Leibniz-Institut für Astrophysik Potsdam

AIP

Magnetic fields in Herbig Ae/Be stars

by Silva Järvinen

In collaboration with

Swetlana Hubrig, Thorsten Carroll, Markus Schöller, and Ilya Ilyin

First measurements

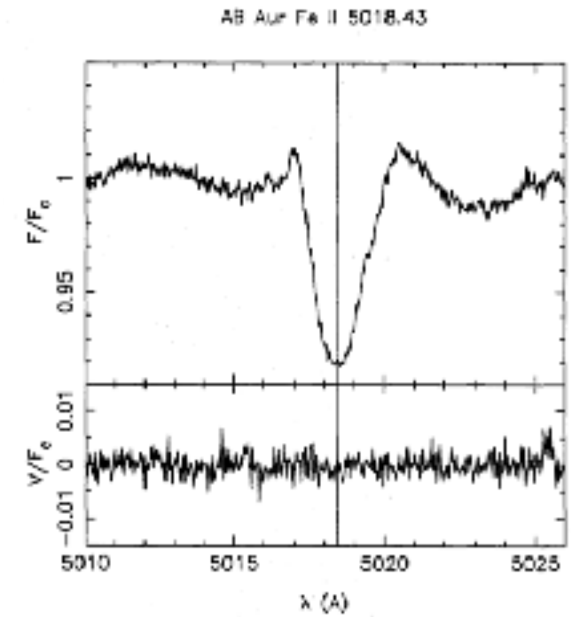
Astron. Astrophys. 278, 187–198 (1993)

ASTRONOMY AND ASTROPHYSICS

Circular polarization and variability in the spectra of Herbig Ae/Be stars

I. The Fe II 5018 Å and He I 5876 Å lines of AB Aurigae*

C. Catala[1], T. Böhm[2], J.-F. Donati[1], and M. Semel[3]



- **3.6 m Canada-France-Hawaii Telescope (CFHT) with the Coudé spectrograph**

© Jean-Charles Cuillandre (CFHT)

First measurements

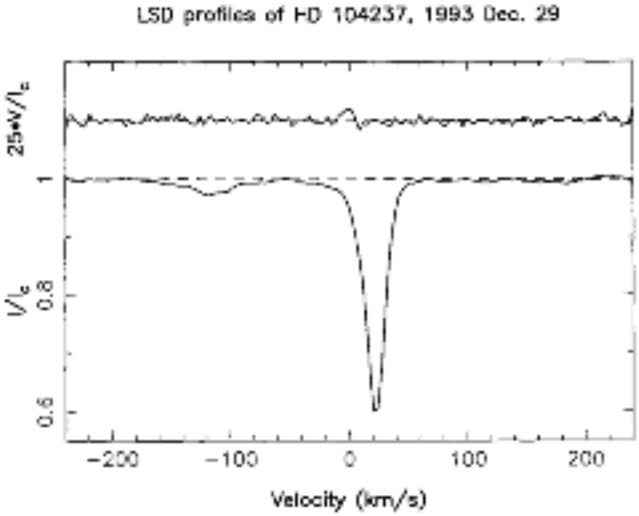
© AAT

Mon. Not. R. Astron. Soc. 291, 658–682 (1997)

Spectropolarimetric observations of active stars

J.-F. Donati,[1★] M. Semel,[2★] B. D. Carter,[3★] D. E. Rees[4★] and A. C. Cameron[5★]

- **Anglo-Australian Telescope (AAT) with the high-res UCL Echelle Spectrograph (UCLES)**
- **HD 100546**
- **HD 104237**
  - **Marginal detection**



First measurements

Glagolevski & Chountonov 2001, ASPC, 248, 535

No detections

Table 1. Magnetic field measurements in Herbig Ae/Be stars.

Star	B_e (G)	σ (G)	Sp	$v \sin i$ (km/s)	Number of spectral lines	Remarks
AB Aur	< 1000	-	A0V	75	-	[1]
HD31648	−50	200	A2/3 p	80	20	
31648	130	150	A2/3 p	96	11	
36112	86	400	A3	70	36	
37022	−630	400	O6p	120	9	Post Ae/Be
37129	−280	200	B2p	70	20	Post Ae/Be
KX Ori	340	250	B3V	30	4	Post Ae/Be
V359 Ori	220	350	B3V	25	4	Post Ae/Be
45677	−530	500	B0IV p	95	6	He+Mg
	15	300	B0IV p	95	6	[2]
53367	350	400	B0III/IV	30	26	He+Me lines
	−330	200	B0III/IV	30	22	He+Me lines
100546	< 100	-	B9V	-	65	[3]
104237	< 100	-	A4V	12	-	[3]
144432	−800	600	A7V	80	26	
179218	−230	150	B9/A0IV/V	60	10	
	350	300	B9/A0IV/V	60	67	
190073	−120	100	A0IV p	10	13	
200775	60	300	B2/3	60	10	
203024	95	600	A	75	18	Comp. prof
208063	730	500	-	35	4	
250550	−520	300	B9	85	37	He+Mg+Si
γ Equ	−1100	100	F0p	-	21	Mag. star

[1] Catala et al. (1993); [2] Borra, Landstreet, & Thompson (1983); [3] Donati et al. (1997)

First low-resolution study

A&A 428, L1–L4 (2004)
DOI: 10.1051/0004-6361:200400091

Astronomy & Astrophysics

Magnetic fields in Herbig Ae stars*

S. Hubrig[1], M. Schöller[1], and R. V. Yudin[2,3]

- **FORS 1 (FOcal Reducer low dispersion Spectrograph) at the VLT**

© ESO/B. Tafreshi

First low-resolution study

Table 1. Basic data of the studied Herbig Ae stars.

HD	Other	V	Sp. type	T_{eff}	log G	$v \sin i$	Ref.	$(V-L)_{\mathrm{obs}}$	P	$\langle B_z \rangle$
139614	CD-27 10778	8.2	A7Ve	8250	4.5	13	(1)	$\sim 2^{\mathrm{m}}0$	~0.1–0.5%	-450 ± 93 G
144432	CD-42 10650	8.2	A9Ve	7750	4.5	54	(1)	$\sim 2^{\mathrm{m}}0$	~0.1–0.5%	-94 ± 60 G
144668	HR 5999	7.0	A7IVe	7800	3.5–4.0	180	(2)	$3^{\mathrm{m}}0$–$3^{\mathrm{m}}5$	~0.5–1.3%	-118 ± 48 G

(1) Meeus et al. (1998); (2) Grady et al. (1994).

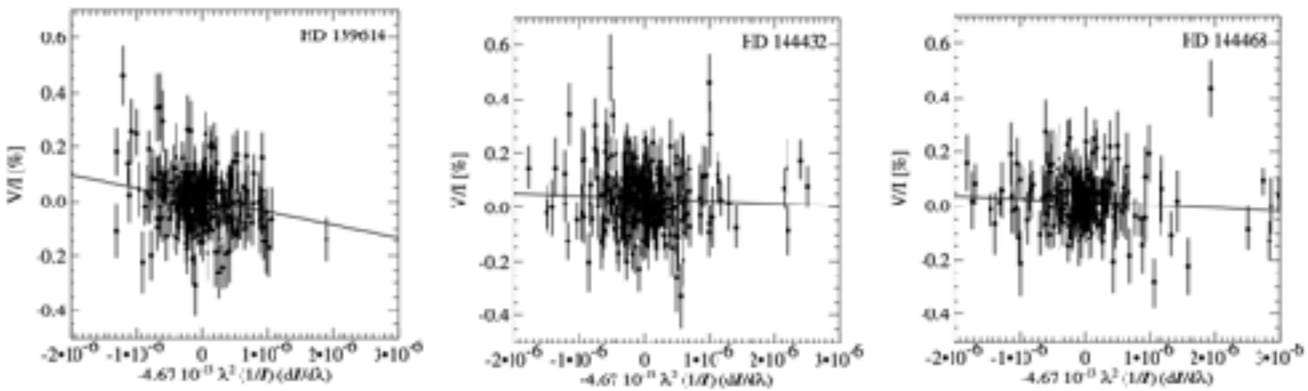


Fig. 1. Regression detection of a -450 ± 93 G magnetic field in HD 139614 and non-detections in HD 144432 and HD 144668.

- **the mean longitudinal magnetic field ⟨Bz⟩ is diagnosed from the slope of a linear regression**

Bagnulo et al. 2002, A&A, 389, 191; Hubrig et al. 2004, A&A, 415, 661

Subsequent studies

A&A 442, L31–L34 (2005)
DOI: 10.1051/0004-6361:200500184

Astronomy & Astrophysics

Discovery of the pre-main sequence progenitors of the magnetic Ap/Bp stars?*

G. A. Wade[1], D. Drouin[1], S. Bagnulo[2], J. D. Landstreet[3], E. Mason[2], J. Silvester[1,4], E. Alecian[5], T. Böhm[6], J.-C. Bouret[7], C. Catala[5], and J.-F. Donati[6]

- **the first results from two independent surveys**
  - **ESO-VLT and the FORS1 spectropolarimeter**
  - **ESPaDOnS spectropolarimeter at the CFHT**

Subsequent studies

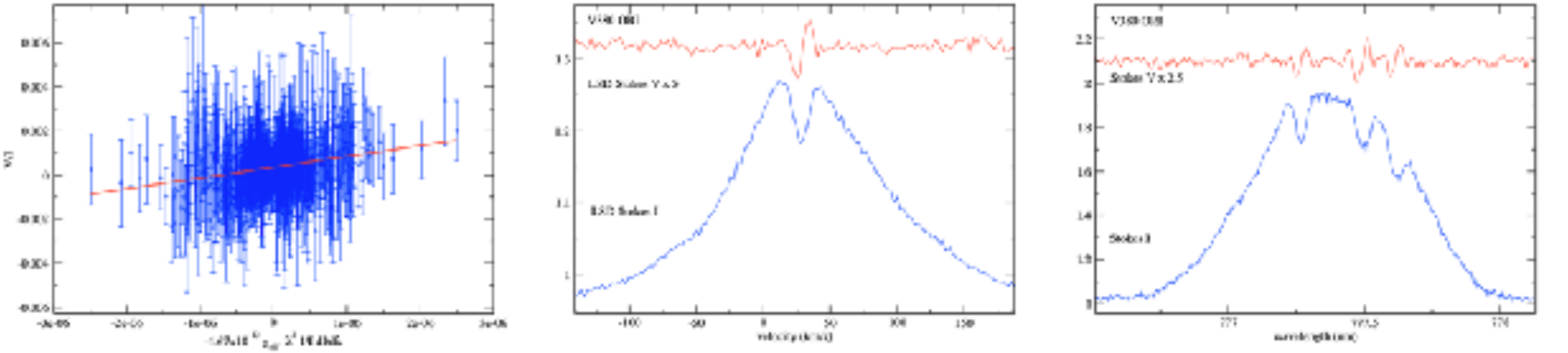


Fig. 1. Magnetic field diagnoses of: *left frame* – HD 101412 (FORS1 Balmer-line regression) *Centre frame* – V380 Ori (ESPaDOnS LSD Stokes *I* and *V* profiles *Right frame* – V380 Ori (O I 777 nm profiles). The Stokes *V* signatures detected in the spectrum of V380 Ori correspond to an approximately dipolar surface magnetic field of intensity ~1.5 kG.

Wade et al., 2005, A&A, 442, L31

Why the detections are so rare?

Why the detections are so rare?

- **The stars are faint and getting sufficient S/N is not trivial**
- **The magnetic fields are weak; the Zeeman split lines have been detected only in one case (HD101412)**

To increase S/N, we have to use techniques like LSD and SVD

LSD: Donati et al. 1997, MNRAS 291, 658

SVD: Carroll et al. 2012, A&A 548, A95

LSD

- **Least Squares Deconvolution (LSD)**

  Donati et al. 1997, MNRAS 291, 658

  - **a cross-correlation technique for computing average Stokes profiles from tens or hundreds of spectral lines simultaneously**
  - **is based on the assumption that all spectral lines have the same profile and that they can be added linearly**

SVD

- **Singular Value Decomposition (SVD)**

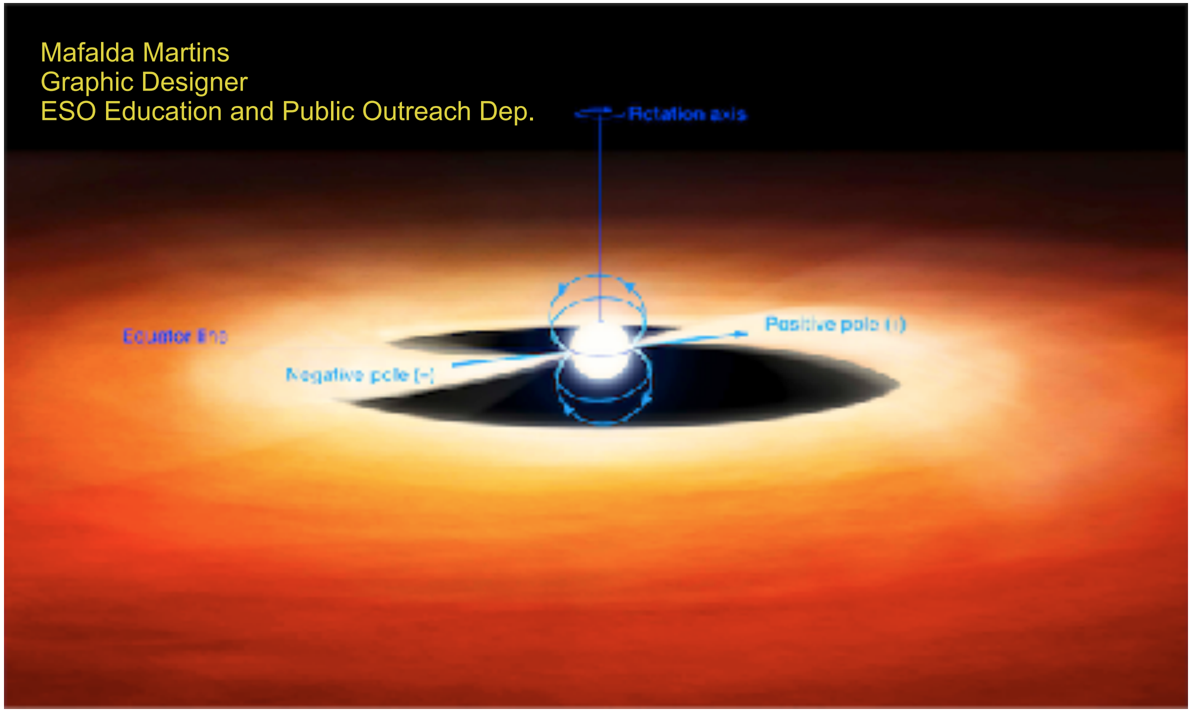
  Carroll et al. 2012, A&A 548, A95

  - **is similar to the Principle Component Analysis approach**
  - **the similarity of the individual Stokes *V* profiles allows one to describe the most coherent and systematic features present in all spectral line profiles as a projection onto a small number of eigenprofiles**

Why the detections are so rare?

- **The complex interaction between the stellar magnetic field, the accretion disk, and the stellar wind makes detecting weak magnetic field difficult**

HD 101412



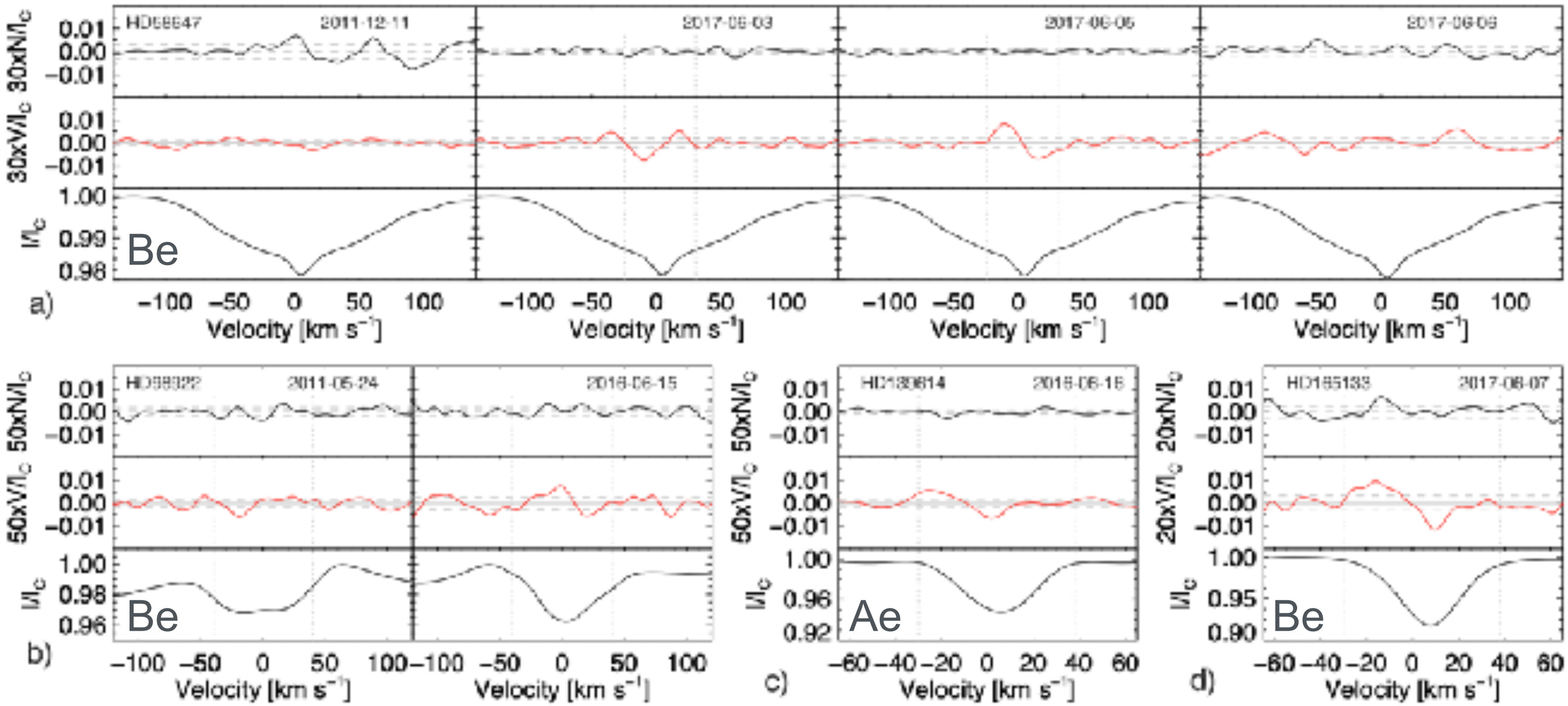
Schöller et al. 2016, A&A 592, A50

Why the detections are so rare?

- **We usually measure circular polarization → the longitudinal magnetic field, which shows a strong dependence on the viewing angle of the observer**

Repeat observations several times

Some examples



Järvinen et al. 2019, MNRAS, 489, 886

- **See also Alecian et al. 2013, MNRAS, 429, 1001**

  → for example, HD 35929 has DD in 1 case out of 5

Magnetic phase curves

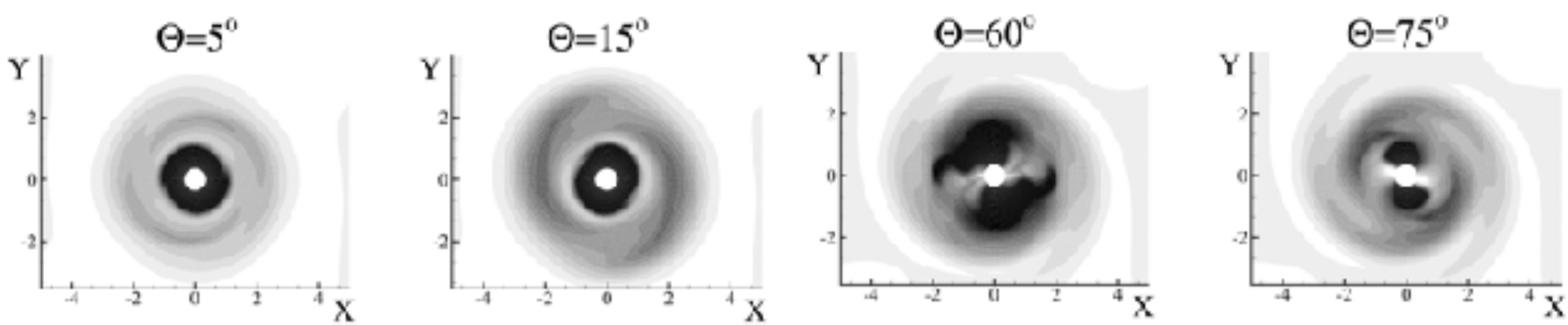
Why phase curves are important?

- **Is the field dominantly dipolar?**
- **Gives the rotation period**

→with other parameters can be used to estimate magnetic obliquity

→the topology of channeled accretion depends on the tilt angle between rotation axis and the magnetic field axis

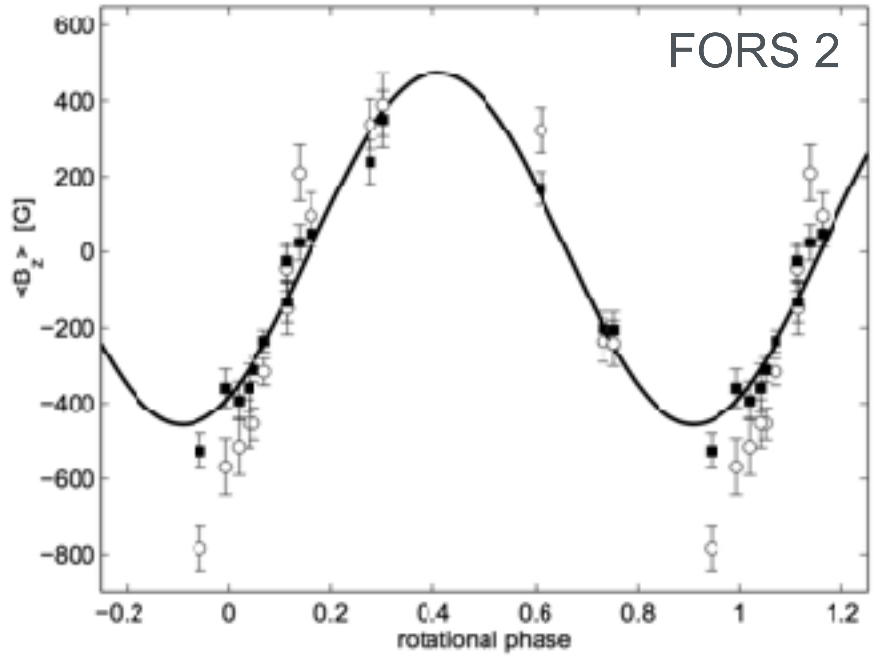
Romanova et al. 2003, ApJ 595, 1009



HD101412

- **The only Herbig star for which the magnetic phase curve presenting the dependence of the mean longitudinal magnetic field strength on the rotation phase has been obtained**

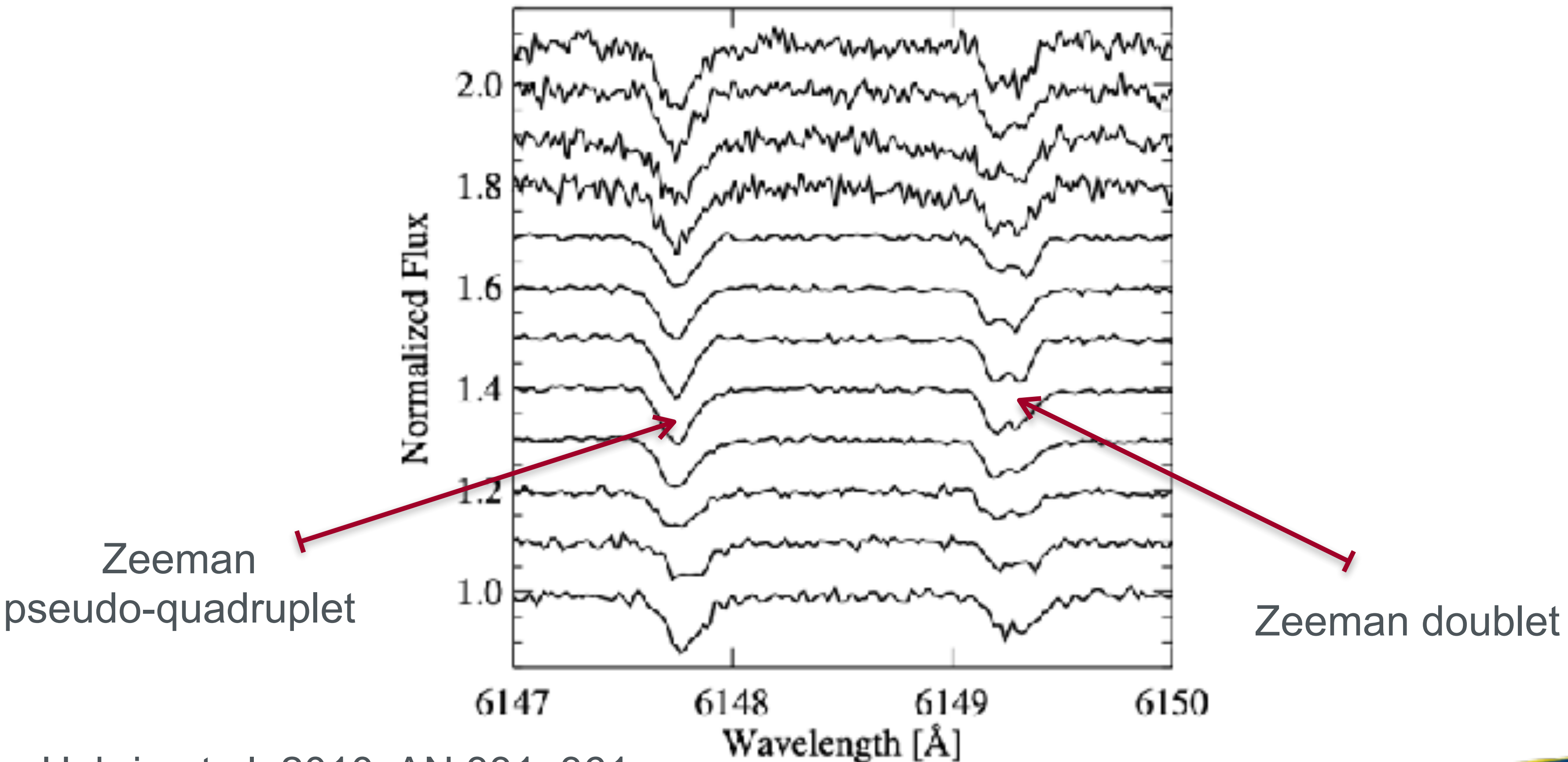
Hubrig et al. 2011, A&A 525, L4



P_{rot}=42 d

HD101412

- **The only Herbig star with magnetically split lines**



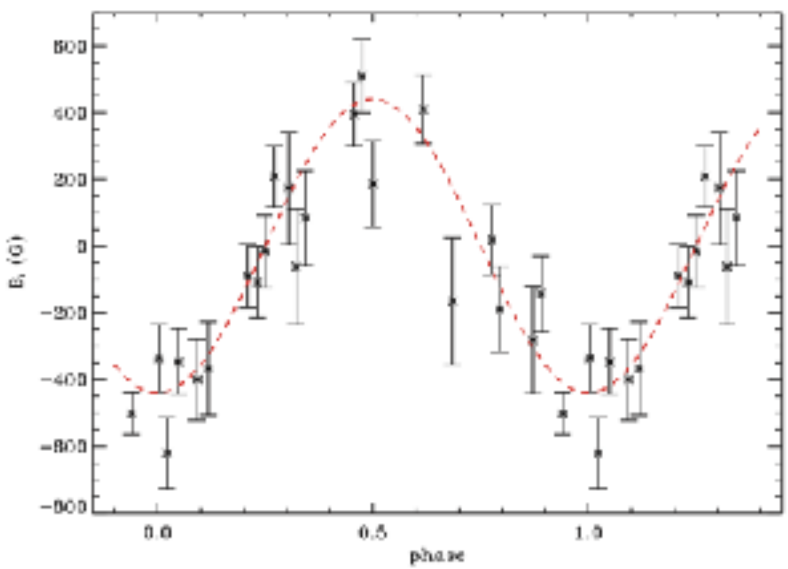
Hubrig et al. 2010, AN 331, 361

V380 Ori

Mon. Not. R. Astron. Soc. **400**, 354–368 (2009) doi:10.1111/j.1365-2966.2009.15460.x

Magnetism and binarity of the Herbig Ae star V380 Ori*†

E. Alecian,[1,2]‡ G. A. Wade,[1] C. Catala,[2] S. Bagnulo,[3] T. Böhm,[4] J.-C. Bouret,[5] J.-F. Donati,[4] C. P. Folsom,[3] J. Grunhut[1] and J. D. Landstreet[6]



P_{rot}=4.3 d

V380 Ori

- **No periodicity in emission hydrogen, helium, calcium and oxygen lines**

  → **the chemically peculiar component not a Herbig star**

- **Herbig status based on the appearance of emission in those lines belonging to the T Tauri component**

  Hubrig et al. 2019, ASPC, 518, 18;
  Shultz et al. 2021, MNRAS, accepted, arXiv:2103.09670

- **Other similar cases, like HD 72106**

  →the magnetic primary is a typical chemically peculiar young Bp star Folsom et al. 2008, MNRAS, 391, 901

HD190073

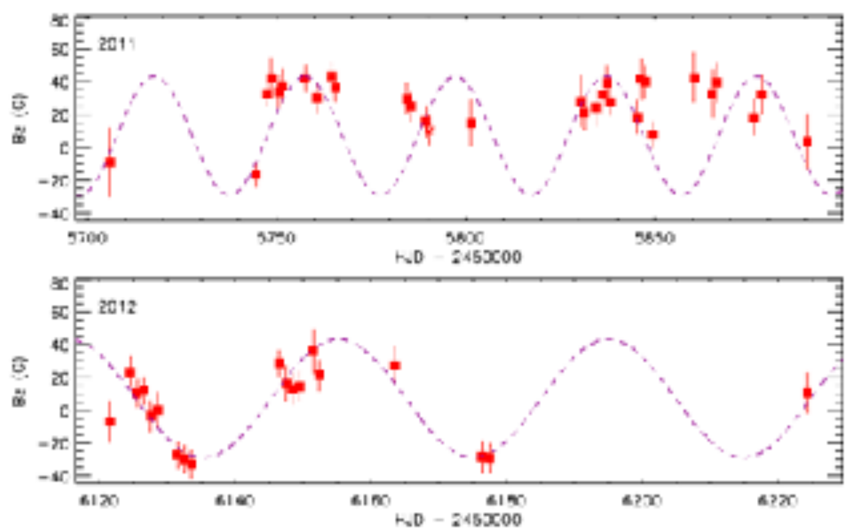
A&A 549, L8 (2013)
DOI: 10.1051/0004-6361/201220796

Astronomy & Astrophysics

Letter to the Editor

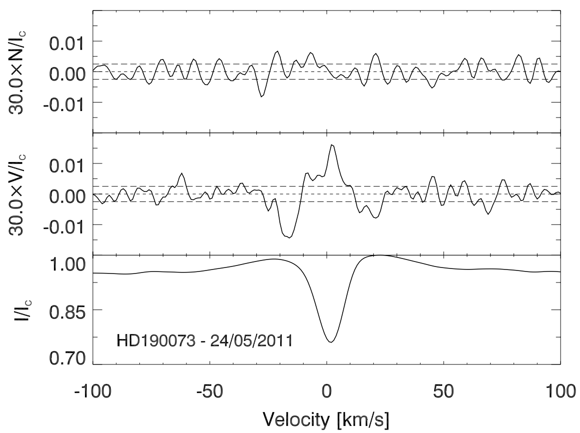
The dramatic change of the fossil magnetic field of HD 190073: evidence of the birth of the convective core in a Herbig star?*

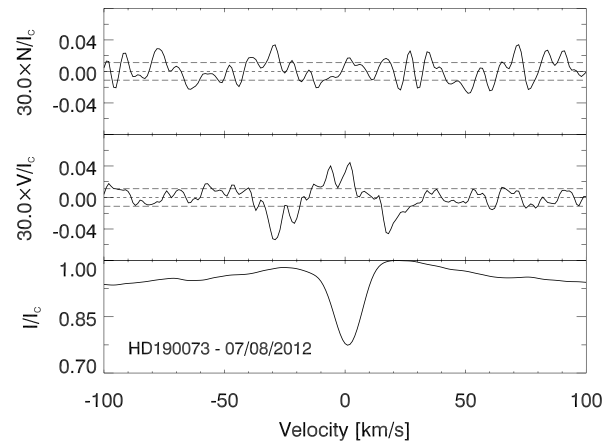
E. Alecian[1], C. Neiner[1], S. Mathis[2,1], C. Catala[1], O. Kochukhov[3], J. Landstreet[4,5], and the MiMeS Collaboration



P_{rot}=39.8±0.5 d

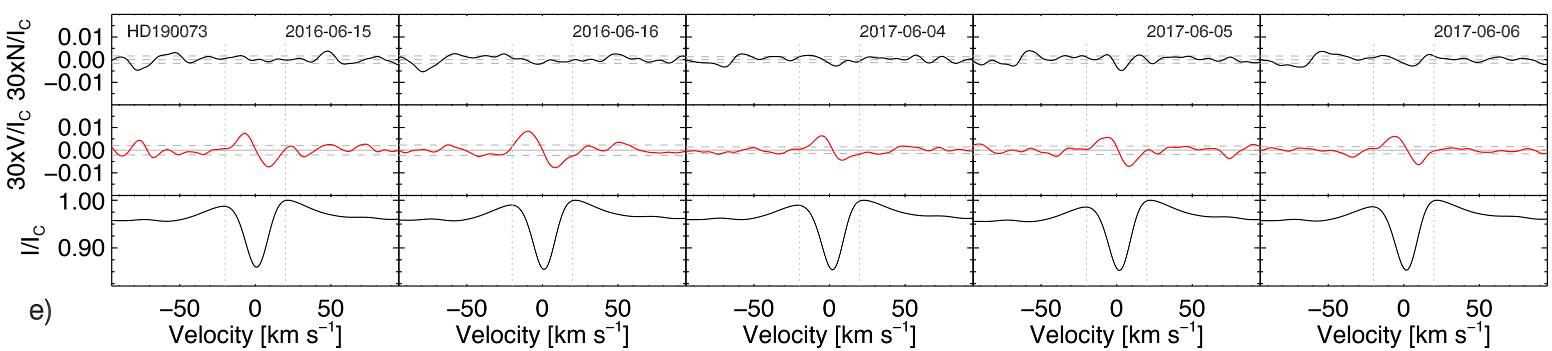
HD190073





Järvinen et al. 2015, A&A, 584, 15

$\langle B_Z \rangle = 17(\pm1) - 34\ (\pm2)$ G



Järvinen et al. 2019, MNRAS, 489, 886

Herbig stars in binaries

Importance of Herbig stars in binaries

- **About 70% of the Herbig Ae/Be stars appear in binary/ multiple systems**

  e.g. Baines et al. 2006, MNRAS, 367, 737

- **Only very few close spectroscopic binaries with orbital periods below 20d are known among Herbig Ae stars**

  Duchêne 2015, Ap&SS, 355, 291

- **The search for magnetic fields and the determination of their geometries in close binary systems plays an important role for understanding the mechanisms that can be responsible for the magnetic field generation**

Importance of Herbig stars in binaries

- **Recent observations of magnetic Ap/Bp stars support magnetic field origin scenario requiring a merger event**

  Mathys 2017, A&A, 601, A14

- **If at least one of the merging stars is on the Henyey part of the pre-main-sequence track towards the end of its contraction to the main sequence, it is possible that the outcome becomes observable as a Herbig Ae/Be star**

  Ferrario et al. 2009, MNRAS, 400, L71

If this scenario is valid, there should be almost no magnetic star in close Herbig Ae/Be and Ap/Bp binaries

Z CMa

A&A 509, L7 (2010)
DOI: 10.1051/0004-6361/200913704

Astronomy & Astrophysics

LETTER TO THE EDITOR

The nature of the recent extreme outburst of the Herbig Be/FU Orionis binary Z Canis Majoris⋆,⋆⋆

- **The strongest longitudinal magnetic field measured so far (-1231±164 G)**
- **Not clear whether the magnetic field was detected for the Herbig Be NW component or for FU Ori -type component**

AK Sco (HD152404)

The first abundance analysis of both components

http://wwwuser.oats.inaf.it/castelli/

```
Herbig  F5 IVe star- Spectroscopic binary. A and B are the primary and the secondary stars.

A: Star parameters: Teff=6500 K, log g=4.5, vturb=1 km/sec (from spectrum)
                    vsini=18 km/sec from several lines in the spectrum.

B: Star parameters: Teff=6500 K, log g=4.5, vturb=2 km/sec (from spectrum)
                    vsini=21 km/sec from several lines in the spectrum.
```

- **Identified elements typical for spectral type F 5 IV-V**
- **Presence of Li I at 6707 Å and He I at 5875.61 Å related with the Herbig nature**
- **Overabundances in both stars for Y, Ba, and La**
- **Abundance pattern similar to that of Herbig stars displaying weak Ap/Bp peculiarities**

Castelli et al. 2020, MNRAS, 491, 2010

AK Sco

- **Close SB2 system (P_{orb} = 13.6d) with approximately equal components surrounded by a circumbinary disk**

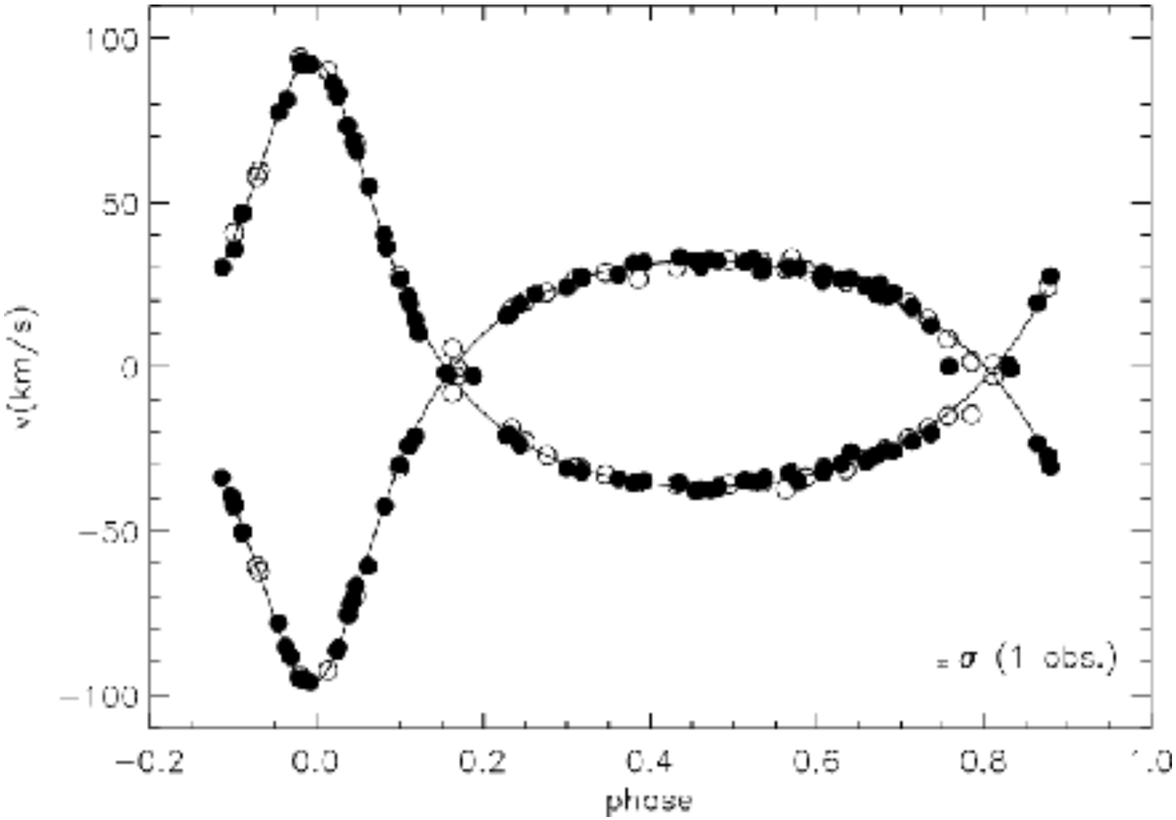
- **The primary is classified as a class II Herbig Ae/Be**

  Menu et al. 2015, A&A, 581, A107

- **The study based on ESPaDOnS spectra reported a non-detection**

  Alecian et al. 2013, MNRAS, 429, 1001

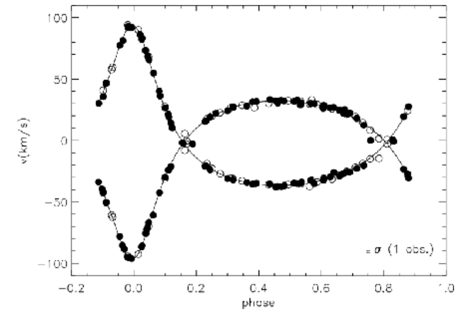
AK Sco



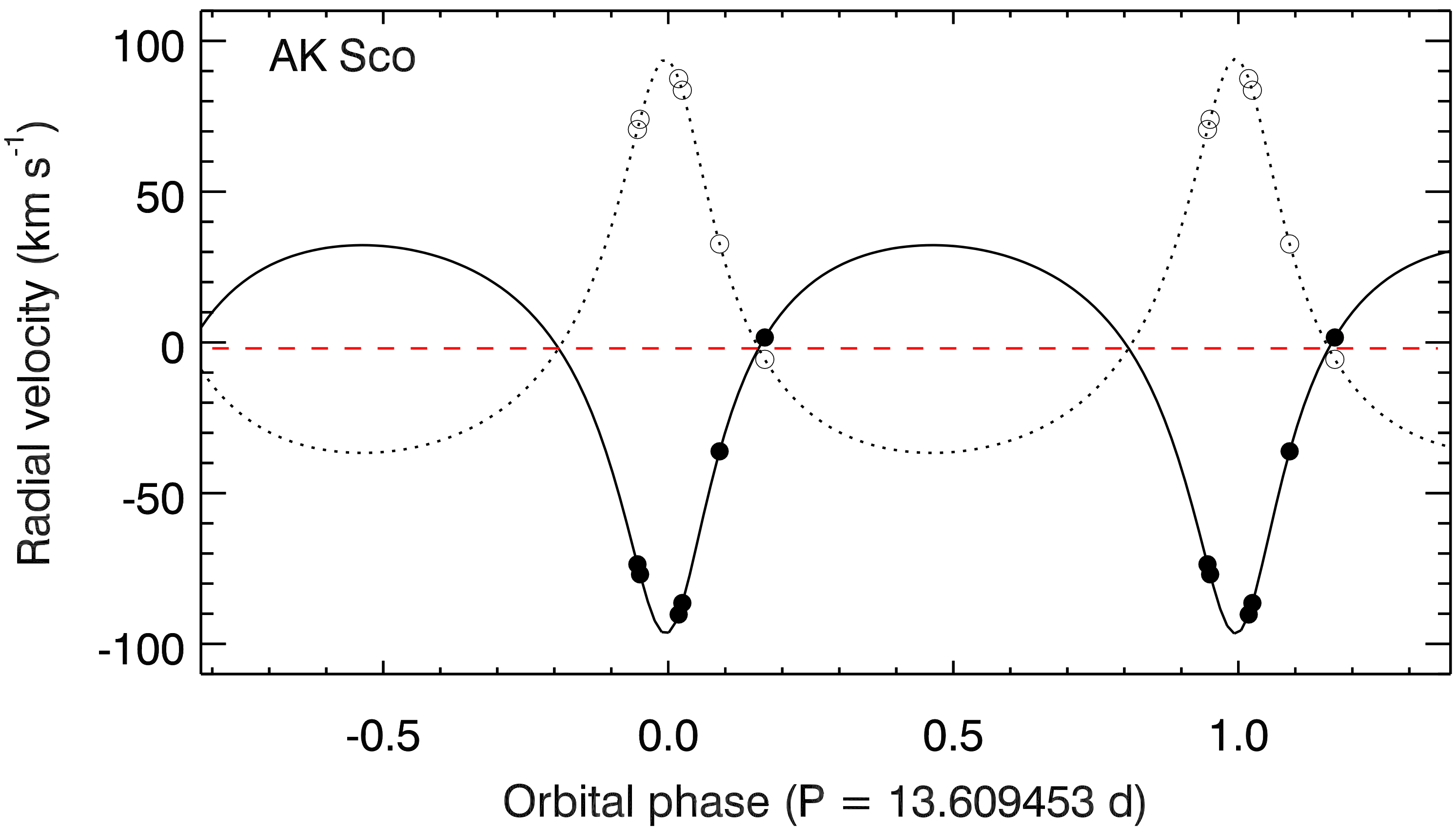
Orbital parameters	
P (days)	13.609453 ± 0.000026
T (J.D.)	46 654.3634 ± 0.0086
K_A (km s^{-1})	64.45 ± 0.23
K_B (km s^{-1})	65.32 ± 0.24
γ (km s^{-1})	−1.97 ± 0.10
e	0.4712 ± 0.0020
ω	185.40° ± 0.33°
σ(1 obs.) (km s^{-1})	1.4
Physical elements	
M_B/M_A	0.987 ± 0.005
$a \sin i$ (AU)	0.14318 ± 0.00005
$M_A \sin i^3$ ($M_\odot$)	1.064 ± 0.007
$M_B \sin i^3$ ($M_\odot$)	1.050 ± 0.007

Alencar et al. 2003, A&A, 409, 1037

AK Sco

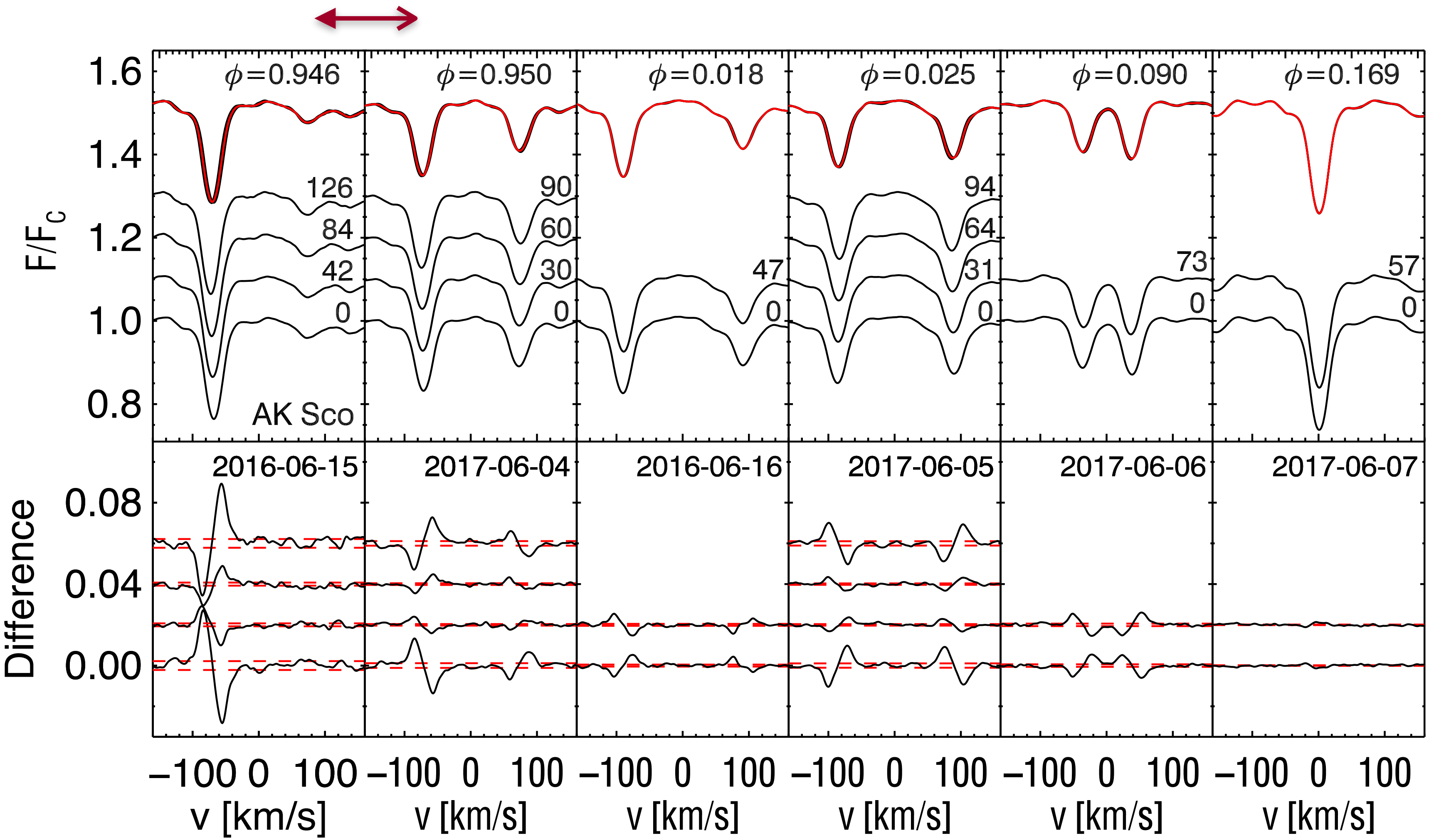


100
50
0
−50
−100
v(km/s)
−0.2
0.0
0.2
0.4
0.6
0.8
1.0
phase
σ (1 obs.)



AK Sco
100
50
0
-50
-100
Radial velocity (km s⁻¹)
-0.5
0.0
0.5
1.0
Orbital phase (P = 13.609453 d)

AK Sco

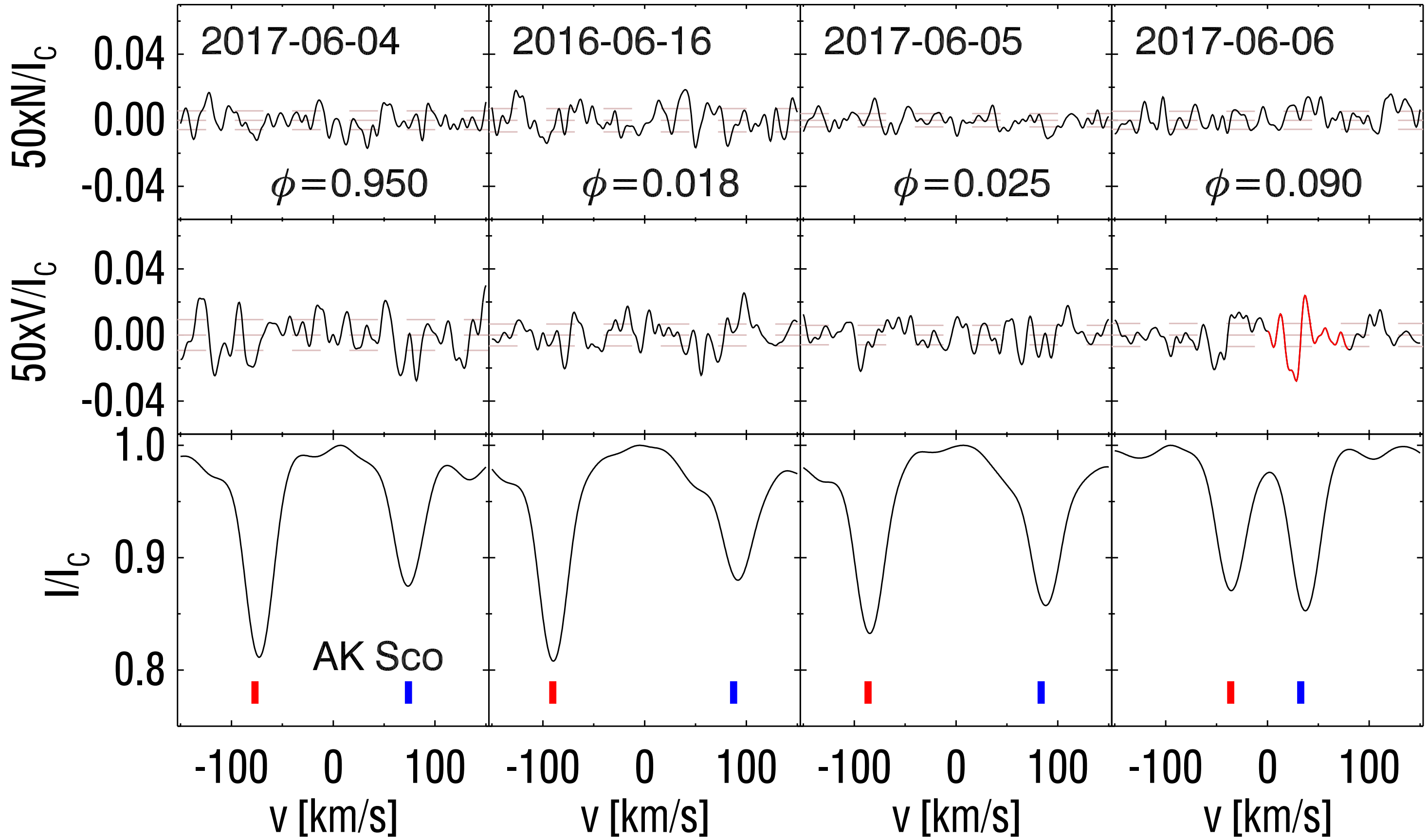


1.6
1.4
1.2
1.0
0.8
F/F$_C$
ϕ=0.946
ϕ=0.950
ϕ=0.018
ϕ=0.025
ϕ=0.090
ϕ=0.169
126
84
42
0
90
60
30
0
47
0
94
64
31
0
73
0
57
0
AK Sco
Difference
0.08
0.04
0.00
2016-06-15
2017-06-04
2016-06-16
2017-06-05
2017-06-06
2017-06-07
−100 0 100
v [km/s]

AK Sco

secondary component

$\langle B_Z \rangle = -83 \pm 31$ G



Järvinen et al. 2018, ApJL, 858, 18

AK Sco

- **Components are expected to be tidally synchronized**

  Alencar et al. 2003, A&A, 409, 1037

→the phase where we detect the magnetic field, we observe the region of the stellar surface facing permanently the primary component

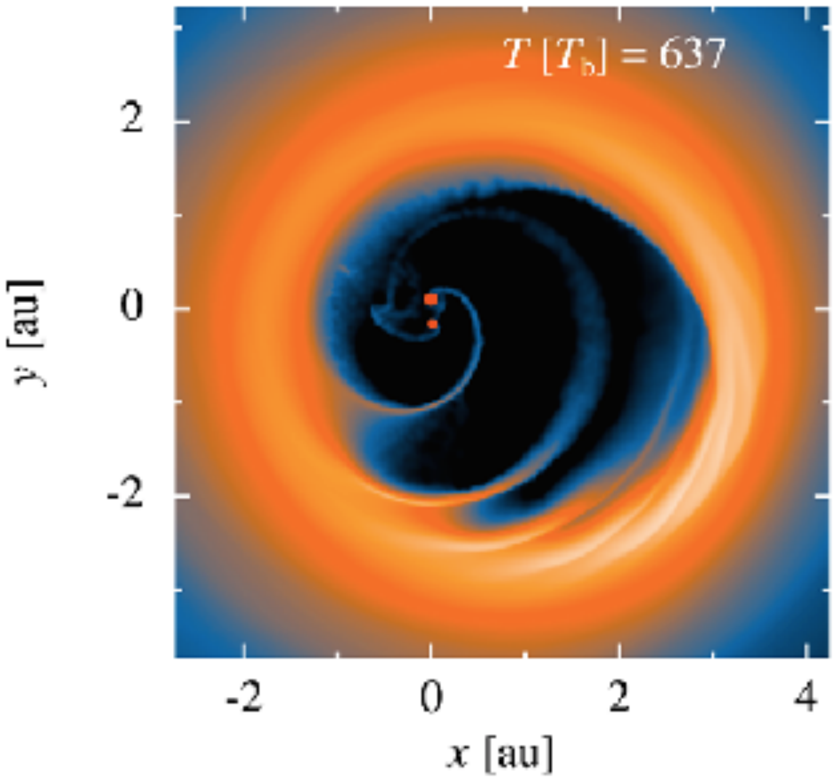
  - **the magnetic field geometry in the secondary component could be possibly closely related to the position of the primary component**

→no detection in the primary, but only a fraction of the orbital cycle is covered

Järvinen et al. 2018, ApJL, 858, 18

HD104237 (DX Cha)

- **Herbig Ae + T Tau**



Dunhill et al. 2015, MNRAS, 448, 3545

	T_{eff} K	log (g)	ξ_{turb}
Primary	8250 ± 200	4.2 ± 0.25	2.5 ± 1
Secondary	4800 ± 200	$3.5- \lesssim 3.7$	1.0 ± 1

(Cowley et al. 2003, MNRAS, 431, 3485)

Physical quantity	Value	Reference
m_1 ($M_\odot$)	2.2 ± 0.2	Böhm et al. 2004
m_2 ($M_\odot$)	1.4 ± 0.3	Assumed
a (AU)	0.22 ± 0.06	Derived
a (mas)	1.9 ± 0.6	Idem
i (°)	17^{+12}_{-9}	Idem
$T_{eff,1}$ (K)	8500 ± 150	Fumel & Böhm 2012
$L_{*,1}$ ($L_\odot$)	35^{+5}_{-4}	van den Ancker et al. 1998
$R_{*,1}$ ($R_\odot$)	2.7 ± 0.2	Derived
$v_{rot,1} \sin i$ (km s^{-1})	12 ± 2	Donati et al. 1997
$P_{rot,1}$ (d)	3.4 ± 2.0	Derived

Garcia et al. 2013, MNRAS, 430, 1839

HD104237

- **Abundance analysis** Cowley et al. 2013, MNRAS, 431, 3485

  See also http://wwwuser.oats.inaf.it/castelli/

- **Possible presence of a magnetic field of the order of 50 G was announced over 20 years ago**

  Donati et al. 1997, MNRAS, 291, 658

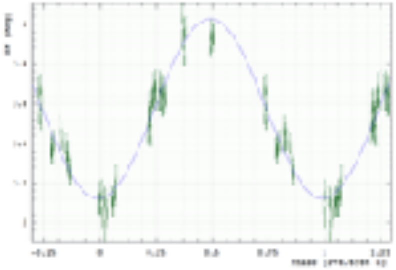
- **Both detections and non-detections reported**

  Wade et al. 2007, MNRAS, 376, 1145; 2011, ASPC, 449, 262;
  Hubrig et al. 2013, AN, 334, 1093

- **EW_{LSD} P_{rot} = 4.7 d (113 h)**

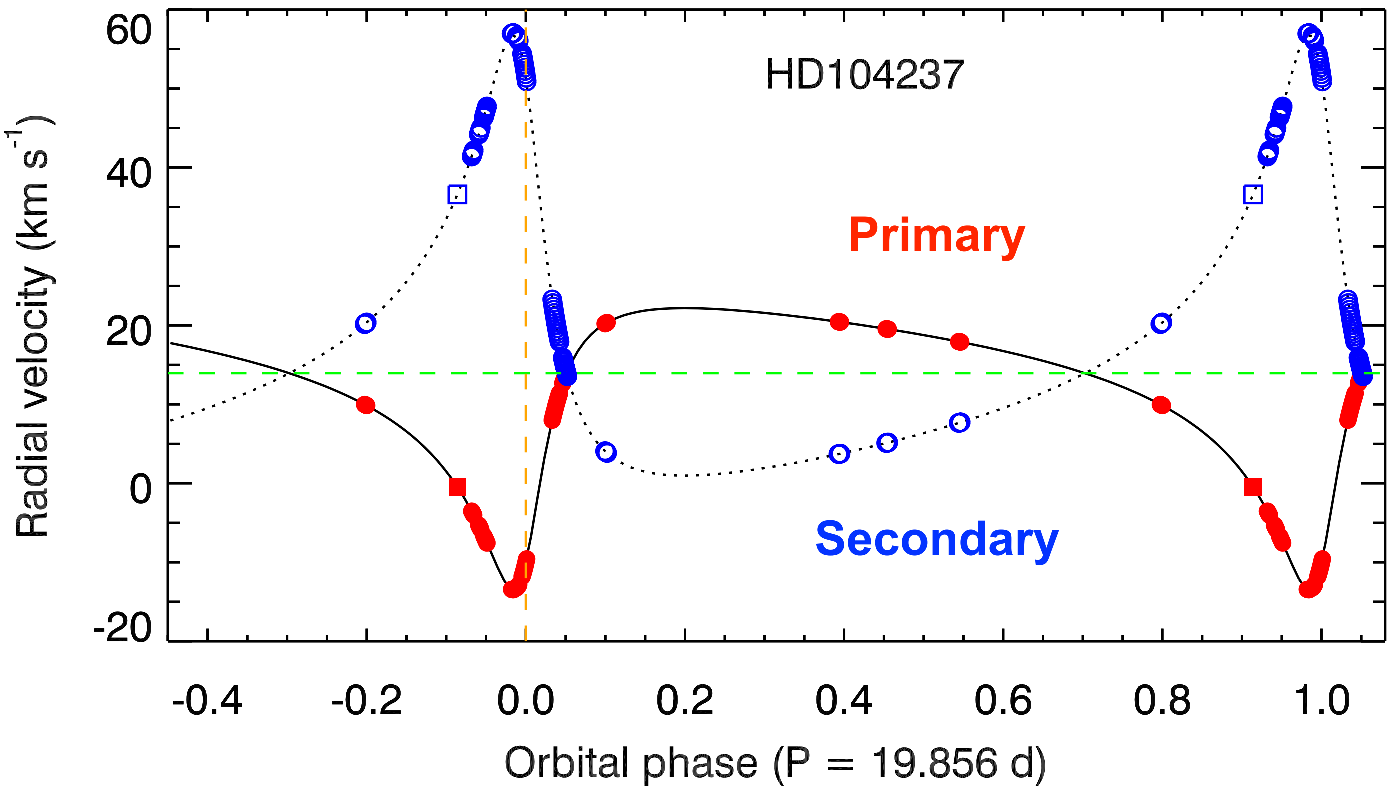
- **P_{rot} (Payγ)= 4.85 d (116 h)**

  21 ISAAC + X-shooter spectra



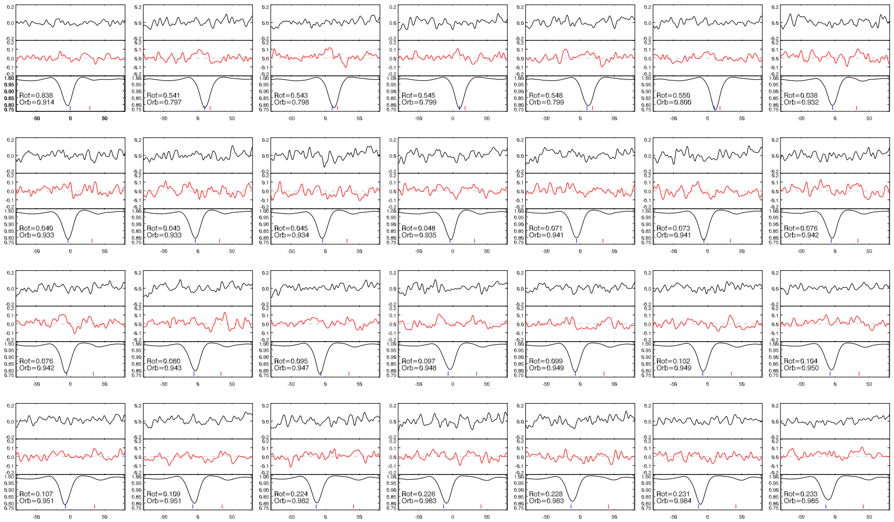
HD104237

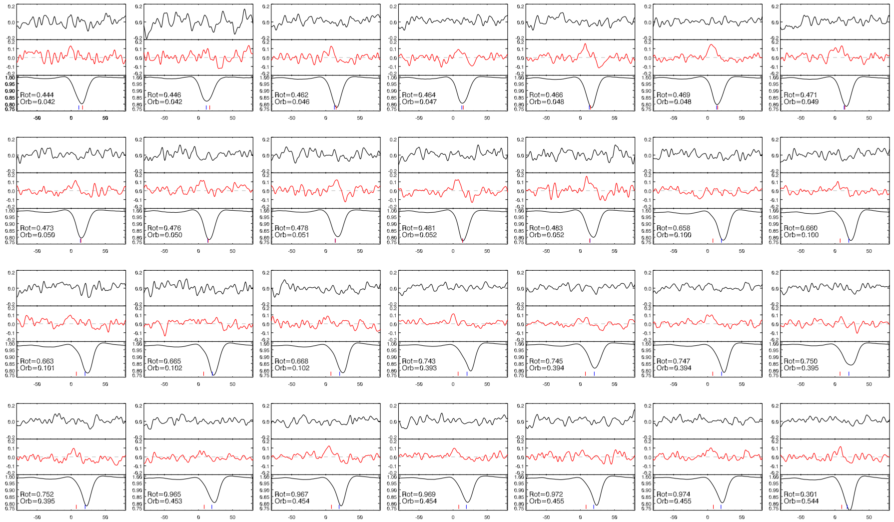
- **88 spectra in ESO archive**

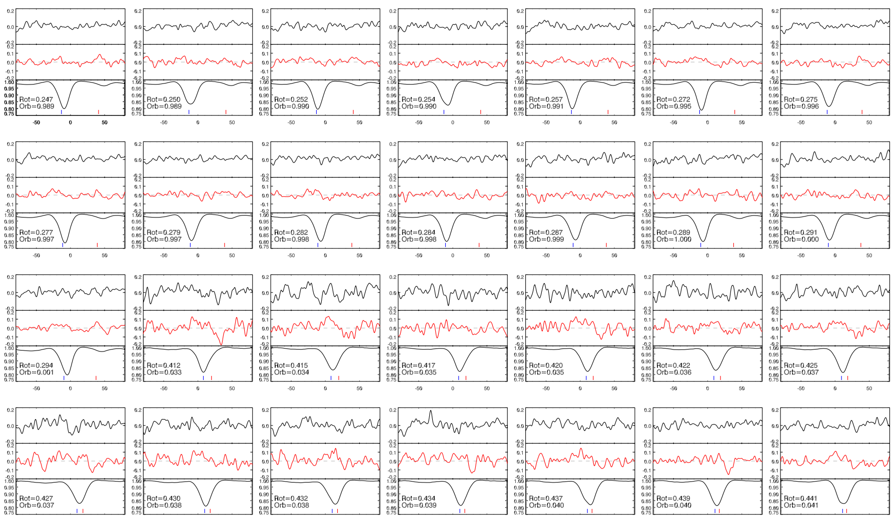


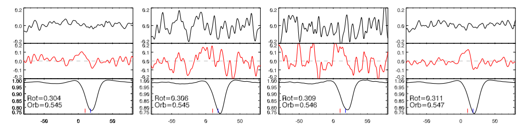
based on orbital parameters by Böhm et al. 2004, A&A, 427, 907

HD104237



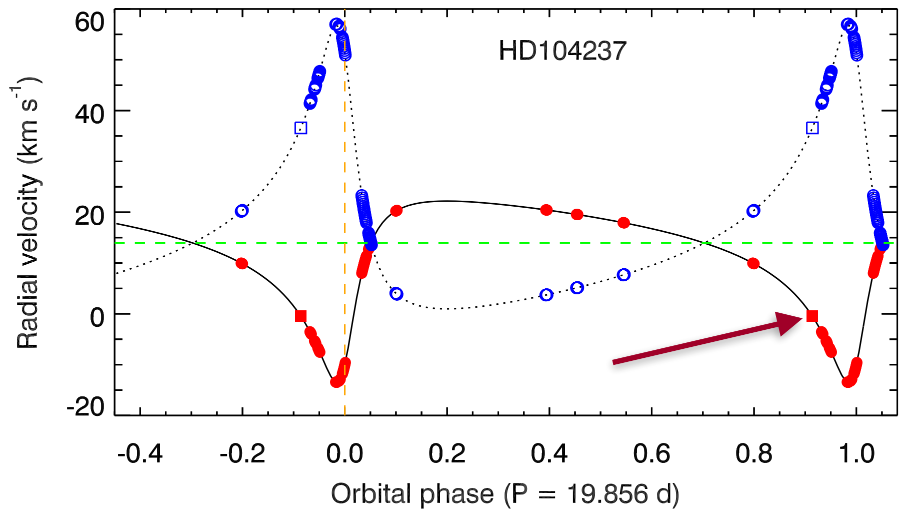




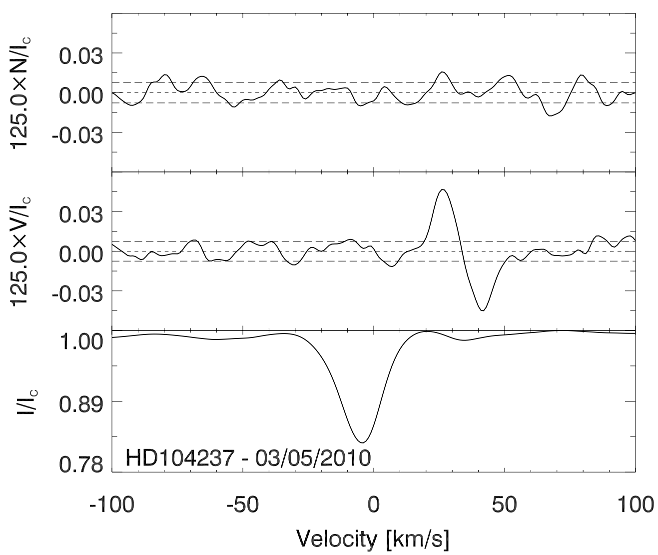


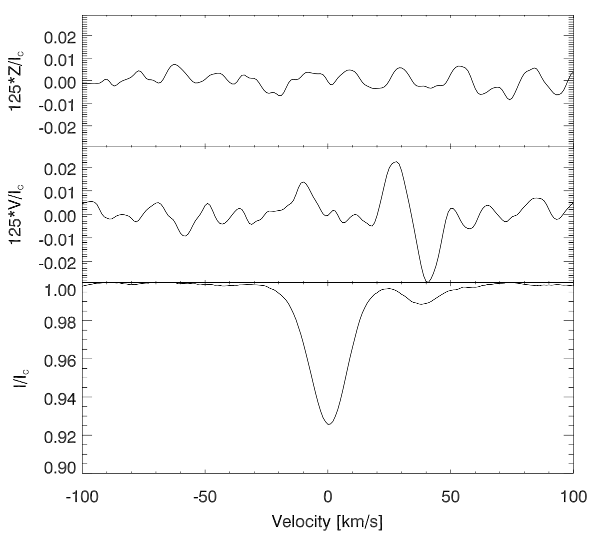
Most of the original data have S/N in the range of 59 - 100

HD104237



$\langle B_Z \rangle = 129 \pm 12$ G

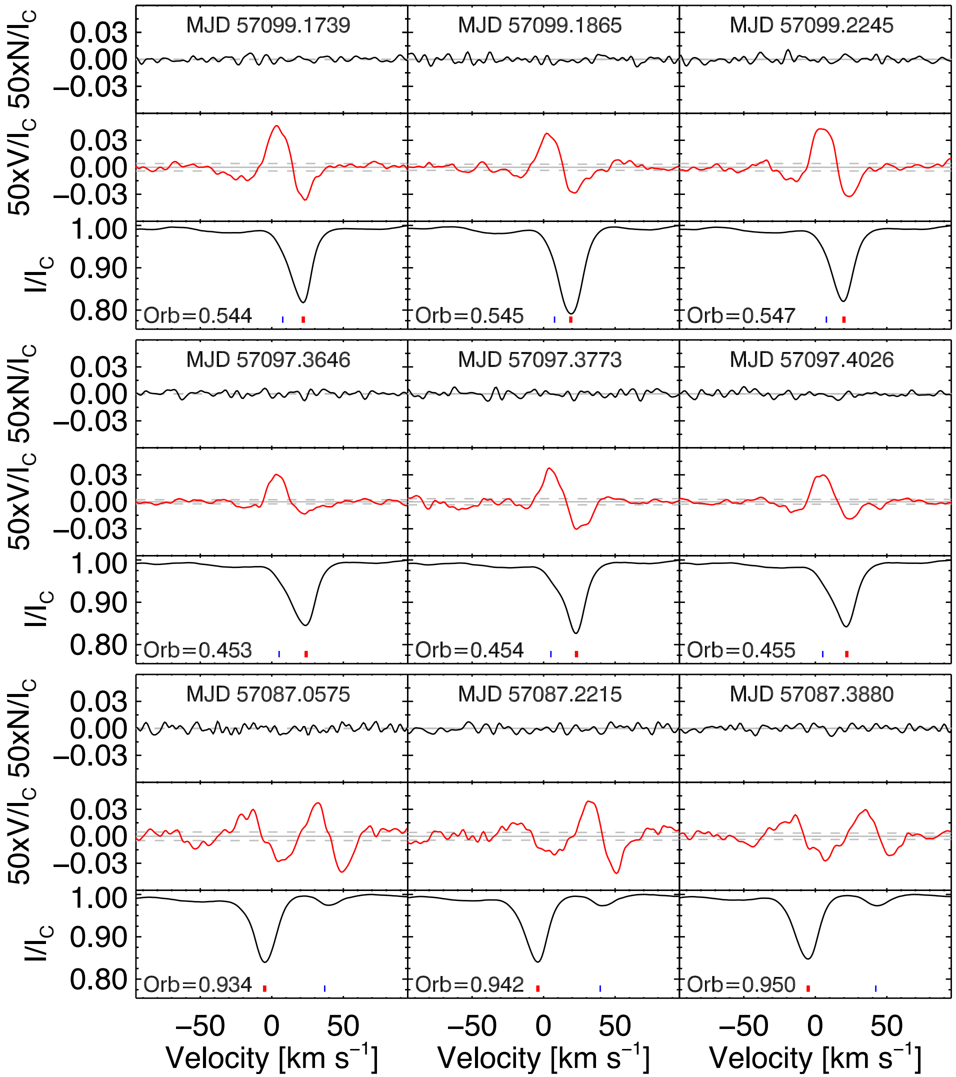


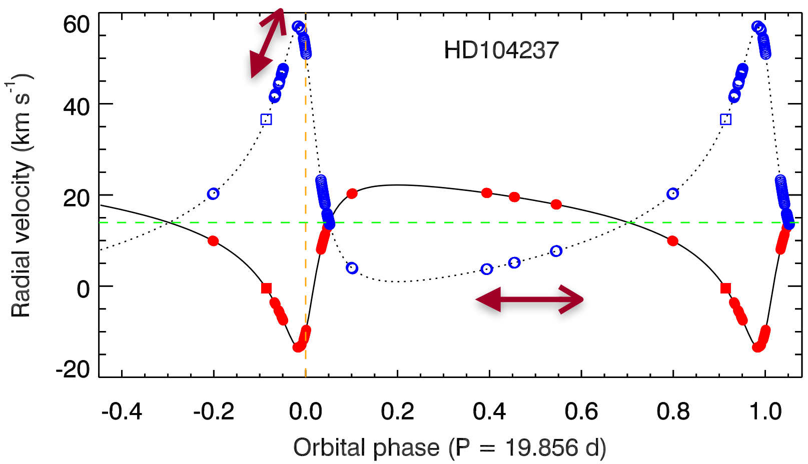


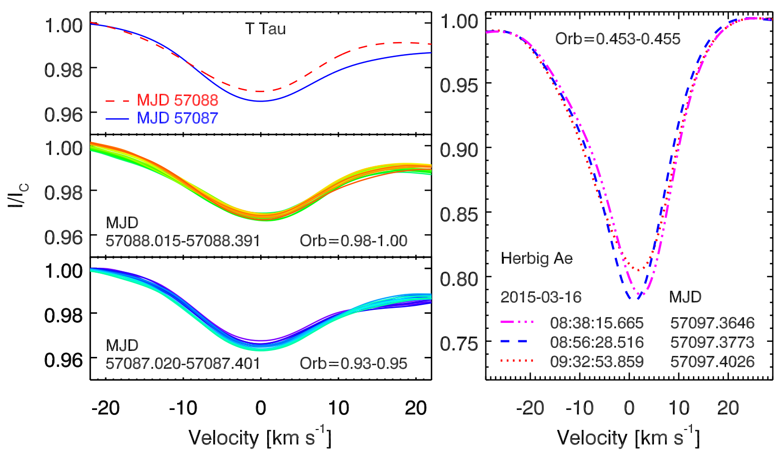
$\langle B_Z \rangle = 13$ G

Järvinen et al. 2015, A&A 584, A15

HD104237

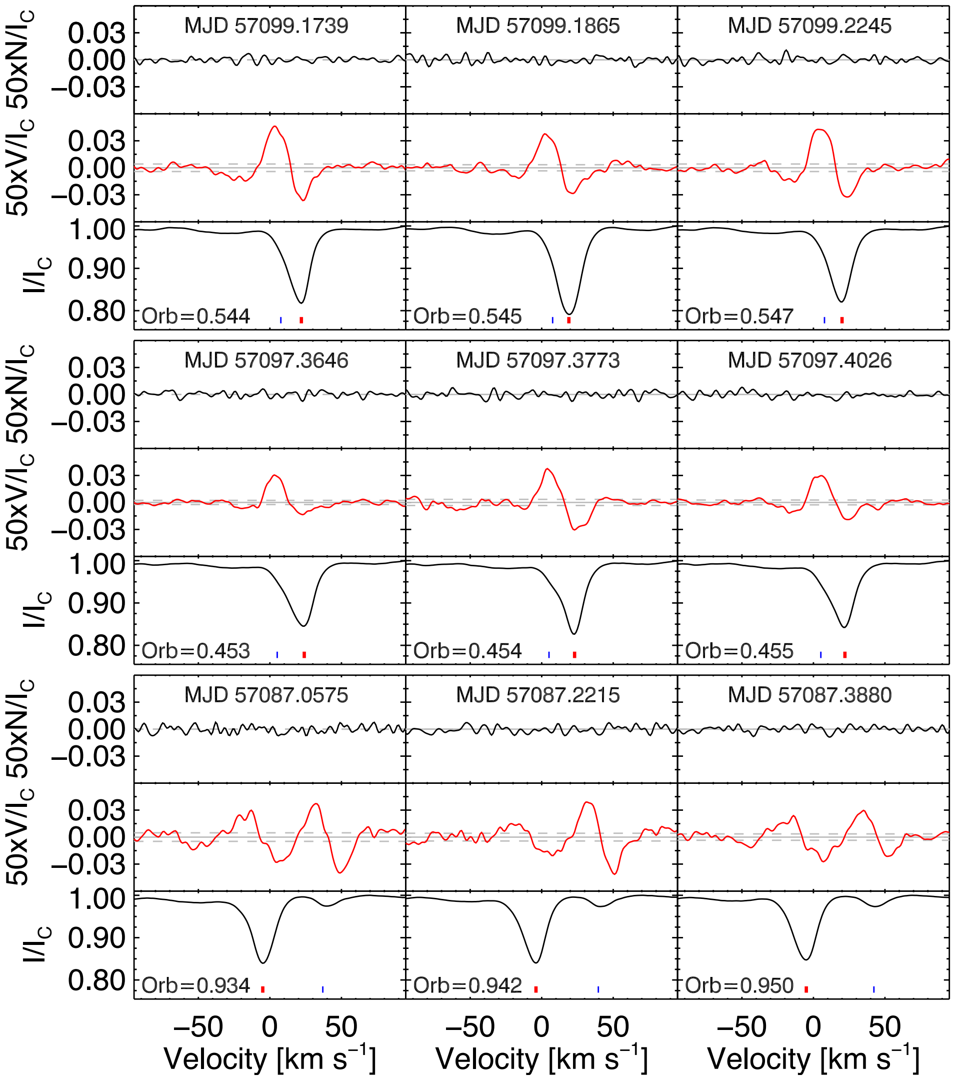






Järvinen et al. 2019, MNRAS, 486, 5499

HD104237



Järvinen et al. 2019, MNRAS, 486, 5499

366±21 G 349±22 G 338±20 G

← 1.4h →

44.8h

144±15 G 410±22 G 189±19 G

← 57min →

$\langle B_Z \rangle$=72±6 G $\langle B_Z \rangle$=47±6 G $\langle B_Z \rangle$=63±6 G

$\langle B_Z \rangle$=609±27 G $\langle B_Z \rangle$=440±23 G $\langle B_Z \rangle$=124±13 G

← 7.6h →

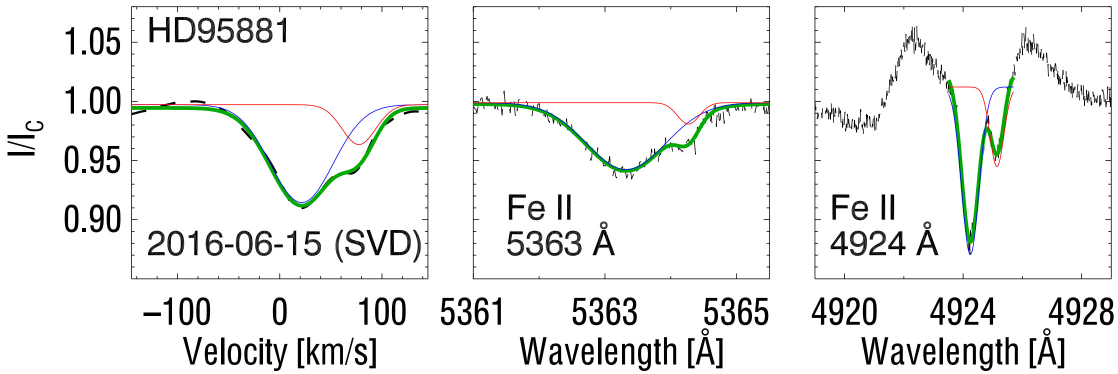
HD95881

Name	T_{eff} (K)	log(g) (cm s^{-2})	log(L_*) ($L_\odot$)	M_* ($M_\odot$)	R_* ($R_\odot$)	A_V (mag)	Age (Myr)	Distance (pc)
HD 95881	$10\,000 \pm 250$	$3.20^{+0.10}_{-0.10}$	$2.98^{+0.15}_{-0.15}$	$6.2^{+0.8}_{-0.7}$	$10.3^{+0.7}_{-0.6}$	$0.00^{+0.05}_{-0.00}$	$0.21^{+0.10}_{-0.07}$	1290^{+90}_{-78}

Fairlamb et al. 2015, MNRAS, 453, 976

- **Spectro-astrometric observations indicate that HD 95881 is a possible sub-arcsecond binary**

Baines et al. 2006, MNRAS, 367, 737

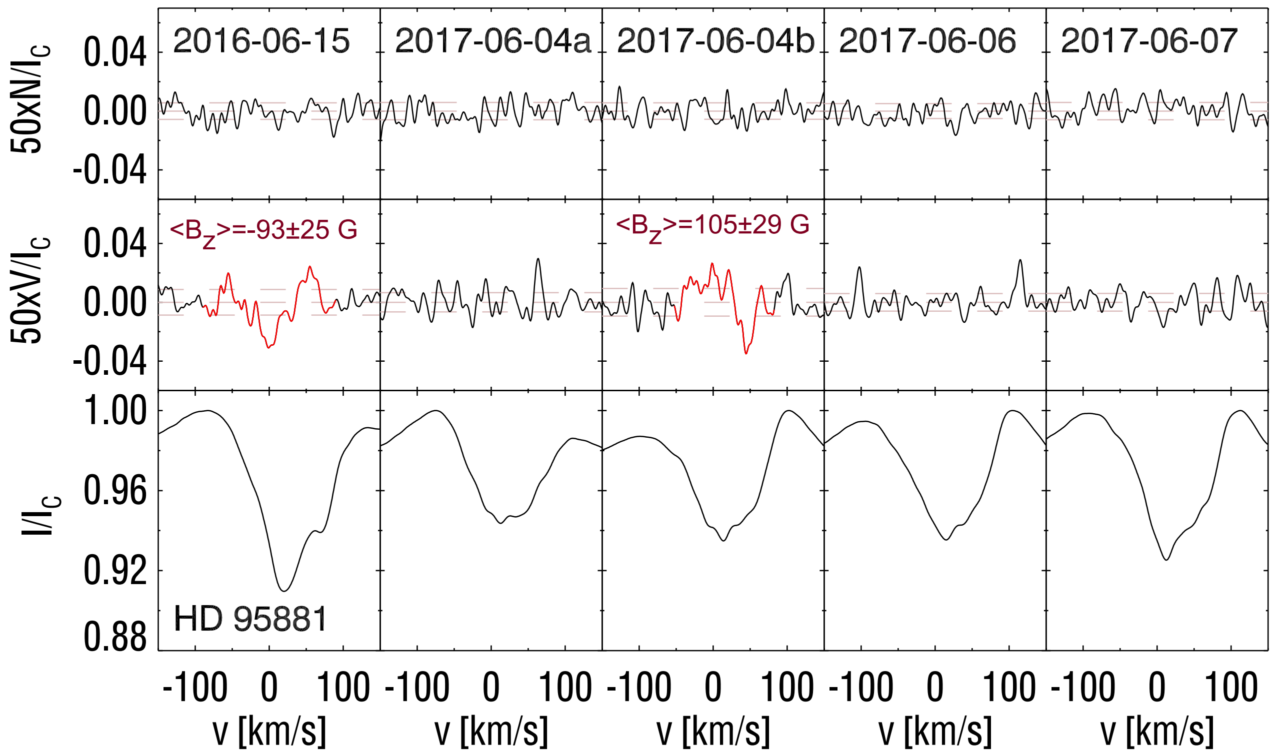


Järvinen et al. 2018, ApJL, 858, 18

HD95881

- **The first low-resolution FORS1 (at the VLT) polarimetric spectra yielded ⟨Bz⟩ = −20±42 G**

Wade et al. 2007, MNRAS, 376, 1145



HARPSpol observations

Järvinen et al. 2018, ApJL, 858, 18

What have we learned?

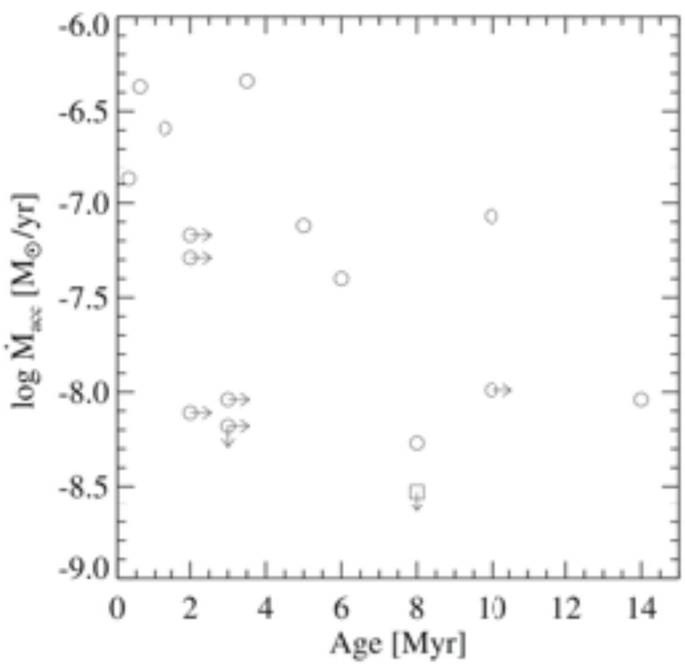
- **Yet the small number of magnetic HerbigAe/Be stars can be due to the weakness of their magnetic fields and/or the large measurement errors**
- **A single snapshot is not sufficient to judge whether a Herbig Ae/Be star is magnetic or not due to a strong dependence on the viewing angle**
- **One has to consider contamination by circumstellar matter when interpreting the line profiles**

Correlations and what do they mean

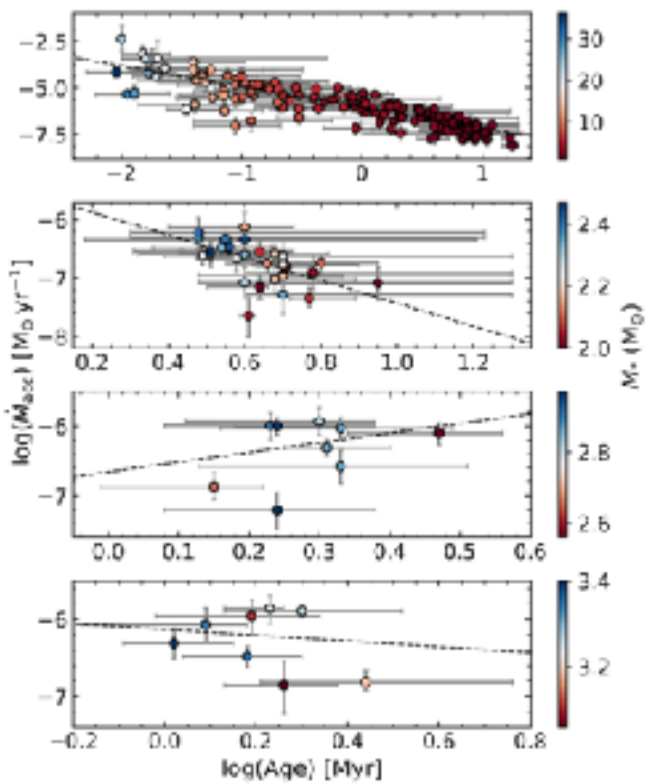
Mass accretion rate

- **Derived from the measured luminosity of Brγ emission line**

  Garcia Lopez et al. 2006, A&A, 459, 837; Muzerolle et al. 1998, AJ, 116, 2965; Calvet et al. 2004, AJ, 128, 1294



Hubrig et al. 2009, A&A, 502, 283



Wichittanakom et al. 2020, MNRAS, 493, 234

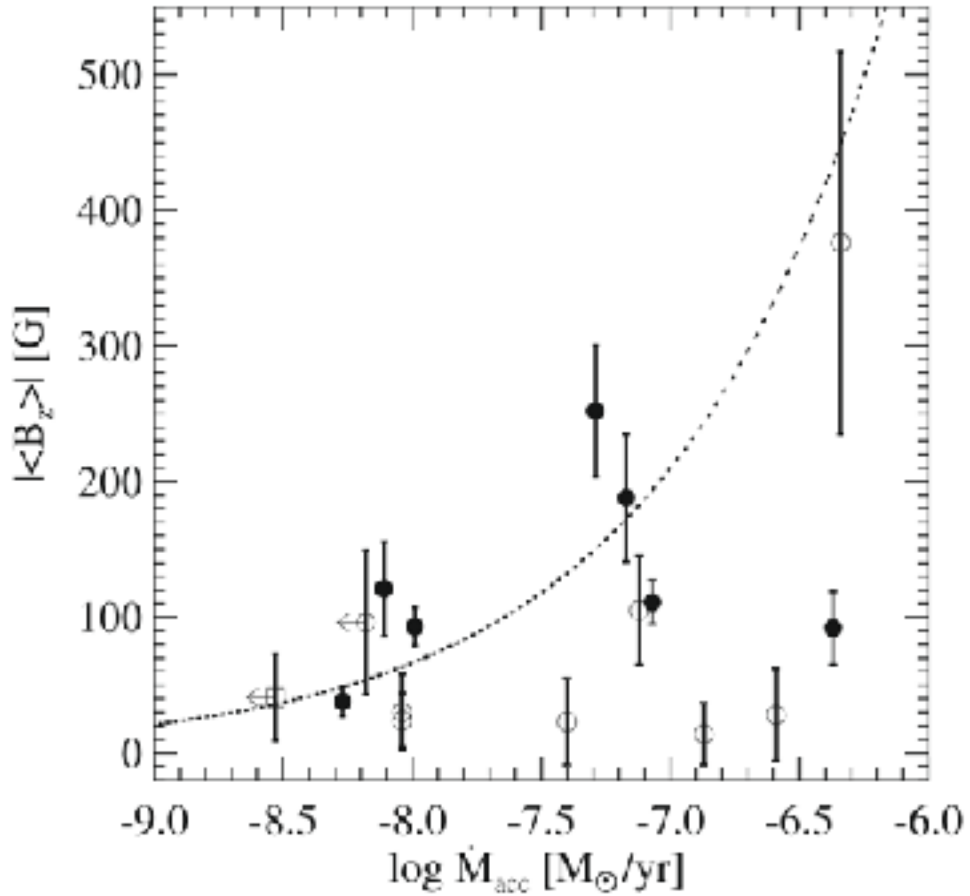
Magnetospheric accretion models

$$B_* = 3.43\left(\frac{\epsilon}{0.35}\right)^{7/6}\left(\frac{\beta}{0.5}\right)^{-7/4}\left(\frac{M_*}{M_\odot}\right)^{5/6} \times \left(\frac{\dot{M}}{10^{-7}\,M_\odot\,\mathrm{yr}^{-1}}\right)^{1/2}\left(\frac{R_*}{R_\odot}\right)^{-3}\left(\frac{P_*}{1\ \mathrm{day}}\right)^{7/6}$$

Johns-Krull et al. 1999,
ApJ, 516, 900

based on
Koenigl 1991, ApJL, 370, L39

- **Equation is for (dipolar) surface field whereas usually longitudinal component is measured**

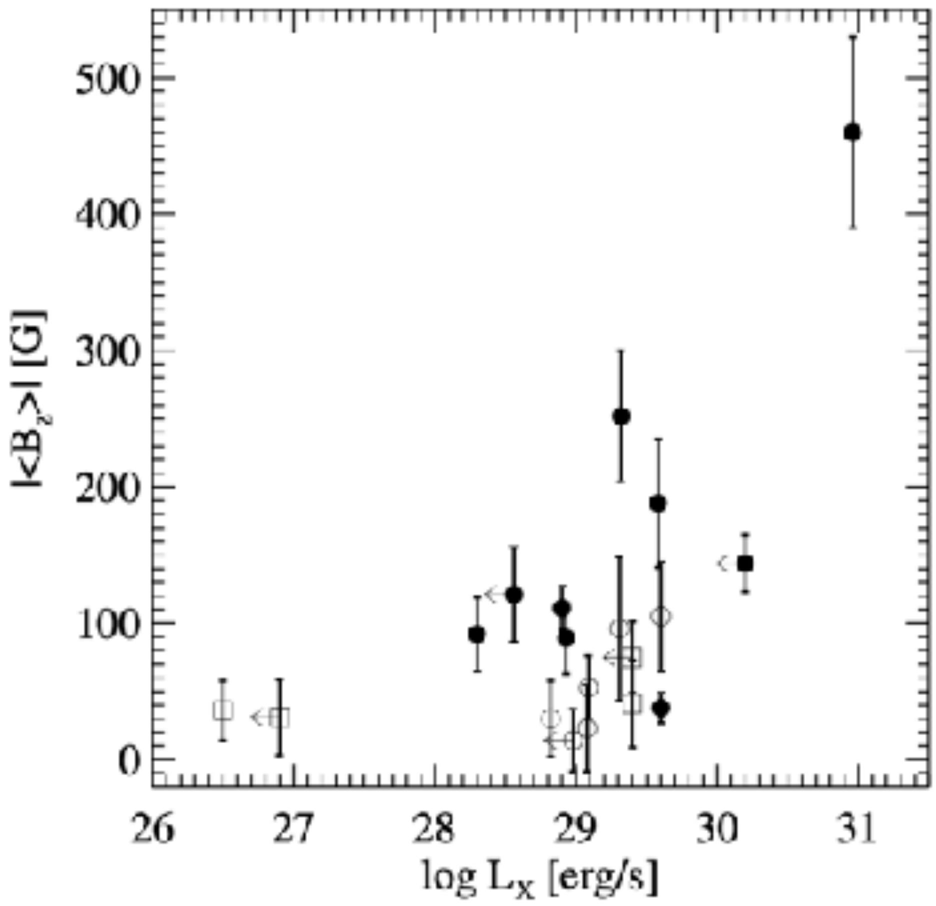


Hubrig et al. 2009, A&A, 502, 283

Magnetic field origin

- Hint for increase of B_z with level of X-ray emission

  →dynamo mechanism responsible for the coronal activity?



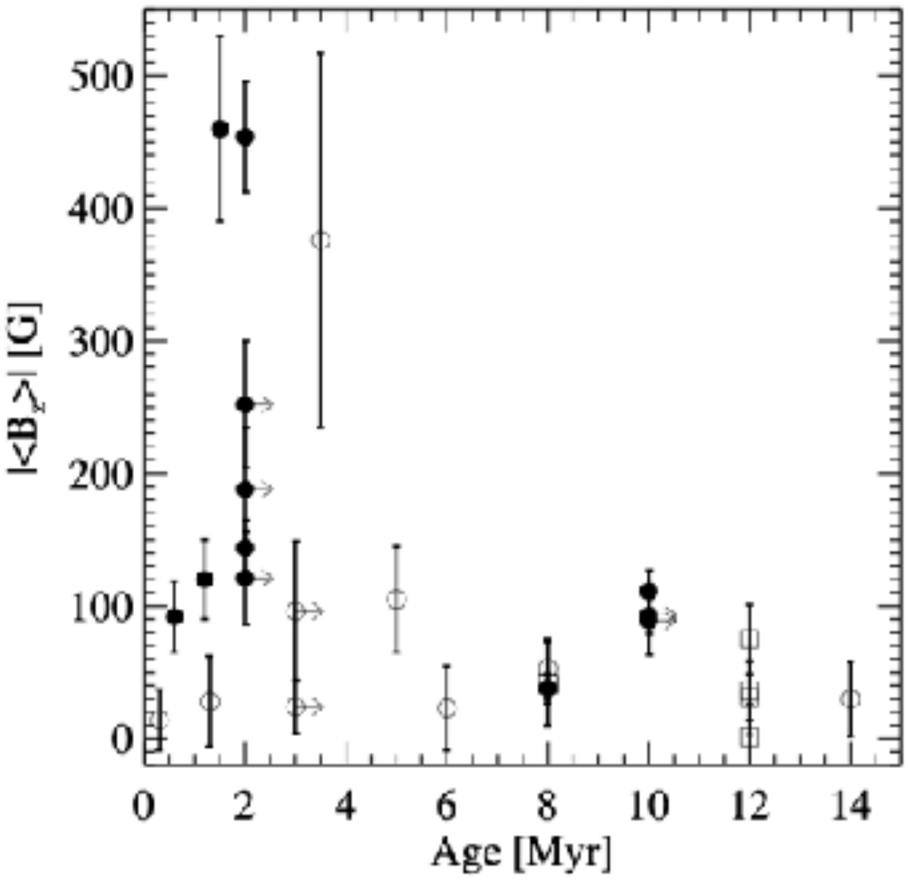
Hubrig et al. 2009, A&A, 502, 283

Magnetic field origin

- **Stronger field in younger stars**
  →dynamo mechanism that decays with age

- **Detected fields just leftovers of those generated by dynamos during convective phases**

Hubrig et al. 2015, MNRAS, 449, L118



Hubrig et al. 2009, A&A, 502, 283

Future work

We need to get rotation periods and magnetic field configuration for a larger sample of Herbig stars

We need to get rotation periods and magnetic field configuration for a larger sample of Herbig stars

We need to get a better orbital coverage and a larger sample of close SB2 systems with a magnetic Herbig Ae/Be primary