Magnetism and Accretion in Intermediate-Mass PMS Stars

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Magnetism plays an important role in pre-main sequence evolution when stars are still accreting matter from their protoplanetary disk. I present recent advancements in our understanding of magnetism in pre-main sequence stars at intermediate-mass and discuss the implications on magnetism and accretion evolution.

1 Introduction

Stellar magnetism at intermediate-mass has been an intense field of research for decades. Nonetheless, we are still seeking its origin. It is now well accepted that the branch of strong magnetism observed on the main-sequence and the radiative pre-main sequence is fossil and is the result of earlier dynamo processes during their formation (e.g. Alecian et al., 2019). One of the promising theories is field relaxation which assumes that dynamo fields resulting from pre-main sequence convection relax inside the growing radiative core and eventually reach the surface (Duez & Mathis, 2010; Emeriau & Mathis, 2015). Magnetic field observations in Herbig Ae/Be and Ap/Bp stars tell us, however, that this process can only efficiently occur in less than 10 % of the stars. In addition, relaxed fields must have intensities and topologies that allow them to settle in radiative interiors and evolve poorly during the remaining life of the stars. The conditions necessary for complying with these observations are currently unknown. To constrain them, we need to study the convective progenitors of intermediate-mass stars, i.e. the intermediate-mass T Tauri stars.

T Tauri stars (TTS) are low-mass, pre-main-sequence stars of typical spectral types K and G with emission lines in their spectrum and associated with dark or bright nebulosities. They are surrounded by an accretion (in classical TTS) or a passive (in weak-line TTS) circumstellar disk, in which planets are forming or are already formed. Classical T Tauri stars (CTTS) are actively accreting material from their disk via magnetospheric accretion. This energetic, star-disk interaction manifests itself via various observables, including variable inverse P-Cygni spectroscopic line profiles. A small sample of T Tauri type stars has also been identified at intermediate-mass (from $\sim 1.5\,\mathrm{M}_\odot$ to $\sim 4\,\mathrm{M}_\odot$), with spectral types ranging from G to mid-F (e.g. Hartmann et al., 2016). We have conducted a spectropolarimetric survey of intermediate-mass T Tauri stars (IMTTS) to determine their magnetic properties and provide observational constraints on the relaxation theory. In the following sections, we summarize the main results of this survey, which are detailed in Villebrun et al. (2019), and then describe their implications on accretion processes at intermediate-mass.

2 Magnetic properties of intermediate-mass T Tauri stars

We have obtained spectropolarimetric observations of a sample of 38 IMTTS using ESPaDOnS, installed at the Canada-France-Hawaii Telescope (CFHT). We use the classical method for magnetic field measurements using ESPaDOnS data, i.e. the Zeeman circular polarisation of photospheric spectral lines. To increase the signal-to-noise ratio (SNR), we use the least-square deconvolved technique (LSD, Donati et al., 1997), providing us with mean LSD Stokes I and V profiles. If the V profile is significantly non-null (using the criteria from Donati et al., 1997), a magnetic field at the surface of the star has been detected. Stokes I and V can then be analysed to estimate the line-of-sight component of the magnetic strength, $B_{\ell,}$ (Wade et al., 2000).

We used the intensity spectra to determine accurate and consistent effective temperatures for the whole sample. We used Gaia distances and published photometric data to determine luminosities. We then placed the stars in the HR diagram to determine their mass, evolutionary stage, and internal structure. Our sample contains stars of masses ranging from $\sim 1.2\,\mathrm{M}_{\odot}$ to $\sim 4\,\mathrm{M}_{\odot}$. From their position in the HR diagram, it is clear that the stars of our sample will become Herbig Ae stars within the next few million years. Our sample provides good coverage of the PMS evolution during which intermediate-mass stars go from almost fully convective to fully radiative.

Magnetic fields have been detected in about half of our sample. We observe a net vertical limit separating magnetic and non-magnetic stars in the HR diagram (see Fig. 1). Our observations have been prepared and conducted to reach the same magnetic detection level for all stars of our sample by adjusting the exposure times with respect to the spectral types, rotational broadening, and magnitudes. This is feasible if all of these parameters are well constrained prior to the observations, and this was the case for the majority of the sample. Therefore, while we may have failed to detect magnetic fields in few stars of the sample because some exposure times were underestimated, this cannot explain all the non-detections we obtain. The observed limit between magnetic and non-magnetic stars in the HR diagram is therefore real and indicates that once this limit is passed, magnetic fields become much weaker. Using CESTAM evolutionary models (Morel & Lebreton, 2007; Marques et al., 2013), we find that the limit corresponds to point at which $\sim 2\%$ of the stellar mass is contained within the convective envelope, which corresponds to $\sim 25\%$ of the stellar radius. This result indicates that convective-dynamo processes may become much less efficient past this limit and that magnetic fields must become much weaker within a few 100 000 years (Villebrun et al., 2019).

While this study provides some constraints on the dynamo and relaxation processes, important factors are still missing in our understanding of the origin of fossil fields. In particular, it is not clear how and when a fossil field residing in the radiative core of the star emerges at the surface. Can it be observed at the stellar surface even if a thin convective envelope is still present? If yes, then how thin must the convective envelope be? To go further, we need to characterise the magnetic fields that have been detected and classify them as either fossil- or dynamo-type. This is a work in progress.

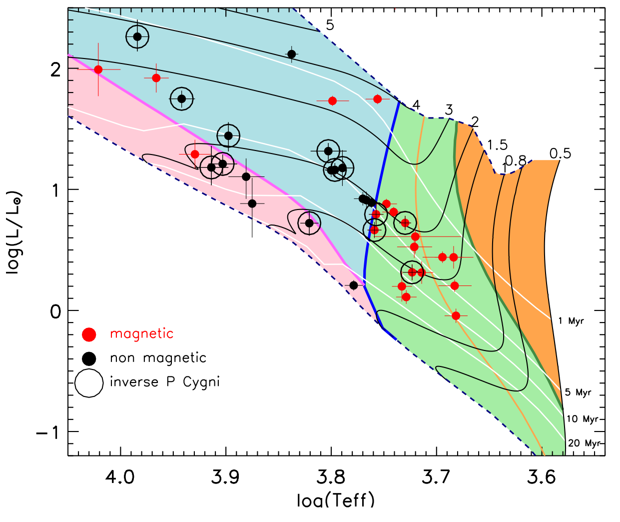

Fig. 1: Pre-main-sequence HR diagram. Color shades distinguish fully-convective stars (orange), stars with a growing radiative core (green), fully-radiative stars (blue), and stars with a growing convective core (pink). Evolutionary tracks from 0.5 to 5 M$_\odot$ are plotted in black full lines from the birthline to the ZAMS (thick dashed lines). White thin lines are isochrones from 1 to 20 Myr. The orange line corresponds to convective envelopes radii being 40% that of the star. Magnetic stars are plotted in red, and non-magnetic ones in dark. Those with accretion signatures are surrounded with a black circle (see text). (Adapted from Villebrun et al. 2019)

3 Accretion vs magnetism in IMTTS

While it was expected that most of the magnetic fields must disappear at one point during the pre-main-sequence evolution (when convection becomes weaker), it is nonetheless surprising that half of our sample that were classified as non-magnetic T Tauri stars. Indeed, many of the typical spectral properties of T Tauri stars are associated with magnetospheric accretion (MA). This process assumes that the stellar magnetic field truncates the disk up to a certain distance from the stellar surface. Material from the inner rim of the circumstellar disk is channelled along the field lines to the stellar surface, and it reaches the surface at free-fall velocities, creating shocks. Those shocks are usually observed as broad emission in Hα but also as redshifted absorption features at large velocities in some Balmer lines when the accretion column crosses the line of sight (e.g. Hartmann et al., 2016). According to this theory, to first order, a correlation should be observed between the strength of the magnetic field and the strength and velocities of the redshifted absorption features.

To test this, we first determined the detection limit of the magnetic fields in stars not detected in our ESPaDOnS data; we used the Monte-Carlo method described in Alecian et al. (2016) and assuming that the undetected magnetic field is a centred dipole. We have computed the expected Stokes V signal assuming a specific magnetic strength at the pole, a random inclination, a random magnetic obliquity, and a random rotation phase. We repeated this computation a thousand times and

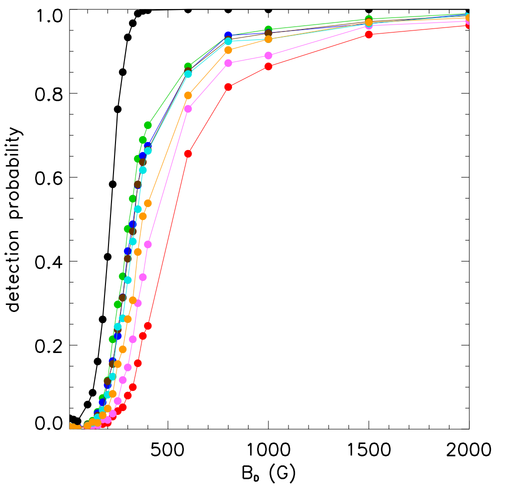

Fig. 2: Detection probabilities for a dipolar field of strength $B_{\rm D}$ at the pole for the individual ESPaDOnS observations of HD 142666 (colored curves, published in Alecian et al. (2013)) and for combining all observations (black curve). Using all observations, we had a 90% chance to detect a magnetic field of strength 300 G or higher.

computed the detection probability for one value of the dipolar field, $B_{\rm d}$ and repeated this operation for different values of $B_{\rm d}$. We assume that above a detection probability of 90%, we would have had a good chance to detect the field and have set the detection limit to the one corresponding to 90% of chance detection (see an example in Fig. 2).

As there has been several claims that Herbig Ae stars show similarities with T Tauri stars, especially in MA sensitive spectral signatures, we have done the same job for the Herbig Ae sample of Alecian et al. (2013). Simultaneously, using our data and the literature, we have identified IMTTS and Herbig Ae stars having inverse P-Cygni profiles in either the He I D3 and Hβ lines or He I 1083 μm, with final velocities of the absorption components reaching at least 100 km s^{-1}. Redshifted absorption components with such large velocities must trace accreting material with, or close to, free-fall velocities. These lines have been chosen as they are known to trace the accretion columns in classical T Tauri stars.

Our results are presented in the HR diagram of Fig. 1. This figure is a modified version of the one presented in Villebrun et al. (2019, V19 hereafter). The CESTAM evolutionary tracks are plotted for different masses in full black lines. For the purpose of this study, the mass range of the CESTAM grid has been extended towards higher mass compared to the grid published in V19. For computational reasons, overshooting had to be considered in the computation of tracks at higher mass; the whole grid was recomputed with overshooting in the core, but this changed nothing in the mass range considered here. The shaded areas of different colours of Fig. 1 correspond to different internal energy transport: fully convective (orange), radiative core + convective envelope (green), fully radiative (blue), and convective core + radiative envelope (pink). The limit between the green and blue regions corresponds to the limit at which the convective envelope contains 2% of the stellar mass. Red points are stars in which magnetic fields have been reliably detected in our data or in the literature (see V19 for the whole literature of the magnetic stars). Black points are IMTTS and Herbig Ae stars in which a magnetic field has not been detected (V19, Alecian et al., 2013); plotted are only the stars for which the detection limit is lower than 500 G. In addition, we highlight in the plot the stars in which inverse P-Cygni (IPC) profiles with properties described above have been observed in our data or in the literature (V19, Alecian et al., 2013; Cauley & Johns-Krull, 2014).

We first observe that many of the T Tauri stars (around $\log T_{\rm eff}$=3.8 and lower) are not categorised with an IPC profile. Our preliminary study is probably biased as we have used only a small sample of observations perhaps obtained at a moment, or under a configuration, in which the accretion column is not aligned with the line of sight. Therefore, if IPC profiles have not been observed, it does not mean that free-fall accreting material is not present.

What is striking, however, is the large number of IPC profiles observed in stars that are not detected as magnetic, especially in the HR region in which a large-scale (dipolar) magnetic field is not expected in 90% of them. Among the nine IMTTS and Herbig Ae stars showing IPC profiles, five (IMTTS) and fours (HAe) have magnetic detection limits of about 500 G and 300 G, respectively, while typical large-scale dipolar magnetic fields in classical T Tauri stars are a few kG. We emphasise that while we may have missed the detection of magnetic fields of higher complexity of several kG, we do not detect strong dipolar fields. The dipolar component is the one of interest in this study as this is the field that dominates at the inner rim of the disk, truncates the disk, and channels the material to the surface at free-fall velocities. The lower the strength of the field, the lower the velocities (Bessolaz et al., 2008).

The apparent lack of correlation between the presence of redshifted absorption at large velocities and the strength of the field raises questions about the magnetospheric accretion scenario. It is interesting to note that a similar conclusion is reached by Reiter et al. (2018), when comparing magnetic and non-magnetic Herbig Ae/Be stars.

4 Conclusion

Using ESPaDOnS observations of PMS stars at intermediate-mass, we have investigated the shape of spectral lines sensitive to circumstellar (CS) material. We have completed the study using published profiles. We focus in particular on solid evidence of CS material in (or close to) free-fall velocities. Surprisingly, such evidence is found in both strongly and weakly magnetised stars, raising doubts on the origin of these signatures originally believed to be the result of magnetospheric accretion processes. This preliminary study must be expanded to include other parameters impacting the accretion velocities in the MA models, such as the mass accretion rate in the inner rim and stellar mass and effective temperature.

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