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Examining magnetospheric accretion in Herbig Ae/Be stars through near-infrared spectroscopic signatures

Markus Schöller,[1] Swetlana Hubrig,[2] Mikhail A. Pogodin,[3] Silva P. Järvinen,[2] Natalia A. Drake,[4,5,6] and J. Andres Cahuasqui[7]

[1]*European Southern Observatory, Karl-Schwarzschild-Str. 2, 85748 Garching, Germany;* mschoell@eso.org

[2]*Leibniz-Institut für Astrophysik Potsdam (AIP), An der Sternwarte 16, 14482 Potsdam, Germany*

[3]*Central Astronomical Observatory at Pulkovo, Pulkovskoye chaussee 65, 196140 Saint Petersburg, Russia*

[4]*Laboratory of Observational Astrophysics, Saint Petersburg State University, Universitetsky pr. 28, 198504 Saint Petersburg, Russia*

[5]*Observatório Nacional/MCTIC, Rua General José Cristino 77, CEP 20921-400, Rio de Janeiro, RJ, Brazil*

[6]*Laboratório Nacional de Astrofísica/MCTIC, Rua Estados Unidos 154, 37504-364 Itajubá, MG, Brazil*

[7]*I. Physikalisches Institut, Universität zu Köln, Zülpicher Str. 77, 50937 Köln, Germany*

Abstract. Models of magnetically driven accretion and outflows reproduce many observational properties of T Tauri stars. For the more massive Herbig Ae/Be stars, the corresponding picture is not well established. Nonetheless, it is expected that accretion flows in pre-main-sequence stars are guided from the circumstellar disk to stellar regions of high latitude along the magnetic field lines inside a magnetosphere. Using near-infrared multi-epoch spectroscopic data obtained with ISAAC, CRIRES, and X-shooter on the VLT, we examined magnetospheric accretion in the two Herbig Ae stars HD 101412 and HD 104237. Spectroscopic signatures in He I 10 830 and Paγ, two near-infrared lines that are formed in a Herbig star's accretion region, show temporal modulation in both objects. For HD 101412, this modulation is governed by its rotation period, which we could recover from the data. We could show that our spectroscopic observations can be explained within the magnetic geometry that we established earlier from magnetic field measurements. For HD 104237, we struggled to clearly identify a rotation period. We intend to apply this method to a larger sample of Herbig Ae/Be stars to learn more about their rotation properties and the accretion mechanisms at work.

1. Introduction

Herbig Ae/Be stars (HAeBes) are predecessors of main-sequence stars in the mass range 2–10 $M_{\odot}$. They show clear signatures of surrounding disks, as evidenced by a

strong infrared excess, and are actively accreting material. The phase between protostar and main-sequence object is a key stage for planet formation: dusty disks provide the material needed for the formation of planets. In Herbig Ae stars, observations suggest a close parallel to T Tauri stars, i.e. the stellar magnetic field truncates the accretion disk at a few stellar radii and gas accretes along magnetic field lines from the protoplanetary disk to the star (magnetospheric accretion (MA); e.g. Muzerolle et al. 2004). In Herbig Be stars, it is presumed that the accretion flow is not disrupted by the magnetic field.

Before 2004, the only magnetic field detection had been reported for the optically brightest ($m_V = 6.5$) Herbig Ae star HD 104237 (Donati et al. 1997), but no further publication confirming this detection existed. Consecutive studies reported the discovery of magnetic fields in seven other HAeBes (Wade et al. 2005, 2007; Catala et al. 2007; Hubrig et al. 2004, 2006, 2007). Alecian et al. (2008) reported eight magnetic HAeBes in a sample of 128 objects. Later on, a study of 21 HAeBes with FORS 1/2 revealed the presence of magnetic fields in six additional stars (Hubrig et al. 2009). Further studies involved the outbursting binary Z CMa (Szeifert et al. 2010), the Herbig Ae star HD 101412 with resolved magnetically split lines (Hubrig et al. 2010), HD 31648 (Hubrig et al. 2011), PDS 2 (Hubrig et al. 2015), and the two systems AK Sco and HD 95881 (Järvinen et al. 2018).

2. Magnetospheric accretion in Herbig Ae/Be stars

While MA is well established as the accretion scenario for T Tauri stars, it is not so clear if this also holds for the HAeBes, mainly driven by the facts that not many magnetic HAeBes have been found and that their magnetic fields are typically an order of magnitude weaker.

Wade et al. (2007) used the equations put forward by Johns-Krull et al. (1999) for T Tauri stars to estimate the magnetic field strength needed to support MA in HAeBes. Assuming $v \sin i = 115\,\mathrm{km\,s^{-1}}$, $R_* = 2R_\odot$, $i = 90°$ (leading to $P_{\rm rot} = 1$ d), $M_* = 2M_\odot$, $\dot{M}_{\rm acc} = 10^{-8} M_\odot\,\mathrm{yr^{-1}}$, which are canonical values for model parameters, one would need $B_{\rm d} = 500$ G for the models by Koenigl (1991) and Shu et al. (1994) and $B_{\rm d} = 100$ G for the model by Collier Cameron & Campbell (1993). The required field strengths increase with mass, period, and mass accretion rate, and decrease with radius.

According to Alecian (2014), the magnetic properties of A and B-type stars were shaped before the HAeBe evolutionary phase. Using pre-main-sequence evolutionary tracks calculated with the CESAM code (Morel 1997), the authors concluded that even stars above $3\,M_\odot$ undergo a purely convective phase before reaching the birthline. Based on all available measurements summarized by Hubrig et al. (2015), we can consider that it is reasonable to assume that the weak magnetic fields detected in a number of HAeBes are leftovers of the magnetic fields generated by dynamos during these convective phases.

Cauley & Johns-Krull (2014) studied the He I 10 830 morphology in a sample of 56 HAeBes. They suggested that early Herbig Be stars do not accrete material from their inner disks in the same manner as T Tauri stars, while late Herbig Be and Herbig Ae stars show evidence for MA. Furthermore, they proposed more compact magnetospheres in HAeBes compared to T Tauri stars. Further, Ababakr et al. (2017) found that 42 of 56 HAeBes in their sample show a polarization change over the Hα line, which is attributed to a small scale asymmetry due to the surrounding disk. The behav-

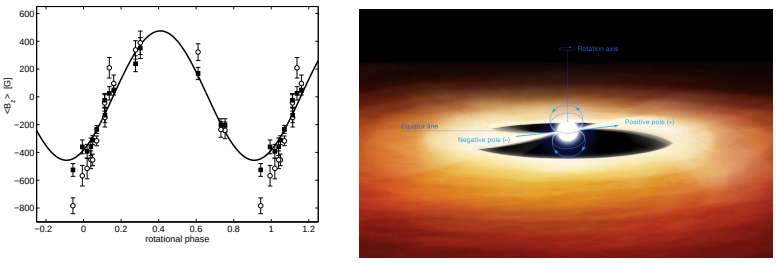

Figure 1. *Left:* Phase diagram with the best sinusoidal fit for $\langle B_z \rangle$ measurements of HD 101412 using all lines (filled squares) and hydrogen lines (open circles; from Hubrig et al. 2011). *Right:* Artist's impression of the MA in HD 101412 looking at the magnetic equator (from Schöller et al. 2016).

ior of Herbig Ae stars was found to be similar to T Tauri stars, while Herbig Be stars earlier than B7/B8 show a line depolarization.

Interferometric searches for magnetospheres in the near-infrared did not come to a final conclusion. Kraus et al. (2008) observed five HAeBes with AMBER on the VLTI and found only in HD 98922 – then not known to be magnetic – a Brγ line-emitting region compact enough to be compatible with a magnetosphere. For the other four sources in the study, including the magnetic HD 104237, they found larger sizes consistent with an extended stellar wind or a disk-wind.

Studying MA in HD 58647, Kurosawa et al. (2016) modeled continuum and Brγ AMBER data and found that a disk wind plus a small magnetosphere explain all measurables. Järvinen et al. (in prep.) found a change of magnetic field polarity on a timescale of days in this star.

Looking at observations obtained with the CHARA array in Hα, there is a wide spread of results. Perraut et al. (2016) found evidence for a disk-wind coming from 0.3 au and for a magnetosphere in AB Aur, Benisty et al. (2013) saw a disk-wind on a scale of 0.2–0.6 au in MWC 361, and Mendigutía et al. (2017) determined a size of 15 R_* in HD 179218, which is likely due to MA, and a size of 16 R_* in HD 141569, for which MA is impossible due to the high rotational velocity of this star. Overall, it is clear that a wider variety of scenarios is needed to explain the Hα emission: coming from compact or extended sources, from a disk, from the accretion flows, and from winds.

3. HD 101412

The Herbig Ae star HD 101412 possesses the strongest magnetic field measured in any Herbig Ae star so far, with a surface magnetic field $\langle B \rangle$ up to 3.5 kG. Hubrig et al. (2011) studied HD 101412 randomly over its until then unknown rotation period and found rotational modulation of the longitudinal magnetic field. From these measurements, they were able to determine several parameters of the star: the rotation period $P_{\rm rot}$ = 42.076 ± 0.017 d, the inclination angle of the rotation axis to the line of sight $i = 80 \pm 7°$, the obliquity angle, i.e. the angle between the rotation axis and the axis of the magnetic dipole, $\beta = 84 \pm 13°$ (see Fig. 1).

The high value for the magnetic obliquity $\beta = 84 \pm 13°$ challenges theoretical scenarios that explain MA. In these scenarios the topology of the channeled accretion

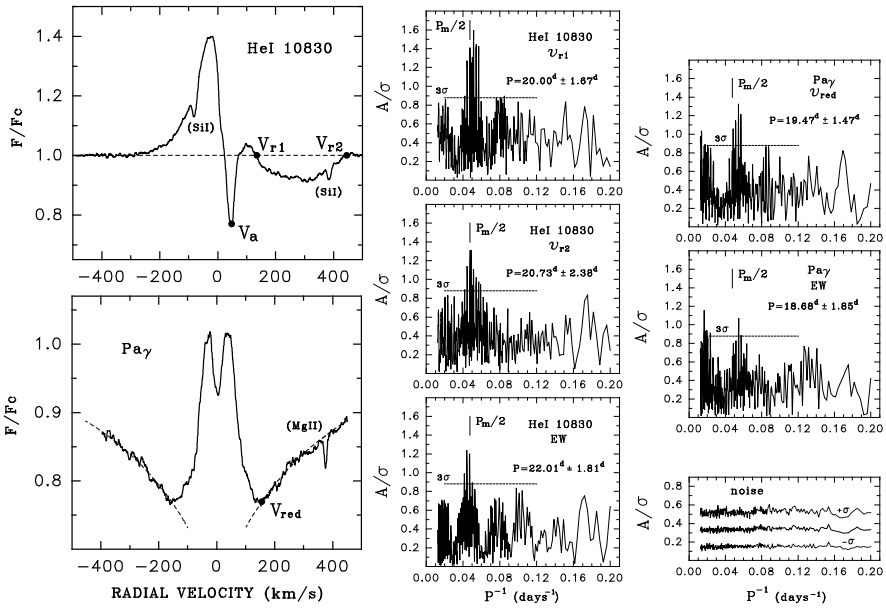

Figure 2. *Left:* Spectral parameters of the He I 10 830 and Paγ line profiles used in the quantitative analysis. *Right:* Different line parameters' A/σ periodograms. Significance levels of 3σ are indicated by the dashed lines. Short vertical lines indicate the value corresponding to half of the magnetic rotation period ($P_{\rm rot}/2 = 21\overset{\rm d}{.}038$). The detected period values and their errors are given in each plot.

critically depends on the magnetic obliquity. For a large dipole inclination, many magnetic field lines will thread the inner region of the disk matter, causing strong magnetic braking (Romanova et al. 2003). This however could explain the long rotation period.

Schöller et al. (2016) used near-infrared spectroscopic observations of HD 101412 to test the magnetospheric character of its accretion. They analyzed the He I 10 830 and Paγ lines in 30 spectra acquired with the CRIRES and X-shooter spectrographs. These lines are thought to form in the star's accretion region. The authors found that the temporal behavior of these diagnostic lines can be explained by rotational modulation of accreting gas with a period $P = 20\overset{\rm d}{.}53 \pm 1\overset{\rm d}{.}68$ (see Fig. 2). The discovery of this period, about half of the magnetic rotation period $P_{\rm rot} = 42\overset{\rm d}{.}076$, indicates that the accreted matter falls onto the star in regions close to the magnetic poles intersecting the line-of-sight twice during the rotation cycle.

4. HD 104237

HD 104237 is a binary system with a Herbig Ae primary and a T Tauri companion. Böhm et al. (2004) found the orbital period $P_{\rm orb} = 19.86$ d for the system and Böhm et al. (2006) the rotation period of the primary $P_{\rm rot,p} = 100 \pm 5$ h from Hα measurements.

Using HARPSpol spectra from the ESO archive, Järvinen et al. (in prep.) determined a highly variable magnetic field, with values of $\langle B_{\rm z}\rangle = 72 \pm 6$ G, $\langle B_{\rm z}\rangle = 47 \pm 6$ G, and $\langle B_{\rm z}\rangle = 63 \pm 6$ G for the primary, and $\langle B_{\rm z}\rangle = 609 \pm 27$ G, $\langle B_{\rm z}\rangle = 440 \pm 23$ G, and $\langle B_{\rm z}\rangle = 124 \pm 13$ G for the secondary, measured over 7.6 h.

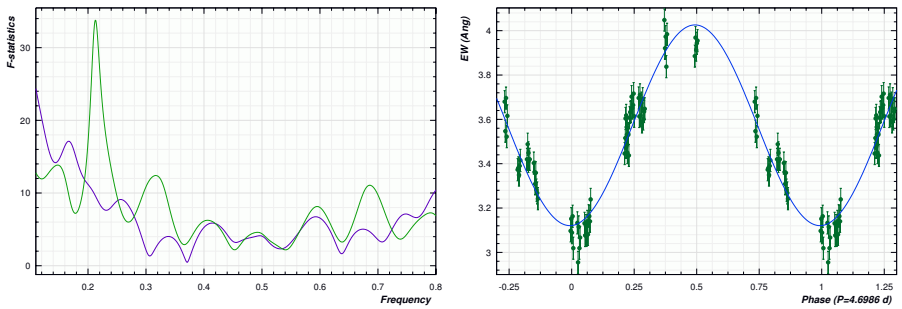

Figure 3. Periodogram (left) and the corresponding phase diagram (right) for HD 104237 obtained for the *EW* of the LSD profiles of 88 HARPSpol spectra.

We used eight ISAAC and 13 X-shooter spectra of HD 104237 from 2013 and 2014, but our period searches from line parameters in He I 5876, He I 10 830, and Paγ only resulted in the detection of the non-significant period $P = 5.37$ d. However, we were able to show from these data that Paγ originates in the primary.

Computing a least-square-deconvolution (LSD) spectrum for each of 88 archival HARPSpol spectra of HD 104237, with individual signal-to-noise ratios between 60 and 100, and measuring the equivalent width (*EW*) of the resulting line, we found a significant rotation period for the primary $P_{\rm rot} = 4.7$ d, which corresponds to 113 h (see Fig. 3).

5. Summary

We have demonstrated that it is in principle possible to determine rotation periods in Herbig Ae/Be stars from accretion tracers. In practice, these rotation period searches can be hampered by low disk inclinations, binarity, and too sparse time series. To further improve our knowledge of the magnetic accretion scenario in HAeBes, we will need a dedicated observing campaign to monitor the magnetic field in about two dozen HAeBes over their rotation cycle.

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