signatures (snapshots already collected on all three stars show that this S/N ratio is adequate for our needs). For all 3 stars, 2 polarisation sequences will be obtained at both sides of the visibility window (lasting about 8 hr, ie 10% of the rotation cycle) to improve phase coverage within each night. As these stars are likely to host differential rotation (given their higher mass, eg Marsden et al 2006), monitoring must be carried out on a timescale of at least 8 n (in stars showing no intrinsic variability) and 16 n (in cTTSs) to be able to recover both the differential rotation and the magnetic topology with tomographic imaging. Additional polarisation sequences will be collected with NARVAL@TBL to improve further phase coverage on these shorter period stars. **For each of these stars, the full monitoring thus requires 18 hr (of ESPaDOnS time) for 1 epoch**

We plan to achieve one complete monitoring for BP Tau, DK Tau, DN Tau, V2247 Oph, DF Tau, V2129 Oph, RY Lup, GQ Lup and SU Aur, and two complete monitorings for AA Tau, DG Tau, T Tau, RY Tau, COUP 932 and TW Hya (see below). **The complete monitoring of all cTTS at all epochs thus requires a total of 386 hr**.

Need for CFHT:

ESPaDOnS@CFHT is the **only instrument worldwide** that can achieve this survey. The other stellar spectropolarimeters worldwide (yielding publishable data) have either too low a spectral resolution (eg FORS1/VLT, with a spectral resolution of order 1,500 max, or ISIS/WHT with a spectral resolution of 7,000) or too low an efficiency (eg McDonald) for detecting Zeeman signatures with sufficient accuracy in photospheric lines (eg Donati et al 2007). Even NARVAL (the ESPaDOnS twin on the 2m Telescope Bernard Lyot at Pic du Midi) can only reach the brightest stars of this Large Program (and will be used to complement phase coverage for the brightest stars).

Existing observations & summary of new observations needed:

ESPaDOnS time was already allocated on a small number of our program stars. Data collected on FU Ori, V2129 Oph and BP Tau are published already (Donati et al 2005, 2007, 2008). Additional time was allocated on AA Tau, T Tau and RY Tau in semester 07b (2 n); however, 95% of the allocation was lost due to dreadful weather conditions. Time (24 hr) is allocated on TW Hya in semester 08a. **All data collected already will be merged to this program**.

For each star, we therefore have/need:

V2129 Oph	1 complete monitoring collected (05a) -	1 more complete monitoring needed
BP Tau	1 complete monitoring collected (06a/b) -	1 more complete monitoring needed
TW Hya	1 complete monitoring allocated (08a) -	2 more complete monitorings needed
SU Aur	1 fragmentary data set collected (06b) -	1 complete monitoring needed
T Tau	2 complete monitorings needed (07b run lost)	
RY Tau	2 complete monitorings needed (07b run lost)	
AA Tau	2 complete monitorings needed (07b run lost)	

DG Tau	2 complete monitorings needed
COUP 932	2 complete monitorings needed
DF Tau	1 complete monitoring needed
DK Tau	1 complete monitoring needed
DN Tau	1 complete monitoring needed
RY Lup	1 complete monitoring needed
GQ Lup	1 complete monitoring needed
V2247 Oph	1 complete monitoring needed
FU Ori	field & variability detected (04b/06a) - 1 complete monitoring needed
V1057 Cyg	field detection + 1 complete monitoring needed
V1515 Cyg	field detection needed

Long-term scheduling:

This Large Program will be carried out over 9 semesters, ie from semester 2008B to semester 2012B. Obtaining data at several epochs for some stars of the program imposes a specific data collection strategy. One possible way of spreading out the required observations is as follows:

in **2008B**:	T Tau, RY Tau, DG Tau, AA Tau	requires 84 hr @ RA=04
	COUP 932	requires 13 hr @ RA=06
in **2009A**:	V2247 Oph, RY Lup, GQ Lup	requires 50 hr @ RA=16
in **2009B**:	FU Ori	requires 128 hr @ RA=06
in **2010A**:	TW Hya,	requires 13 hr @ RA=12
	V1057 Cyg, V1515 Cyg	requires 48 hr @ RA=20
in **2010B**:	DK Tau, DN Tau, DF Tau	requires 61 hr @ RA=04
in **2011A**:	V1057 Cyg or V1515 Cyg	requires 128 hr @ RA=20
in **2011B**:	BP Tau, SU Aur	requires 42 hr @ RA=04
in **2012A**:	TW Hya, V2129 Oph	requires 26 hr @ RA=12-16
in **2012B**:	T Tau, RY Tau, DG Tau, AA Tau	requires 84 hr @ RA=04
	COUP 932	requires 13 hr @ RA=06

The MagIcS LEGACY database:

All ESPaDOnS data collected with MaPP will feed the **MagIcS LEGACY database**, gathering all spectra accumulated with ESPaDOnS@CFHT and NARVAL@TBL. This database, expected to contain ultimately about 100,000 spectra, will be accessible to the entire community.

This database is expected to be very useful for many studies in fundamental physics in general and in astrophysics in particular. For instance, studies in **atomic physics** will be able to access spectra on very-low-mass strongly-magnetic stars (such as those MaPP will collect) to study molecular bands and investigate, eg their magnetic sensitivities (not yet known accurately enough to perform precision modeling studies). Studies of the **interstellar medium** will also greatly benefit from the high-resolution spectra contained in the database to detect the presence of specific chemical species (using the diffuse interstellar bands they generate) and analyze their physical properties (eg molecular structure). Similarly, studies in **galactic physics** and **cosmology** may use high-resolution spectra to investigate stellar populations, derive redshifts and identify optical counterparts of GRBs with increased accuracy. Finally, studies of **secular changes**, **cyclic** or **sporadic phenomena** (eg orbits, cycles, activity, flares, outbursts, mass ejection/accretion events, all directly relevant for young PMS stars) will also strongly benefit from this database and its MaPP subsample.

The first beta version of the MagIcS LEGACY database will come online in Spring 2008 and will include a small selection of high-S/N ESPaDOnS and NARVAL spectra.

4. Target information (1 page)

name	coordinates (2000)		mV	ST	M (M_{sun})	Prot (d)	Macc ($\times10^{-8}$ M_{sun}/yr)	Jet?
FUOrs:								
FU Ori	05 45 22.3	+09 04 12.3	9	G	0.4		1000	no
V1515 Cyg	20 23 48.0	+42 12 25.9	12	G				yes
V1057 Cyg	20 58 53.7	+44 15 28.5	12	G				yes
cTTSs:								
BP Tau	04 19 15.8	+29 06 26.8	12.3	K7	0.7	7.6	2.9	no
T Tau	04 21 59.4	+19 32 06.4	9.8	G5	2.3	2.8	4.4	no
RY Tau	04 21 57.4	+28 26 35.5	10.2	K1	2.2	3.0		yes
DF Tau	04 27 02.7	+25 42 22.3	11.0	M1	0.4	8.5	20	
DG Tau	04 27 04.7	+26 06 16.3	12.8	G2	0.7	6.3	90	yes
DK Tau	04 30 44.2	+26 01 24.7	12.6	K7	0.8	8.4	3.8	
AA Tau	04 34 55.4	+24 28 53.2	12.8	M0	0.7	8.2	0.3	no
DN Tau	04 35 27.3	+24 14 58.9	12.5	M0	0.6	6.0	0.3	
SU Aur	04 55 59.3	+30 34 01.5	9.4	G2	1.9	2.8	0.5	no
COUP 932	05 35 17.9	-05 22 45.4	11.4	K1	2.5	8.5	~10	
TW Hya	11 01 51.9	-34 42 17.0	11.1	K8	0.7	2.8	0.2	no
RY Lup	15 59 28.3	-40 21 51.2	11.1	K4	1.5	3.8		no
GQ Lup	15 49 12.1	-35 39 03.9	11.4	K7	0.7	8.4		no
V2129 Oph	16 27 40.3	-24 22 02.6	11.4	K5	1.4	6.5	1.0	no
V2247 Oph	16 27 19.5	-24 41 40.5	13.2	M0	0.9	3.5	<10	

Notes on the CTTSs: targets were selected for their potential interest for MaPP and to offer a range of masses (from 0.4 to 2.5 M_{sun}), rotation periods (from 2.8 to 8.5 d), mass accretion rates (from 0.2 to 100×10^{-8} M_{sun}/yr) and jet properties:

- stars in the **Taurus/Auriga star formation cloud** have well known characteristics (eg ages of 2-3 Myr) and numerous published studies describe their spectral properties, rotational modulation and intrinsic variability (eg Johns-Krull et al 2007; Grankin et al 2007);
- COUP 932 (in the Orion Nebula Cloud) is especially interesting for its very young age (0.3 Myr) and its well-studied X-ray light curve obtained by Chandra (Getman et al 2005);
- TW Hya is also very well studied and the newly discovered close-in giant planet orbiting within the inner disc rim makes it a primary target for MaPP - this is the oldest star of our sample (8-10 Myr);
- the selected cTTSs in Lupus (1-3 Myr old) and Ophiucus (2 Myr old) are the best studied/brightest members of their respective star forming region. GQ Lup may also host a giant planet, but much further out in its accretion disc (100 AU).

Right ascension distribution of the observations:

2008B:	84 hr @ RA 04:30
	13 hr @ RA 05:30
2009A:	50 hr @ RA 16:00
2009B:	128 hr @ RA 06:00
2010A:	13 hr @ RA 11:00
	48 hr @ RA 20:30
2010B:	61 hr @ RA 04:30
2011A:	128 hr @ RA 20:30
2011B:	42 hr @ RA 04:30
2012A:	13 hr @ RA 11:00
	13 hr @ RA 16:30
2012B:	84 hr @ RA 04:30
	13 hr @ RA 05:30

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 by **Donati** with a version of Libre_ESpRIT (optimized for young stars with strong emission lines) and will feed the MagIcS LEGACY database. When a full data set is available, we will retrieve Zeeman signatures from photospheric lines (using LSD) and will also extract Zeeman signatures from lines (eg HeI D) formed in accretion funnels. Accurate radial velocities from photospheric lines will be derived from LSD profiles.
2. **Complementary data:** Whenever possible, additional data from NARVAL/TBL will be collected and processed by **Donati** in exactly the same way as the ESPaDOnS data. **Hussain** will organize complementary observations with Chandra/XMM, while **Trung/Houde** will setup observations with ALMA (from 2010). **Johns-Krull/Valenti** will be in charge of organizing the coordinated Phoenix/Gemini nIR observations. **Bouvier/Grankin** will coordinate the simultaneous photometric observations with Mt Maidanak observatory and/or SuperWASP.

B. Data modeling

1. **Tomographic imaging:** Magnetic imaging from spectropolarimetric data sets will be carried out by **Donati** with the same code and model as that used already for V2129 Oph and BP Tau (Donati et al 2007, 2008). **Hussain** and **Trung** have also developed similar magnetic imaging codes, with which the imaging results will be checked for consistency.
2. **Spectroscopic modeling:** detailed spectroscopic modeling from the collected spectra and updated fundamental parameters (mass, radius, age, accretion rates) will be derived by **Valenti/ Mohanty**. Detailed modeling of nIR spectra will be carried by **Johns-Krull**. Analyzing radial velocity data for the potential presence of close-in giant planets will be done by **Donati/Valenti**. All tools necessary for this step are already available (eg Johns-Krull et al 1999b).
3. **Magnetic field extrapolation** from the surface topologies derived by tomographic imaging will be derived by **Gregory/Jardine** with their (existing) code as well as all further interpretation on the location of accretion funnels
4. **Modeling the Chandra/XMM data** will be carried out by **Hussain/Gregory/Jardine** given their extensive experience; **Trung/Houde** will be in charge of analyzing & modeling **the ALMA data**.

C. Simulations

1. **Simulations of the magnetised cloud collapse** will be carried simultaneously by **Pudritz** in Canada and **Hennebelle** in France and compared to the observations of FUOrs secured with ESPaDOnS & ALMA to obtain diagnostics about the origin of the field and the dissipation of angular momentum and magnetic flux throughout the collapse. Both groups have extensive experience, tested codes and published results on the subject.
2. **Star/disc magnetic interactions,** featuring in particular magnetic topologies similar to those observed with ESPaDOnS, will be carried out both by **Ferreira/Zanni/Dougados** in Grenoble and by **Romanova/Long** at Cornell, with the aim of finding out how much star/disc magnetic coupling is able to influence angular momentum evolution. Quantitative comparisons with new theoretical models will also be achieved by **Mohanty.** Modeling the influence of accretion on the **internal structure of the protostar** will be carried out by **Chabrier**. Again, all codes are already available for this simulation step.
3. **Constraining conditions of jet formation** from the magnetic topologies observed in cTTSs and accretion discs will be carried out **Dougados/Ferreira/Zanni** in Grenoble using all the theoretical tools and models they developed in the last decade.
4. **Reevaluating giant close-in planet formation and migration** from the data collected on protostellar discs and cTTSs will be carried out by **Romanova/Terquem** using the 3D MHD codes they developed with their own team.

D. Coordination, scheduling & publications

Meetings gathering most co-Is will be organized throughout the project in the framework of the **MagIcS collaboration**, and whenever enough data and modeling results have been obtained (typically every yr and in particular at mid project, ie in 2010b) in order to (i) share and discuss all available results and potentially identify new modeling efforts, (ii) compare results with theoretical predictions and suggest new simulations, and (iii) discuss the presentation/publication strategy. At mid-course, all stars will have been observed at least once, giving us a chance to re-optimize our sample and data collection if needed. Global project coordination will be done by the PI.