

Investigating the pre-main sequence magnetic chemically peculiar system HD 72106

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Abstract. The origin of the strong magnetic fields observed in chemically peculiar Ap and Bp stars has long been debated. The recent discovery of magnetic fields in the intermediate mass pre-main sequence Herbig Ae and Be stars links them to Ap and Bp stars, providing vital clues about Ap and Bp stars and the origin and evolution of magnetic fields in intermediate and high mass stars. A detailed study of one young magnetic B star, HD 72106A, is presented. This star appears to be in a binary system with an apparently normal Herbig Ae star. A maximum longitudinal magnetic field strength of $+391 \pm 65$ G is found in HD 72106A, as are strong chemical peculiarities, with photospheric abundances of some elements ranging up to 100x above solar.

1 Introduction: HAeBe and Ap stars

A few percent of main sequence A and B stars display strong, globally ordered magnetic fields; these are the so-called Ap and Bp stars. The origin and evolution of these magnetic fields is currently the subject of intensive research. An important avenue of this research is the investigation the progenitors of Ap and Bp stars. Herbig Ae and Be (HAeBe) stars are the pre-main sequence progenitors of the main sequence A and B type stars. As such, HAeBe stars have intermediate masses and display emission, infrared excess, and tend to be associated with dust and nebulosity. It has been long suggested that some HAeBe stars may evolve into magnetic main sequence Ap and Bp stars. If this were the case, it was hoped that there would be some distinguishing observable feature in HAeBe stars linking them to Ap stars.

Pioneering observations in 2005 and 2006 successfully detected magnetic fields in HAeBe stars for the first time (Wade et al. 2005, Catala et al. 2006). The detected fields appear to display similar intensities and geometries when compared to Ap stars (Alecian et al. 2006). The longitudinal field strengths detected are on the order of hundreds of gauss, and the geometries are predominantly dipolar. Additionally, the incidence of magnetic fields in HAeBe stars is similar to that of the magnetic Ap and Bp stars. This strongly supports the idea that magnetic HAeBe stars do in fact represent the progenitors of main sequence magnetic Ap and Bp stars.

In this paper we investigate one particularly interesting young magnetic B star, HD 72106A, in detail.

2 HD 72106

HD 72106 is a visual double system, with a $0.8''$ separation. The primary component has a definitely detected magnetic field (Wade et al. 2005), and the secondary is clearly a Herbig Ae/Be (HAeBe) star (Vieira et al. 2003). The secondary shows strong, variable emission in $H\alpha$, as shown in Fig. 1.

The system has a very large proper motion in α : -5.18 ± 1.08 mas/yr, and in δ : 9.73 ± 1.36 mas y^{-1} but no relative motion between components is observed (Hartkopf et. al. 1996 & Hipparcos data, Høg et al. 2000). The radial velocities of both components are identical to within ± 1 km s^{-1} , at 22 km s^{-1} . As well, the Hipparcos parallax solution for the system places the two stars at the same distance: $288(+202/-84)$ pc. This indicates that the two stars are travelling in tandem, and strongly suggests that the system is in fact a binary. This is critical because, if the system is truly binary, then both components likely have the same age and initial formation conditions.

Wade et al. (2006) determine, for the primary, an effective temperature of 11000 ± 1000 K, a $\log g$ of 4.0 ± 0.5 , and a mass of $2.4 \pm 0.4 M_{\odot}$. For the secondary they derive an effective temperature of 8000 ± 500 K, a $\log g$ of 4.25 ± 0.25 , and a mass of $1.75 \pm 0.25 M_{\odot}$.

The two stars can be placed on an H-R diagram (Wade et al. 2006), and have consistent ages of about 10 Myr, near the zero-age main sequence, when compared with isochrones from Palla & Stahler (1993). This is consistent with the components being co-eval. Both the H-R diagram position and the association of HD 72106A with the HAeBe secondary provide evidence that the primary is a pre-main sequence or very early zero-age main sequence star. The H-R diagram of both stars is shown in Fig. 2.

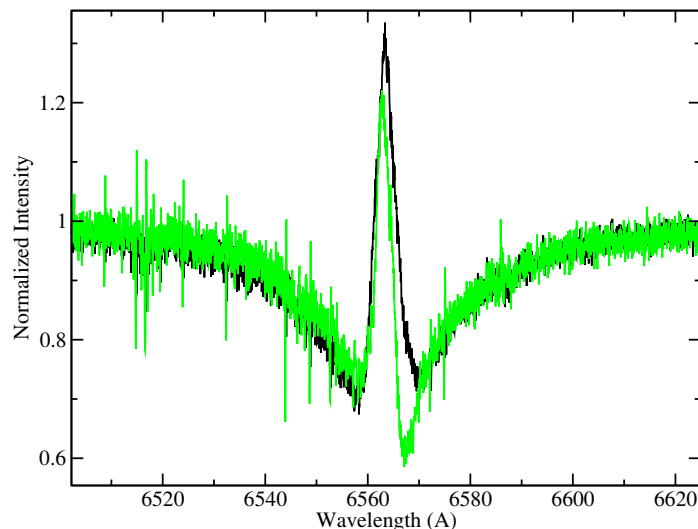


Figure 1: Observed $H\alpha$ profiles for HD 72106B (the apparently non-magnetic secondary) from 11 Jan. 2006 (dark/black) and 11 Feb. 2006 (light/green). Strong and variable emission is observed, indicating the presence of an emitting circumstellar envelope.

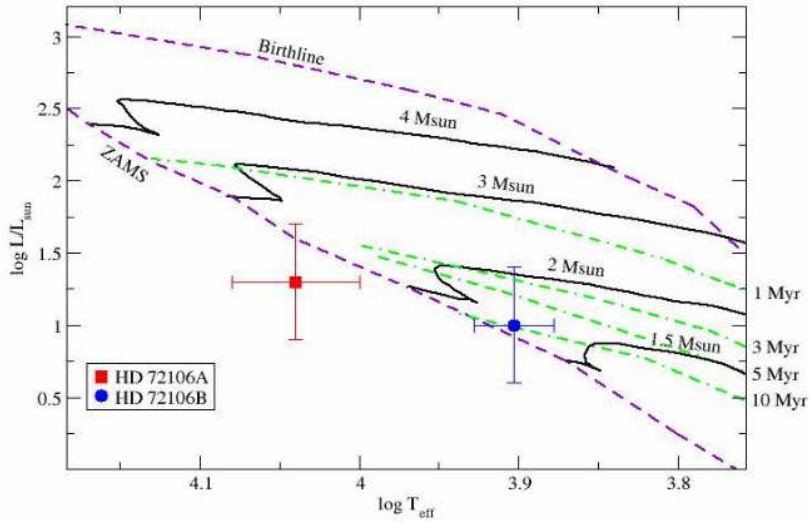


Figure 2: The pre-main sequence H-R diagram of the HD 72106 system. The solid lines are the model evolutionary tracks of Palla and Stahler (1993), with masses as labeled, and the dot-dashed lines are isochrones, with ages labeled. The birthline (which assumes an accretion rate of $10^{-5} M_{\odot} \text{ yr}^{-1}$) and zero age main sequence (ZAMS) are shown as dashed lines.

3 Spectrum Reconstruction

Ten Stokes V spectra of HD 72106 were obtained between February 2005 and February 2006 with ESPaDOnS, the high-resolution echelle spectropolarimeter mounted at CFHT. The spectra cover a wavelength range from 3700 Å to just past $1 \mu\text{m}$. Problematically, the ESPaDOnS pinhole is $1.6''$ in diameter, whereas the two components of HD 72106 are separated by $0.8''$. With good seeing and careful guiding it is possible to isolate individual components. This was accomplished on one occasion. However, the majority of our spectra are of combined light from the system. Observations were conducted using atmospheric dispersion correction, with careful attention to keeping the system centroid centred in the pinhole.

In order to isolate the spectrum of the primary star, we subtracted the individual spectrum of the secondary (obtained on a night of excellent seeing) from the combined spectrum, weighted by its luminosity contribution. Assuming the stars are located at the same distance, their apparent magnitudes, suitably bolometric-corrected, yield their relative luminosities. The relative apparent magnitudes of the components of HD 72106 are well known (eg. Fabricius & Makarov 2000), and the Hipparcos parallax solution puts both components at the same distance. The subtraction process also assumes that the spectrum of the secondary is non-variable, which is a reasonable assumption for metallic lines of a non-magnetic late A star (excluding $H\alpha$). Thus, with the relative apparent magnitude, we can perform the subtraction effectively.

To check this method, Balmer lines (excluding $H\alpha$), as well as several deep, apparently non-variable metallic lines, were compared in the recovered spectra and in the individual observed spectrum of the primary. A very good agreement was found. Presented in Fig. 3 is a typical observed spectrum of the combined system, compared with a spectrum of just the secondary, and the reconstructed spectrum of the primary, resulting from the subtraction process, compared with a spectrum of just the primary.

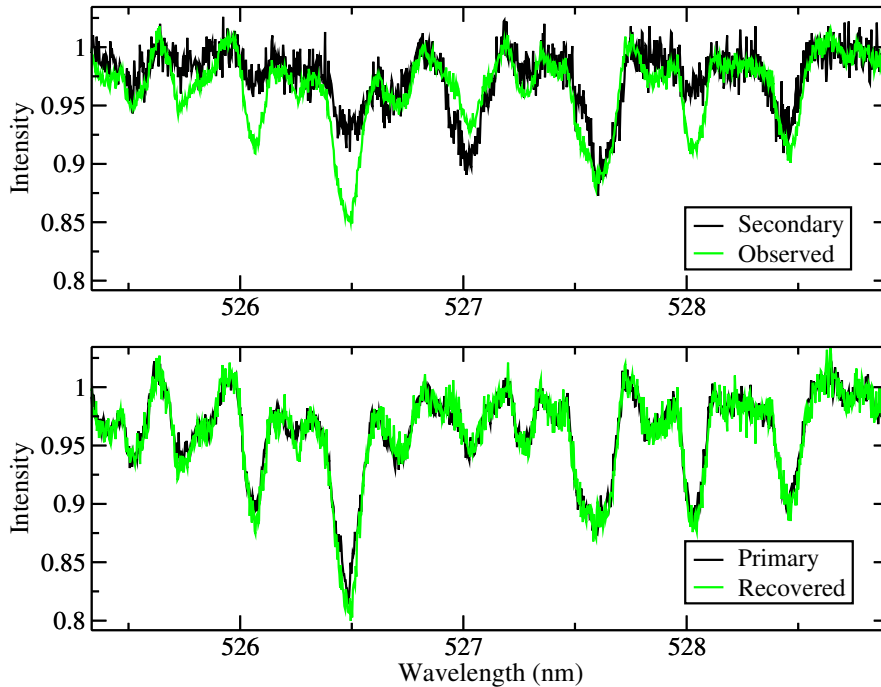


Figure 3: The top frame shows a sample of the spectrum from the secondary (in black) and an observed spectrum of the combined light from the system (in gray). The bottom frame compares the spectrum reconstructed spectrum of the primary (in gray), resulting from the weighted subtraction process, with an observation of just the primary (in black). A very good correspondence is obtained (although some differences are expected due to the line profile variability of the primary).

4 Magnetic Field Measurements

Least Squares Deconvolution (LSD) (Donati et al. 1997) was performed on the reconstructed spectra of the primary. LSD is a method of effectively averaging over many lines in a spectrum in order to improve the signal to noise ratio of the line profile. A line mask for a 10000 K Bp star, and spectra with the contribution of the secondary removed, were used. Significant Stokes V signatures are detected at all observed phases. Longitudinal magnetic field measurements were obtained from the LSD Stokes V profile for each observation. The largest longitudinal field found was $+391 \pm 65$ G. Stokes V profiles with larger amplitudes were observed, but with crossover signatures, corresponding to weaker longitudinal fields. The Stokes I and V LSD profiles corresponding to the 391 G measurement are shown in Fig. 4, and are labeled 0.4015 in the phase column.

5 Period Searching

Clear variability, presumably due to rotation, can be seen in the spectrum of HD 72106A, with an apparent period around two days. To investigate this further we first searched our measured longitudinal magnetic field data for a period. This was done using a modified Lomb-Scargle technique, fitting sinusoids through the data to produce a periodogram, and looking for a minimum in χ^2 . Unfortunately, due to the small number of longitudinal field observations, a unique solution could not be found.

In an attempt to improve our period determination, a more sophisticated technique was used.

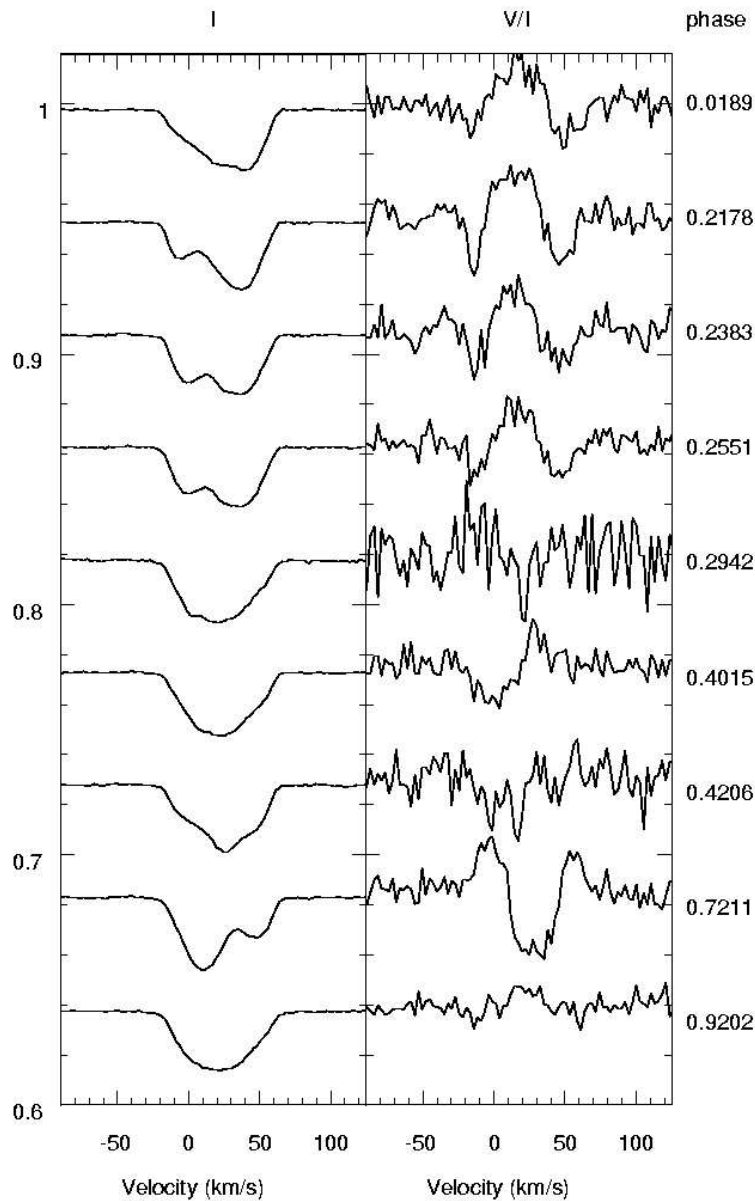


Figure 4: The Stokes I and V profiles obtained for HD 72106A, phased according to a 1.953 day period. The Stokes V profiles, detected significantly at all phases, have been multiplied by 20 times relative to the I profiles, and shifted vertically for clarity. The profiles are labeled by phase, with an arbitrary zero point. Clear variations of the Stokes I profile are apparent.

This method is still based on fitting a sinusoid through a time series of data points to produce a periodogram. However, now the set of measurements for one pixel in the LSD profile is used as the time series of data points. The periodogram for one data point may be heavily affected by noise, but if one averages the periodograms of all the pixels in the LSD line profile, producing an average periodogram, the effects of noise are substantially reduced and the true period is found. To verify the technique, periods were determined for a number of known Ap stars (Auriere et al., in preparation), as well as synthetic test spectra, with good results.

While this improved the situation significantly by reducing the number of possible periods, it

still did not produce a unique period solution for HD 72106A. Examining phased LSD profiles by eye allowed us to reject several more periods as un-physical, but a few possibilities still remain around 1.8 and 1.9 days. A set of LSD profiles phased with one of the better candidate periods is presented in Fig. 4.

6 Spectrum Synthesis

Preliminary spectrum modeling has been performed for both the primary and the secondary, for a single phase only, using observations of the individual components. The Zeeman2 spectrum synthesis code was used, with ATLAS9 model atmospheres corresponding to the temperatures and gravities deduced by Wade et al. (2006). In the primary, a dipole magnetic field of 1 kG was assumed, oriented along the line of sight, with no microturbulence. A homogeneous abundance distribution both vertically and horizontally was assumed. In the secondary, a homogeneous vertical and horizontal abundance distribution was used, with no magnetic field. Microturbulence was left as a free parameter in the fitting procedure.

We find that the primary displays clear chemical peculiarities. The abundance pattern is typical of those of Ap/Bp stars, although the abundance enhancements are remarkably strong. In particular, strong overabundances of Cr, Fe, Si, and Ti are found. In contrast, the secondary displays solar abundance for all elements detected.

Clear structure and variability can be seen in the line profile of the primary, due to abundance spots on the surface of the star. These appear most clearly in lines of Fe and Cr, but can also be observed in some Ti and Si lines. Complex, variable line profiles of this type are typical of Ap stars, and are explained by the presence of abundance non-uniformities in the stellar photosphere. The secondary displays smooth line profiles with no visible asymmetries (although the S/N of this star is relatively poor, and additional observations are required to confirm this).

A sample spectrum of the primary, with a best fit synthetic spectrum, is shown in Fig. 5. Best fit abundances and $v \sin i$ for the primary are shown in Table 1. For the secondary, best fit abundances, $v \sin i$, and microturbulence can also be seen in Table 1, with sample observed and synthetic spectra in Fig. 6 .

Element	Primary	Secondary
Al	-0.2 ± 0.4	
Si	$+1.0 \pm 0.2$	
Ca		-0.4 ± 0.4
Ti	$+1.0 \pm 0.3$	-0.1 ± 0.4
Cr	$+1.9 \pm 0.1$	$+0.1 \pm 0.3$
Fe	$+0.9 \pm 0.1$	-0.1 ± 0.3
Ba		-0.3 ± 0.5
$v \sin i$	$41 \pm 3 \text{ km s}^{-1}$	$50 \pm 4 \text{ km s}^{-1}$
ξ	$\sim 0 \text{ km s}^{-1}$	$2.5 \pm 0.5 \text{ km s}^{-1}$

Table 1: Preliminary best-fit abundances, $v \sin i$, and microturbulence values for HD 72106A and HD 72106B. Abundances are based on the 4500-4700Å region.

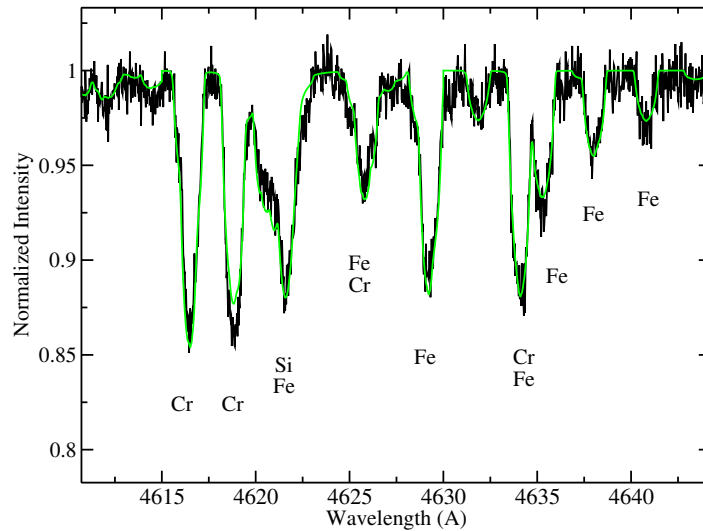


Figure 5: Observed (black) and best fit synthetic (gray) spectra for HD 72106A. Major contributors to each feature have been labeled.

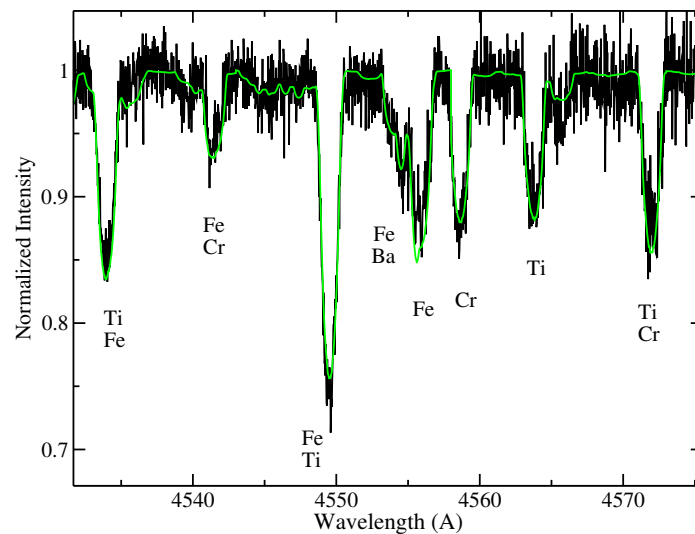


Figure 6: Observed (black) and best fit synthetic (gray) spectra for HD 72106B. Major contributors to each feature have been labeled.

7 Conclusions

These results demonstrate that strong chemical peculiarities, of the type seen in Ap/Bp stars, together with magnetic fields, can exist in late B-type stars at the pre-main sequence or very early zero-age main sequence phase. A maximum longitudinal magnetic field of $+391 \pm 65$ G was found in HD 72106A. Overabundances of up to 2 dex above solar were also found, along with a complex absorption line structure, suggesting an inhomogeneous surface abundance distribution of elements. These properties are all characteristic of Ap stars. In contrast, HD 72106B which presumably formed at the same point in time, under the same conditions as the primary, displays solar abundances and

no magnetic field. Thus the HD 72106 system provides a unique link between Ap stars and their pre-main sequence progenitors.

Further circular polarisation observations of the HD 72106 system are currently planned. This will allow us to better sample the spectroscopic and polarimetric cycle of the primary to determine a unique rotational period. With additional observations we can model the magnetic field geometry and map the surface distributions of elements. Additional observations will also allow us to test the stability of the spectrum of the secondary and further test the spectrum reconstruction technique. With these new observations we will be able to more completely describe this unique and remarkable system.

References

- Alecian E., Catala C., Donati J.-F., et al., 2006, *A&A*, in preparation
Aurière M., Silvester J., Wade G. A., et al., in preparation
Catala C., Alecian E., Donati J.-F., et al., 2006, *A&A*, submitted
Donati J.-F., Semel M., Carter B. D., et al., 1997, *MNRAS*, **291**, 658
Fabricius C. & Makarov V. V., 2000, *A&A*, **356**, 141
Hartkopf W. T., Mason B. D., McAlister H. A., et al., 1996, *AJ*, **111**, 936
Høg E., Fabricius C., Makarov V. V., et al., 2000, *A&A*, **355**, L27
Palla F. & Stahler S. W., 1993, *ApJ*, **418**, 414
Vieira S. L. A., Corradi W. J. B., Alencar S. H. P., et al., 2003, *AJ*, **126**, 2971
Wade G.A., Drouin D., Bagnulo S., et al., 2005, *A&A*, **442**, L31
Wade G. A., Bagnulo S., Drouin D., Landstreet J. D., Monin D., 2006, *MNRAS*, submitted