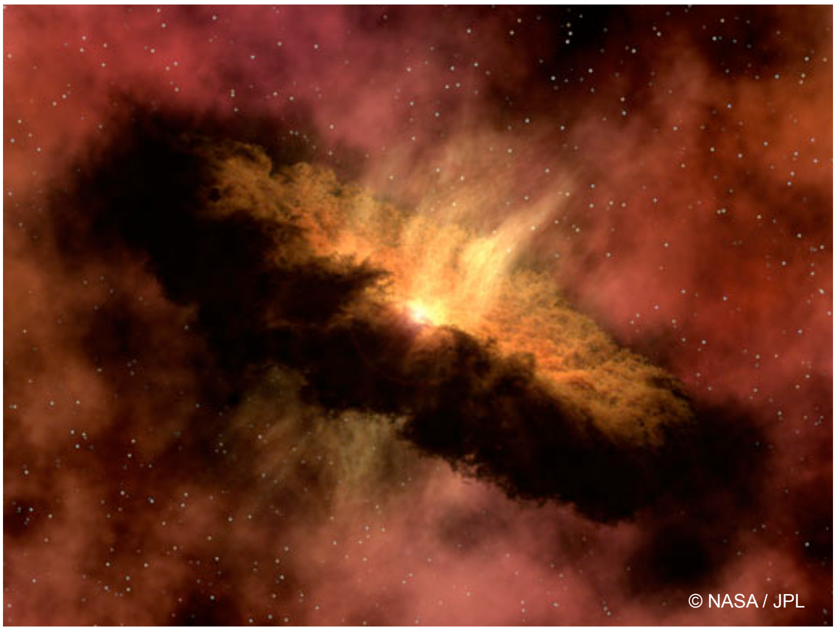
✳ MaPP ✳
Magnetic Protostars & Planets

a Large Program with ESPaDOnS@CFHT



Abstract

MaPP is studying how magnetic fields impact the later phases of stellar & planet formation, when protostars are still surrounded by, and accreting mass from, a planet-forming accretion disc. Observationally speaking, MaPP is **the first spectropolarimetric survey of a small sample of protostars and protostellar discs** and was selected as a CFHT Large Program, with 690 hr of allocated time scheduled on semesters 2008b to 2012b.

We present herein the mid-term report of MaPP, with a short description of the major results obtained already. We also propose a change in the observing schedule for the second half of the program, given the results obtained so far.

We finally propose two **logical extensions to MaPP that could further boost the overall science return** - to be carried out from 2013a to 2014b. The first one aims at extending by 2 yr our monitoring of 4 prototypical cTTSs to better characterize their magnetic changes/cycles; with the second one, we propose to concentrate on disc-less protostars as the missing link between the study of accreting protostars (the ongoing MaPP project) & that of main-sequence stars.

1. Summary of MaPP science goals

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 focuses on the core regions of protostellar accretion discs, the newly born star and their potential close-in giant planets.

MaPP is **the first spectropolarimetric survey on a significant sample of low-mass protostars, including a few bright protostellar accretion discs.** MaPP allows one to 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 can answer several major open questions on star formation and ultimately lead to updated models incorporating the effect of magnetic fields**. MaPP is part of the international **MagIcS**[1] initiative aimed at coordinating research efforts on stellar magnetism.

The **major unresolved issues** on which MaPP concentrates are:

- **what is the origin of the disc field? how much angular momentum and magnetic flux is dissipated during the cloud collapse?** This is addressed 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 (ie FUOrs) from which the jets are fired;
- **how does magnetospheric accretion control the angular momentum and how much does it modify the internal structure of the protostar?** This is studied by measuring the intensity and complexity of the magnetic fields that protostars (ie classical T Tauri stars or cTTSs) host and weave with their accretion disc to funnel the disc material towards the stellar surface.
- **why are some discs/protostars showing jets while some others are not?** Here we investigate how jets relate to the magnetic fields in accretion discs and to those on protostars;
- **how do close-in giant planets form and stop their inward migration?** This is addressed by trying to detect close-in giant planets potentially present in the central regions of protostellar accretion discs or around more evolved protostars.

MaPP was selected as a Large Program at CFHT in 2008 and allocated a total of **690 hr of telescope time over 9 semesters** (2008b-2012b), for carrying out **the first spectropolarimetric survey of 15 cTTSs and 4 FUOrs** (with multiple visits for some of them).

2. MaPP observations & results obtained in 2008b-2010a

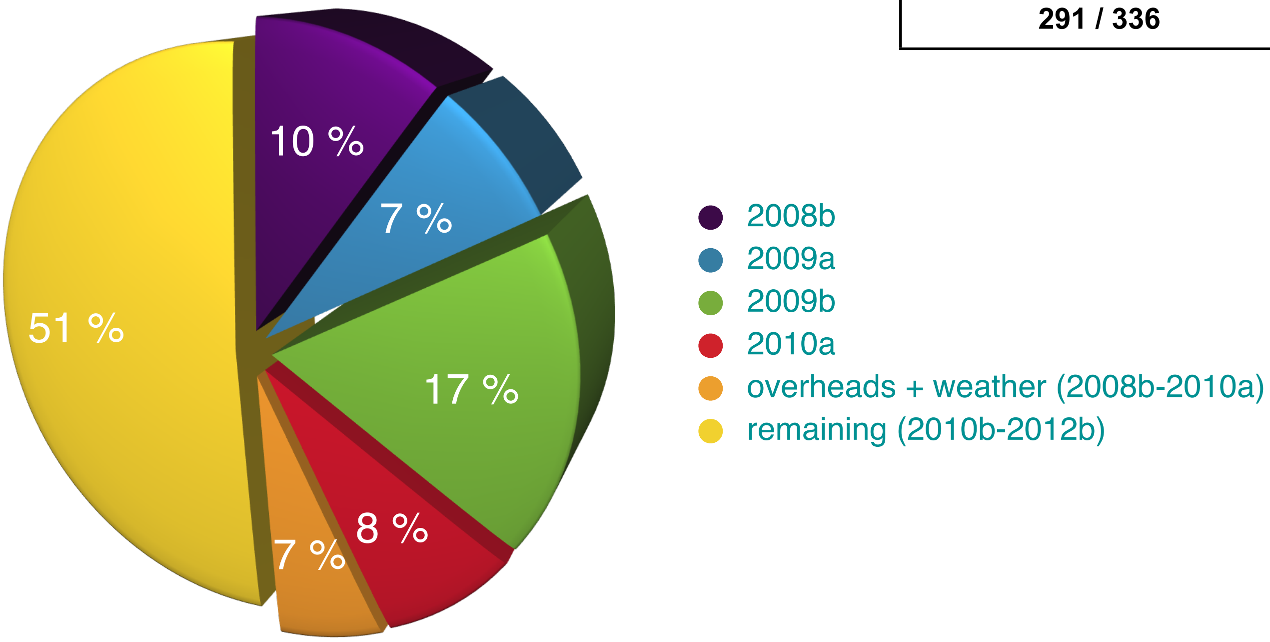
Up to now, about half of the MaPP observations (336 hr) have been carried out, with a **full amount of 291 hr spent on the sky**, and 45 hr spent in overheads & lost to weather problems. Table 1 & Figure 1 summarize the details of the observations carried out so far, demonstrating in particular that QSO has been fairly successful at collecting valuable MaPP data.

Additional observations were also collected at various times with NARVAL@TBL (the ESPaDOnS twin mounted on the 2m Telescope Bernard Lyot atop Pic du Midi), with HETG @Chandra (for V2129 Oph & DG Tau), with HARPS@ESO (for V2129 Oph), with SMARTS (photometry & spectroscopy) and with photometric telescopes in Ukraine, Uzbekistan & Armenia. The NARVAL@TBL observations have been plagued by poor weather, yielding a total of only 65 hr of observing time on the sky (out of an allocation of ~400 hr). **Multi-site & multi-wavelength coordinated campaigns** (involving in particular HETG@Chandra) were organized for 2 specific

[1] MagIcS (standing for «Magnetic Investigation of various classes of Stars throughout the HR diagram») involves stellar astrophysicists (both observers & theoreticians) from all over the world, and in particular from France & Canada whose long-standing partnership in this field of research led to the construction of new instruments and to a rich harvest of new discoveries.

Table 1 & Figure 1: Observations carried out with MaPP in semesters 2008b-2010a, corresponding to a total observing time of 336 hr or 49% of the full MaPP allocation (690 hr). Up to now, 87% of the allocated time was used for observations while only 13% was lost to overheads (read-out) & weather problems, demonstrating that QSO is successful at collecting MaPP observations.

semester	dates	stars	observed / allocated (hr)
2008b	Dec 04 - Dec 18 Dec 29 - Jan 09	T Tau, RY Tau, DG Tau, AA Tau, COUP 932, Z CMa	68 / 97
2009a	Jun 30 - Jul 13	V2129 Oph, RY Lup, GQ Lup	48 / 50
2009b	Nov 23 - Dec 09 Dec 30 - Jan 06 Jan 22 - Feb 01	FU Ori, DG Tau	119 / 128
2010a	Feb 22 - Mar 07 Jul 16 - Jul 21	TW Hya, V1057 Cyg, V1515 Cyg	56 / 61
			291 / 336



targets (V2129 Oph in 2009a and DG Tau in 2009b) to provide stronger constraints on the magnetospheric accretion processes taking place on cTTSs.

Since the first MaPP observations slightly less than 2 yr ago, sets of polarized spectra have been collected for **9 cTTSs & 4 FUOrs** (see Table 1), with data secured at 2 different epochs for DG Tau. Fields are detected on all 9 cTTSs, with Zeeman signatures from photospheric lines changing with time as expected from rotational modulation. **The full analysis has been completed for 2 stars**[2] up to now, namely AA Tau (Donati et al 2010b, MNRAS in press, astro-ph: 1007.4407) and V2129 Oph (Donati et al 2010c, MNRAS submitted, see also Fig 2), using in particular a mature version of the imaging code. In particular, these studies have enabled to obtain **2 major results**:

[2] Preliminary results for 2 other cTTSs (namely BP Tau & V2247 Oph) were also derived from pre-MaPP data with an experimental version of the imaging code. These initial results suggested in particular that the magnetic properties of cTTSs resemble those of low-mass main-sequence stars, with intermediate-mass (BP Tau-like) cTTSs hosting much stronger dipolar components than higher-mass cTTSs (Donati et al 2008, MNRAS 386, 1234) and very-low-mass (V2247 Oph-like) cTTSs showing more complex fields and strong differential rotation (Donati et al 2010a, MNRAS 402, 1426). Pre-MaPP data are progressively merged into MaPP as new data are collected (as done for V2129 Oph, Donati et al 2010c, MNRAS submitted).

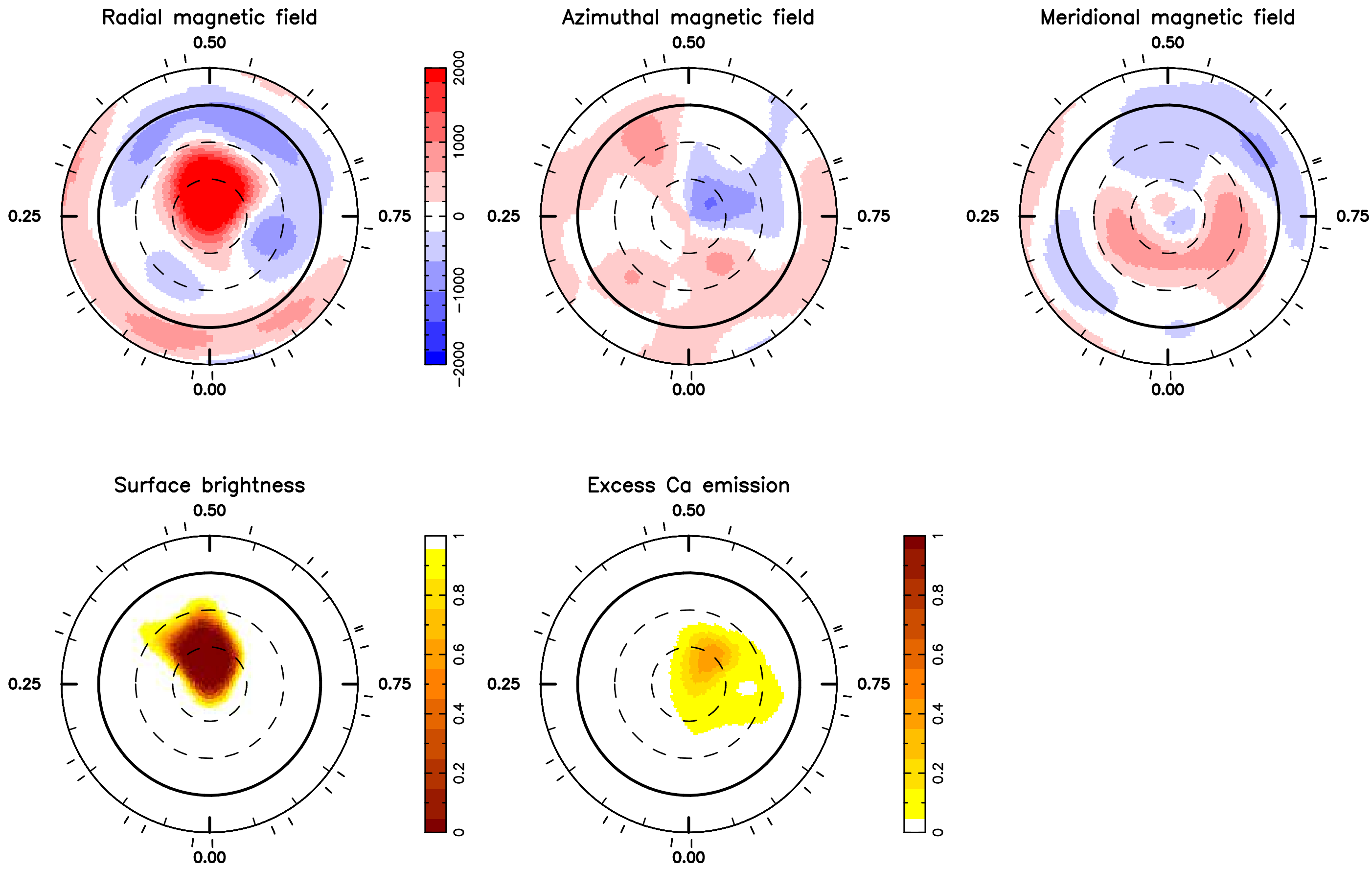


Figure 2: Maps of the radial, azimuthal and meridional components of the magnetic field (upper row, left to right panels), photospheric brightness and accretion-powered Ca II emission (lower row, first and second panels) at the surface of V2129 Oph in 2009 July, derived with the latest version of the imaging code. Magnetic fluxes are labeled in G. In all panels, the star is shown in flattened polar projection down to latitudes −30°, with the equator depicted as a bold circle and parallels as dashed circles. Radial ticks around each plot indicate phases of observations (from Donati et al 2010c, MNRAS submitted). The large-scale topology of V2129 Oph has significantly changed since our pre-MaPP observations in 2005 June, unambiguously demonstrating that the field is **produced through non-stationary dynamo processes**.

- large-scale magnetic fields of cTTSs are variable on time scales of a few years, implying that they are **produced through non-stationary dynamo processes** (rather than being fossil remnants from the cloud collapse). This is the first direct observational evidence that fields of cTTSs are of dynamo origin.
- fully convective cTTSs (like AA Tau) can host a strong enough large-scale dipole (at least some of the time) that may potentially **slow down their rotation through propeller-type star/disc magnetospheric interactions.** This is the first direct evidence that magnetic fields can be the cause of the slow rotation of cTTSs.

In particular, these results significantly improve our understanding of magnetospheric accretion processes & angular momentum regulation in cTTSs (our second main science goal, see Sec 1). Three more papers on other cTTSs, namely COUP 932 (Skelly et al 2010b, to be submitted soon), TW Hya (Donati et al 2011, in preparation) and DG Tau (Morin et al 2011, in preparation) will appear in the coming semester and 2 others (one on T Tau & RY Tau and another on RY Lup & GQ Lup) will follow soon afterwards. Comparing results from DG Tau & RY Tau (both having jets) to those of AA Tau/BP Tau & T Tau (showing no jets but with otherwise similar properties) will bring clues for our third main science goal (see Sec 1).

Several additional papers describing companion data sets and their implications (eg Argiroffi et al 2010,to be submitted soon, focussing on the Chanda data collected on V2129 Oph as part of the MaPP campaign) or presenting results from numerical simulations (eg Romanova et al 2010, MNRAS in press, astro-ph:0912.1681, see also Fig 3; Long et al 2010, MNRAS

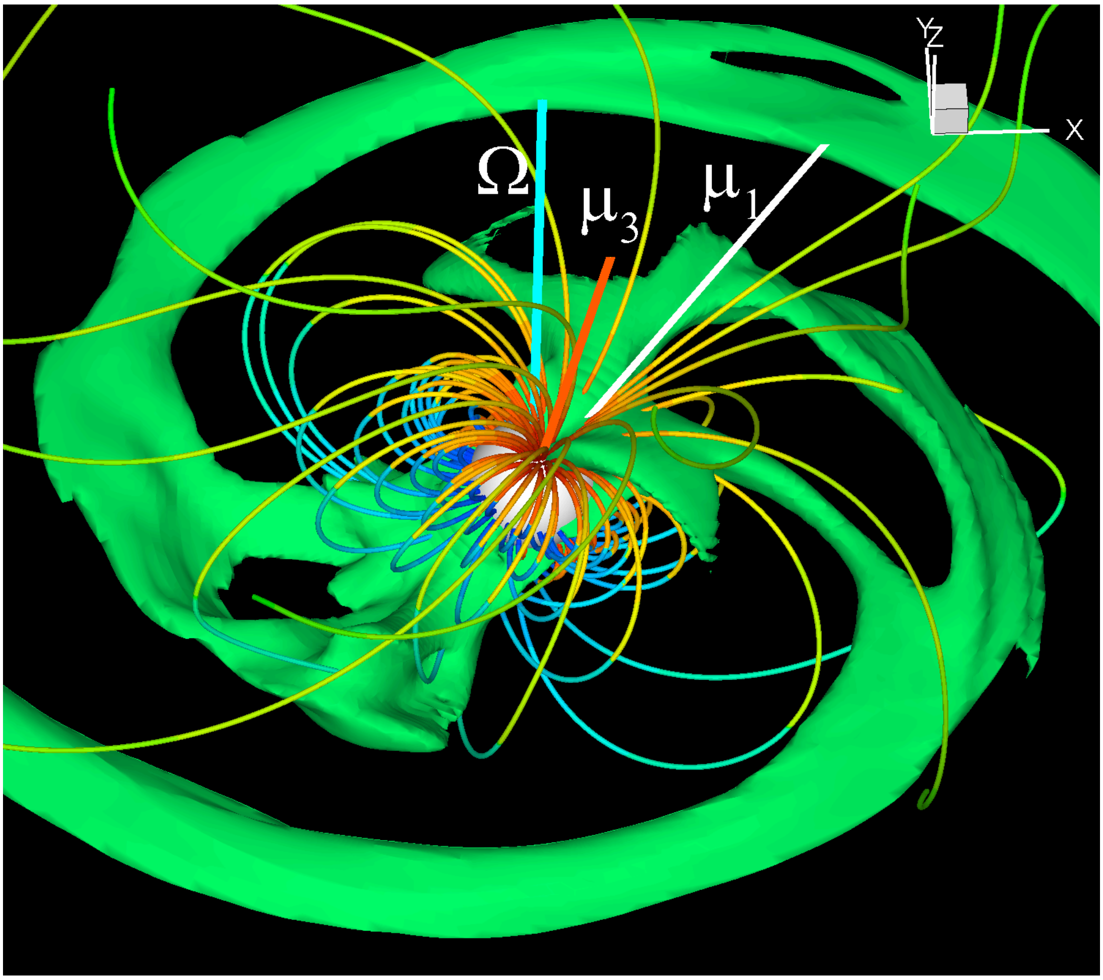


Figure 3: 3D view of matter flowing from the accretion disc onto the star in the dipole+octupole model of V2129 Oph. The accretion funnels are shown by a constant density surface in green. The thick cyan, white & red lines depict the rotational axis and the dipole & octupole moments respectively (from Romanova et al 2010, MNRAS in press).

submitted, astro-ph:1009.3300) or theoretical models (eg Mohanty & Shu 2008, ApJ 687, 1323) based on MaPP (or pre-MaPP) data are also in press or in preparation.

MaPP data also confirm that magnetic fields are present on FU Ori (the FUOr prototype); the extended data set collected in 2009b on FU Ori will enable the field to be characterized in much more detail, even though moderate weather conditions at CFHT did not allow us to collect as uninterrupted a data set as we initially aimed for. Data collected on 3 other FUOrs (Z CMa, V1057 Cyg & V1515 Cyg show no evidence of magnetic field, forcing us to readapt the observing program of the following semesters (see Sec 3). Two more papers (one on FU Ori and one on the other targets) are expected on this topic, in which we will discuss in particular the progress regarding the first & fourth main science goals (see Sec 1).

The observing plan, reduced spectra and preliminary results are all available to the MaPP community from the wiki site dedicated to the MaPP project (http://lamwws.oamp.fr/magics/mapp), updated at the end of each semester.

3. The second half of MaPP (2010b-2012b)

Observations in 2010b with ESPaDOnS@CFHT (72 hr) are already scheduled and will focus on AA Tau, DN Tau and DK Tau. Coordinated observations with COS@HST (PI Greg Herczeg) are planned on AA Tau & DN Tau; NARVAL@TBL observations (for which MaPP was recently granted LP status) are also scheduled in 2010b (for a total of 135 hr). In particular, this campaign will allow us to better **characterize magnetospheric accretion processes in low-mass cTTSs** thanks to the simultaneous COS@HST observations in the fUV that will provide an

Table 2: Revised MaPP observation plan for semesters 2010b–2012b, covering the remaining 354 hr of the full MaPP allocation. Time in 2010b is already scheduled. Given the magnetic non-detection obtained in 2010a on V1515 Cyg & V1057 Cyg, we propose to modify the initial observation plan for semesters 2011a to 2012b. The proposed change consists in transferring 64 hr from 2011a to the following semesters (13 hr to 2011b, 13 hr to 2012a and 28 hr to 2012b), with the main RAs of observations remaining unchanged.

semester	stars	allocated (hr)	comments / changes
2010b	AA Tau, DN Tau, DK Tau	72	coordinate w/ COS@HST
2011a	V2247 Oph, GQ Lup, RU Lup	64	in place of V1515 Cyg / V1057 Cyg (-64 hr wrt old schedule)
2011b	BP Tau, SU Aur, DF Tau	55	adding in DF Tau (+13 hr)
2012a	TW Hya, V2129 Oph, RY Lup	39	adding in RY Lup (+13 hr)
2012b	COUP 932, DG Tau, AA Tau, DN Tau, DK Tau	124	replacing T Tau & RY Tau w/ DN Tau & DK Tau; more time on COUP 932 to estimate nebular contribution to emission lines (+28 hr)
		354	ie 690 - 336 hr (see Table 1)

optimal view of accretion regions at the surface of the star; they will also us to estimate whether (and how much) the field of AA Tau evolved since our previous observations (in 2008b).

The magnetic non-detection obtained in 2010a on V1515 Cyg & V1057 Cyg strongly suggests **not** to spend 128 hr in 2011a on either target, as initially planned. We thus propose a revised observation plan for semesters 2011a-2012b, where **half the time initially planned in 2011a** (ie 64 hr) **is transferred to the following semesters**. Table 2 presents the revised MaPP observing plan, in which the main RAs of observations are essentially unchanged (with respect to the previous schedule).

Since all stars to be observed in the remaining MaPP time were already detected as magnetic (either from pre-MaPP snapshots or from previous MaPP observations), **we foresee no other changes regarding the proposed program** until the end of MaPP in 2012b.

4. Potential extensions to MaPP

MaPP is presently dedicated to magnetic fields of cTTSs & FUOrs only and involves surveying & monitoring the Zeeman signatures of a small sample of prototypical targets of each class (about 15 cTTSs and 4 FUOrs). As outlined in Sec 1, this is the first such effort worldwide; results obtained so far are extremely promising and demonstrate that major advances in the field are expected from MaPP. In particular, MaPP should yield a very clear view of **how the large-scale topologies of low-mass protostars** (in the range 0.3 to 2.5 $M_\odot$) **depend on protostellar parameters** such as mass, rotation & accretion rates; this should largely clarify how these fields are likely to affect the final accretion phases of stellar & planet formation.

Our recent demonstration that large-scale magnetic fields of cTTSs are time-variable, potentially as a result of dynamo magnetic cycles, clearly emphasizes the importance of **monitoring the magnetic topologies of cTTSs on long timescales** (typically 5-10 yr), at least for a restricted subsample; with such a monitoring, we could characterize the time-averaged magnetic properties of cTTSs as well as their fluctuations, expected to play a critical role in star-disc magnetic coupling models and thus to strongly impact the corresponding predictions regarding their angular momentum evolution. We thus suggest **a first logical extension of MaPP**, consisting in a prolonged magnetic monitoring for 4 stars of our sample (namely V2129 Oph, V2247 Oph, BP Tau & AA Tau) from 2013a to 2014b, with one star observed each semester (eg V2247 Oph in 2013a, BP Tau in 2013b, V2129 Oph in 2014a, AA Tau in 2014b). Including the pre-

MaPP data collected on all 4 stars, this extension will allow us to **increase our monitoring baseline by 2 years**, giving a full baseline of 9 yr (for V2129 Oph), 8 yr (for BP Tau), 7 yr (for AA Tau) and 5 yr (for V2247 Oph). This extension would require a total CFHT time of **85 hr over 4 semesters**, ie 12% of the current MaPP allocation.

Once accretion phases are over and massive accretion discs are dissipated (or have evolved into transitional discs), protostars no longer show signs of accretion and only marginal IR excesses (with respect to cTTSs) and are labeled as wTTSs (ie weak emission-line T Tauri stars). They correspond to Class III protostars and are thus presumably slightly more evolved (though not necessarily older) than cTTSs (also called Class II protostars).

Another logical & complementary follow-up of MaPP is thus to **carry out a small survey of the large-scale magnetic properties of wTTSs** as a function of their masses and rotation rates, to be compared to those of low-mass main-sequence stars whose large-scale field properties exhibit drastic changes with mass and rotation rates (see, eg, Fig 3 of Donati & Landstreet, 2009, ARA&A 47, 333). This small survey could reveal in particular how magnetic topologies of protostars look like once they emerge from the accretion phases, how they differ from those of accreting cTTSs and how they link to those of mature main-sequence low-mass stars. Constraining theoretical models of planet formation/migration by looking for **close-in giant planets around wTTSs** is also expected to be much easier than with cTTSs (as planned in the ongoing MaPP project) given their much lower level of intrinsic activity. This **MaPP extension** thus shows up as the **missing link** between the present MaPP survey and the existing main-sequence one - a logical step that we urgently need to complete before competing teams start working on the subject.

One of the brightest wTTSs (V410 Tau) was recently observed by our team (Skelly et al 2010a, MNRAS 402, 1426) using NARVAL@TBL, demonstrating that the program is obviously feasible. Observing ~14 wTTSs of different masses & rotation rates (using both ESPaDOnS@CFHT and NARVAL@TBL for the bright & faint sample members with typical V magnitudes of ~11 & ~13 respectively) at a typical rate of about 14 hr per star (eg 10 visits of 4x20 min each) would thus allow to complete the proposed program. This second extension of MaPP would require a total CFHT time of **98 hr over 4 semesters** (and a similar amount on the TBL side), ie 14% of the current MaPP allocation.

5. MaPP meetings & funding

Several MaPP meetings / workshops of various sizes were organized since the beginning of MaPP:

- an initial kickoff MaPP meeting in Grenoble (2008 March 26-27, involving about 10 participants)
- an international MaPP workshop in Toulouse on «dynamos of fully-convective stars & protostars» (2009 Mar 26-27, involving about 25 participants)
- a small MaPP workshop in Palermo dedicated to the multi-wavelength multi-site campaign carried out on V2129 Oph (2010 Feb 1-2, involving about 10 participants)

The **mid-term MaPP meeting is planned for the first semester of 2011**, will likely take place in Toulouse and will be a larger-scale workshop presenting all results obtained to date and focussing on all follow-up studies (eg theoretical modeling, numerical simulations, complementary observations) that will be carried out in the framework of MaPP.

In addition to being a CFHT LP, MaPP is also a research program that was **selected for funding by the French «Agence Nationale pour la Recherche»** (ANR).

6. MaPP-related refereed publications since 2008

MaPP-related studies & reviews based on CFHT data:

- Donati JF, Jardine MM, Gregory SG et al, 2008, MNRAS 386, 1234

Magnetospheric accretion on the cTTS BP Tauri

- Donati & Landstreet 2009, ARA&A 47, 333
  Magnetic fields of non-degenerate stars
- Donati JF, Skelly MB, Bouvier J, et al 2010a, MNRAS 402, 1426
  Complex magnetic field & strong differential rotation on the low-mass cTTS V2247 Oph
- Donati JF, Skelly MB, Bouvier J, et al 2010b, MNRAS in press, astro-ph:1007.4407
  Magnetospheric accretion & spin-down of the prototypical cTTS AA Tau
- Donati JF, Bouvier J, Walter FM, et al, 2010c, MNRAS submitted
  Non-stationary dynamo processes & magnetospheric accretion on the cTTS V2129 Oph
- Skelly MB, Donati JF, Bouvier J, et al, 2010b, MNRAS to be submitted soon
  The complex magnetic topology of the very young cTTS MT Ori = COUP 932

MaPP-related studies based on complementary data:

- Hussain GAJ, Cameron AC, Jardine MM, et al, 2009, MNRAS 398, 189
  Surface magnetic fields on two accreting cTTSs: CV Cha and CR Cha
- Skelly MB, Donati JF, Bouvier J, et al, 2010a, MNRAS 403, 159
  Dynamo processes in the wTTS V410 Tau
- Argiroffi C, Flaccomio E, et al, 2010, A&A to be submitted soon
  X-ray emission from the cTTS V2129 Oph

Theoretical modeling, numerical simulations & reviews based on MaPP studies:

- Jardine MM, Gregory SG, Donati JF, 2008, MNRAS 386, 688
  Coronal structure of the cTTS V2129 Oph
- Gregory SG, Matt SP, Donati JF, Jardine MM, 2008, MNRAS 389, 1839
  The non-dipolar magnetic fields of accreting cTTSs
- Mohanty S, Shu FH, 2008, ApJ 687, 1323
  Magnetocentrifugally driven flows from young stars and discs (VI)
- Gregory SG, Jardine MM, Gray CG, Donati JF, 2010, RPP in press, astro-ph/1008.1883
  The magnetic fields of forming solar-like stars
- Romanova MM, Long M, Lamb FK, et al., 2010, MNRAS in press, astro-ph:0912.1681
  Global 3D simulations of disc accretion onto the cTTS V2129 Oph
- Long M, Romanova MM, Kulkrani AK, Donati JF, 2010, MNRAS submitted, astro-ph:1009.3300
  Global 3D simulations of disc accretion onto the cTTS BP Tau