The B fields in OB stars

A.F. Kholtygin et al. (Saint-Petersburg University, Russia)

On behalf of the BOB collaboration:

Morel, T., Castro, N., Fossati, L., Hubrig, S., Langer, N., Przybilla, N., Schöller, M., Arlt, R., Barbá, R., Briquet, M., Carroll, T., de Koter, A., Dufton, P. L., González, J. F., Hamann, W.-R., Herrero, A., Ilyin, I., Irrgang, A., Kharchenko, N., Kholtygin, A., Maíz Apellaniz, J., Mathys, G., Nieva, M.-F., Oskinova, L., Piskunov, A., Reisenegger, A., Sana, H., Schneider, F., Scholz, R., Simon Díaz, S., Spruit, H., and Yoon, S.-C.

Physics and Evolution of Magnetic and Related Stars

SAO, Russia, August 25-31, 2014

The role of magnetic fields in massive stars

Magnetic fields have fundamental effects

- on the evolution of massive stars,
- on their rotation,
- on the structure, dynamics, and heating of radiative winds.

During the last years an increasing number of massive stars have been investigated for magnetic fields.

Currently, about a dozen of magnetic O-type stars and more than two dozens of magnetic early B-type stars (excluding classical He-strong/He-weak Bp stars?) are known.

The origin of magnetic fields in massive stars

The origin of magnetic fields is still under debate: it has been argued that magnetic fields could be "fossil", or magnetic fields may be generated by strong binary interaction, i.e. in stellar mergers, or during a mass transfer or common envelope evolution.

Recent magnetic field surveys in OB stars: MiMeS and BOB

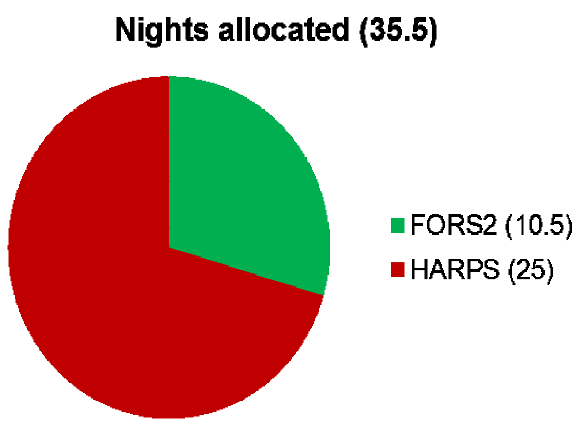
- Aims: To understand nature and origin of magnetic field and to study physics of their atmospheres, winds and magnetospheres.
- MiMeS studies were carried out using high-resolution spectropolarimetry (Narval, ESPaDOnS, and HARPS; R~65000–110000).
- Recent FORS2 and HARPS runs are carried out in the framework of the ESO large program BOB “Magnetic fields in OB stars”, Prg. 191.D-0255, (PI Th. Morel) for which 35.5 nights with FORS2 and HARPS over 2.5 years have been granted.

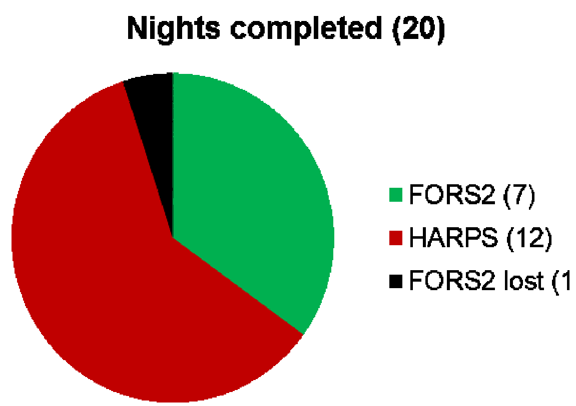
The B fields in OB stars (BOB) project overview

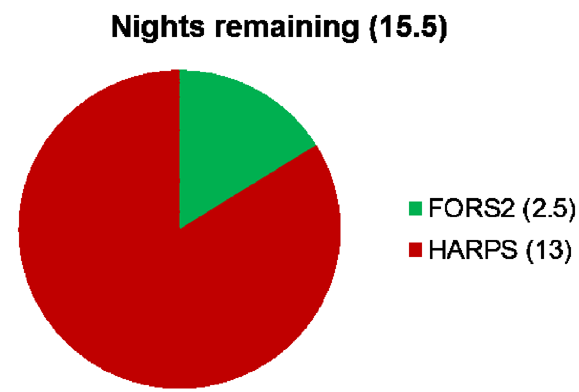
A total of 35.5 nights allocated over 2.5 years (ESO P91-P96) on FORS2 and HARPSpol

Survey biased towards slow rotators to enhance field detectability

For both FORS2 and HARPS, data reduction and analysis carried out completely independently by two groups (Bonn and Potsdam)







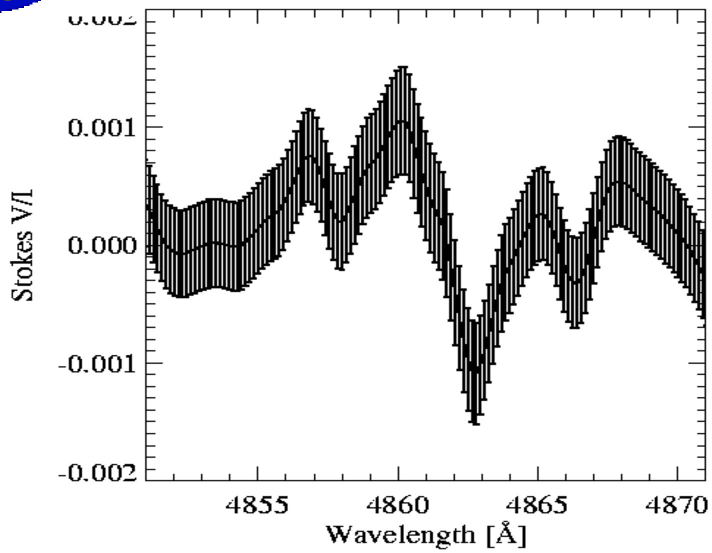
The B fields in OB stars (BOB) project

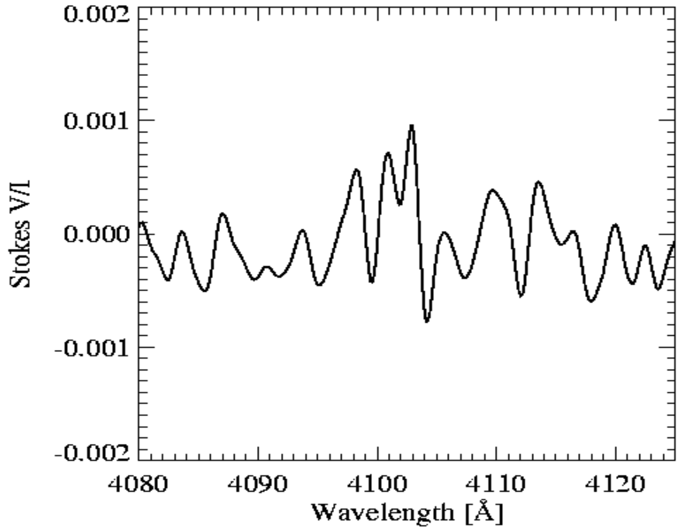
	MiMeS	BOB
Number stars surveyed	**~525**	**97**
Number new firm detections	**~35**	**5**
Detection rate	**7±1%**	**~5%**

But ~15 candidates are still being followed up: detection rate may be (slightly) revised upwards

Polarization V spectra observed with FORS1/2

(Focal Reducer low dispersion Spectrograph)

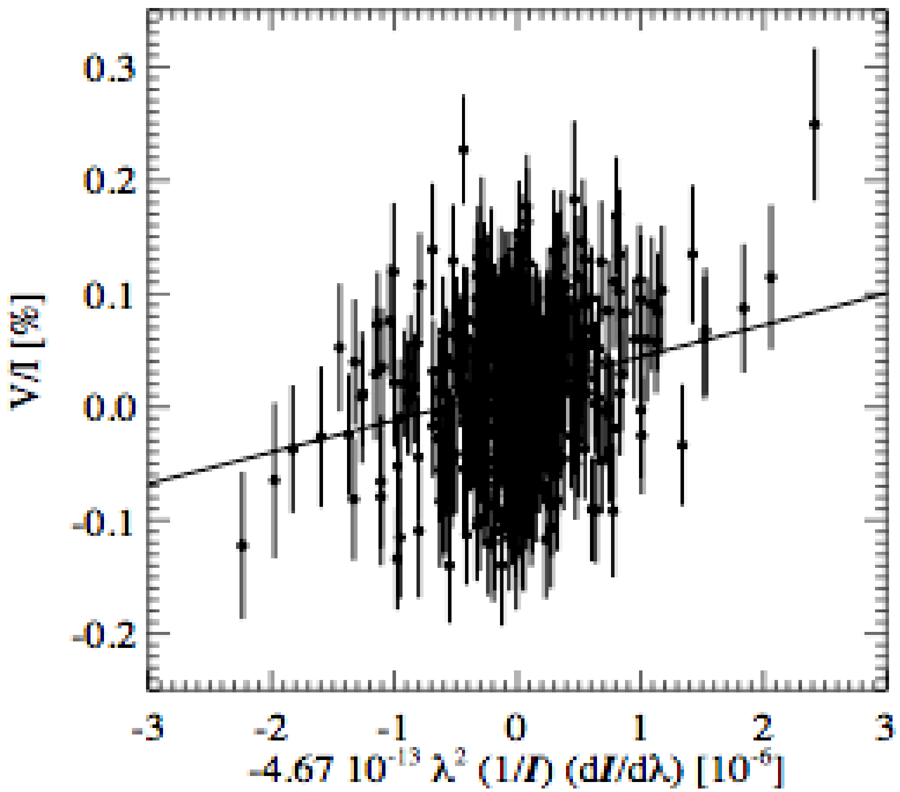




$$\frac{V}{I} = \frac{1}{2}\left\{\left(\frac{f^{\mathrm{o}} - f^{\mathrm{e}}}{f^{\mathrm{o}} + f^{\mathrm{e}}}\right)_{\alpha=-45^\circ} - \left(\frac{f^{\mathrm{o}} - f^{\mathrm{e}}}{f^{\mathrm{o}} + f^{\mathrm{e}}}\right)_{\alpha=+45^\circ}\right\}$$

α gives the position angle of the retarder waveplate and f^o and f^e are ordinary and extraordinary beams, respectively.

Determination of the magnetic field



The mean longitudinal magnetic field is the average over the stellar hemisphere visible at the time of observation of the component of the magnetic field parallel to the line of sight. It is diagnosed from the slope of the linear regression:

$$\frac{V}{I} = -\frac{g_{\mathrm{eff}}\, e \lambda^2}{4\pi m_{\mathrm{e}} c^2}\,\frac{1}{I}\,\frac{\mathrm{d}I}{\mathrm{d}\lambda}\,\langle \mathcal{B}_z \rangle$$

Spectral lines in O-type stars show complex profiles. Many lines appear in emission or display P Cyg-type profiles. Most stars rotate very fast - low-resolution Balmer line spectropolarimetry is preferred.

Searches for magnetic fields in OB stars: high-resolution spectropolarimetry

- The method:

  Least-Squares Deconvolution introduced by Semel (1989) and Donati (1997). Assumptions: line formation is similar in all lines, weak-field approximations (works below 1 kG), overlapping lines add up linearly…

  The LSD method does not work well for non-radial pulsating OB type stars.

- First detections:

  Θ^1OriC - Donati et al. 2002

  HD 191612 – Donati et al. 2006

  τ Sco – Donati et al. 2006

  ξ^1CMa (FORS1)– Hubrig et al. 2006

Different categories of O-type stars

- **Of?p stars:** Walborn (1973) introduced the Of?p category for massive O stars displaying recurrent spectral variations in certain spectral lines, sharp emission or P Cygni profiles in He I and the Balmer lines, and strong C III emission lines around 4650 Å. Only five Galactic Of?p stars are currently known: HD 108, NGC 1624-2, CPD-28 2561, HD 148937, and HD 191612. Interestingly, our kinematical assessment of space velocities of the three brightest, HD 108, HD 148937, and HD 191612, indicates that all three can be considered as candidate runaway stars (Hubrig et al. 2011).
- **Ofc stars:** These stars display normal spectra with C III $\lambda\lambda$4647-4650-4652 emission lines of comparable intensity to those of the Of defining lines N III $\lambda\lambda$4634-4640-4642 (Walborn 2010).
- Other examples: fp, ((f+)), ((f)), (f), (n) (nf), nn…

HD 54879: A magnetic O9.7 V star

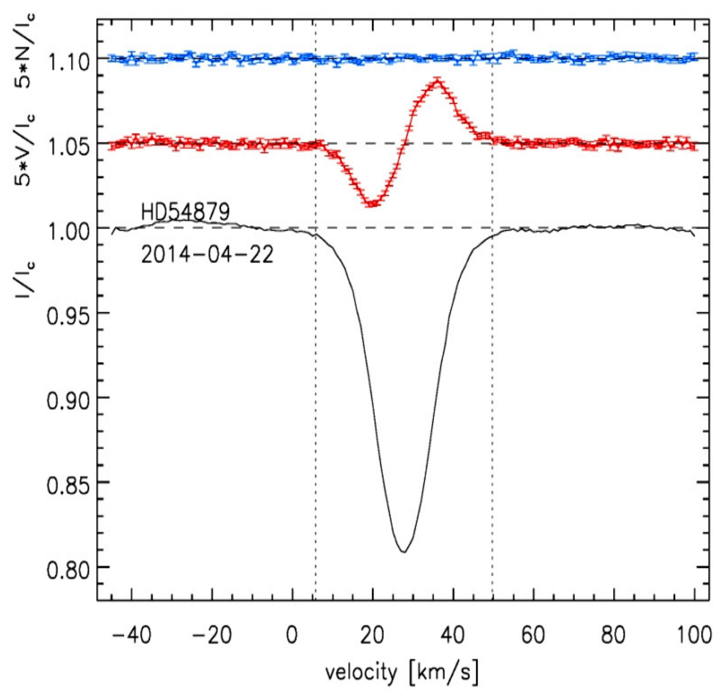
Detection **FORS2 observations**

		Hydrogen lines		All lines	
		V	N	V	N
07 02 2014	Bonn	-654±111	23±80	-503±56	70±46
	Potsdam	-639±121	-16±119	-460±65	76±66
08 02 2014	Bonn	-978±104	-35±81	-653±50	40±4
	Potsdam	-877±91	-102±105	-521±62	23±63

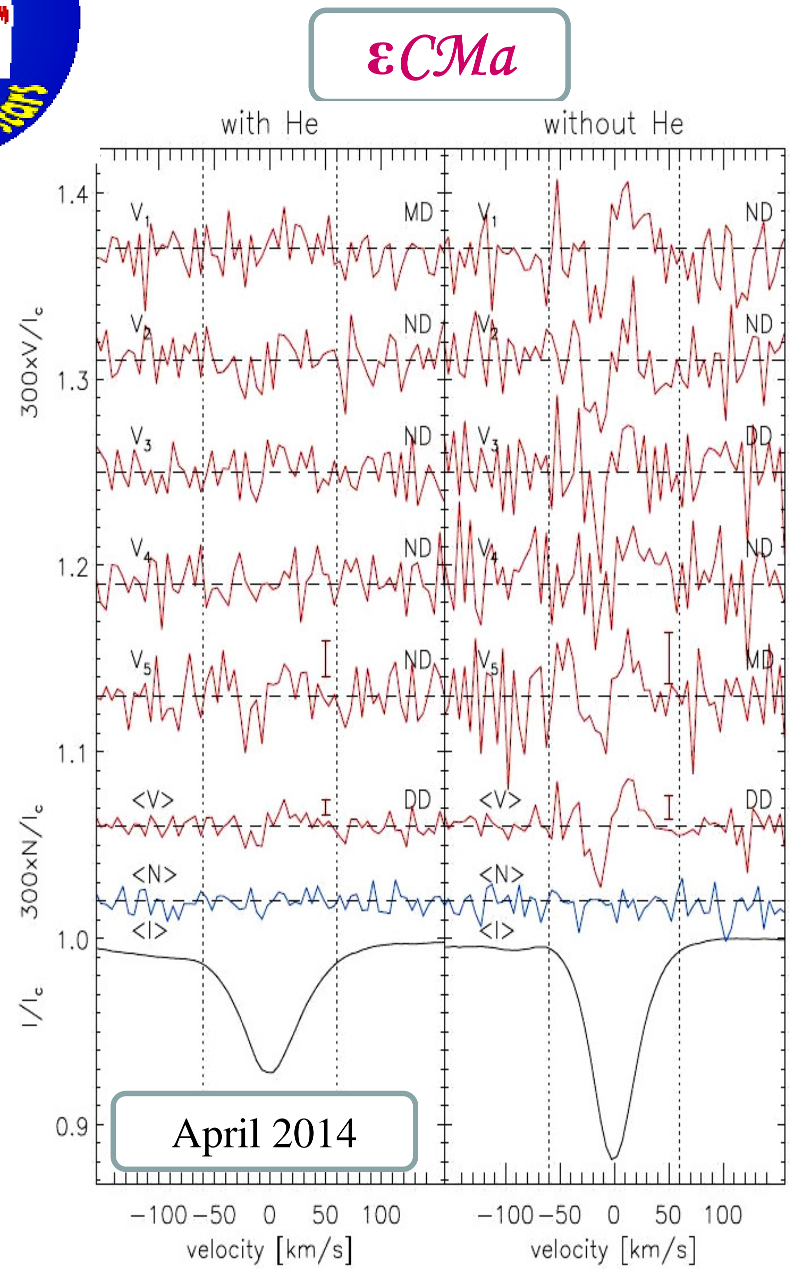
HARPS observations

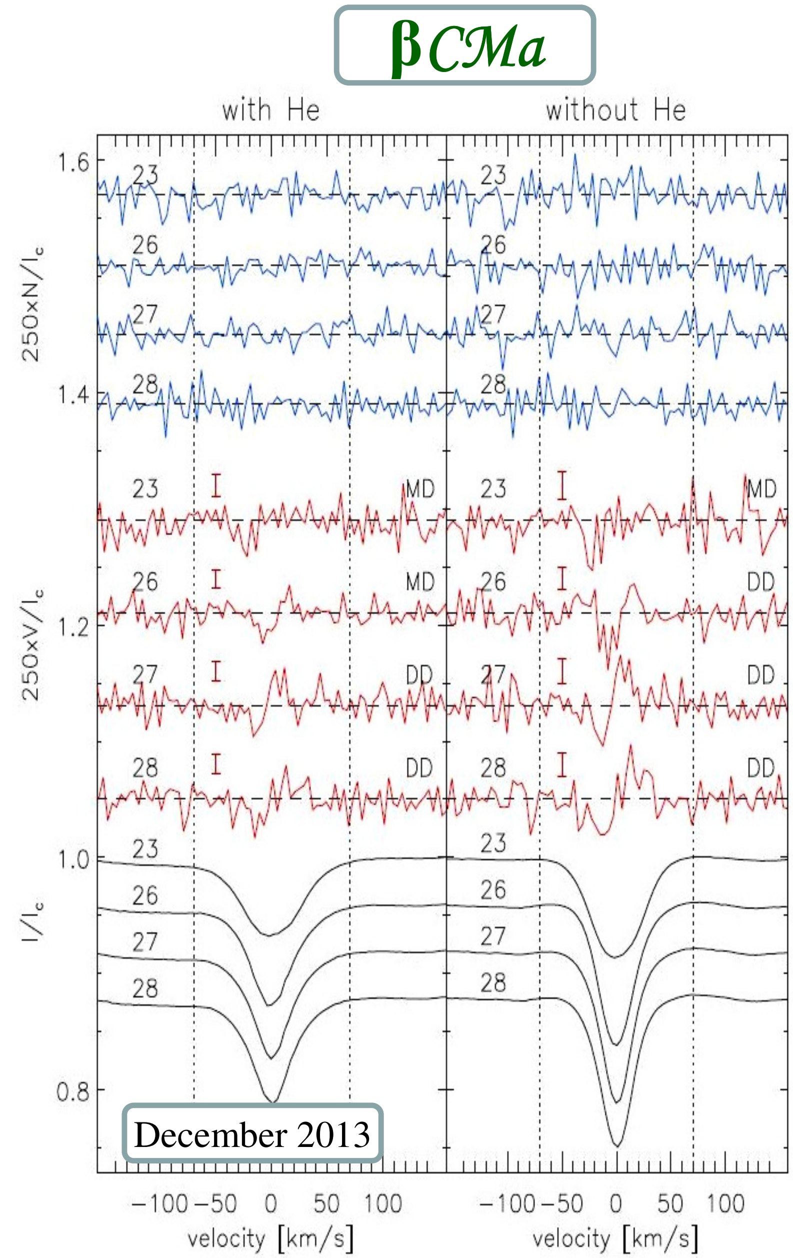
ND: FAP > 10^{-3} MD: 10^{-5} < FAP < 10^{-3} DD: FAP < 10^{-5}

		V		N	
22 04 2014	Bonn	**-592±7**	**DD**	**-20±7**	**ND**
	Potsdam	**-584±15**	**DD**	**-22±10**	**ND**

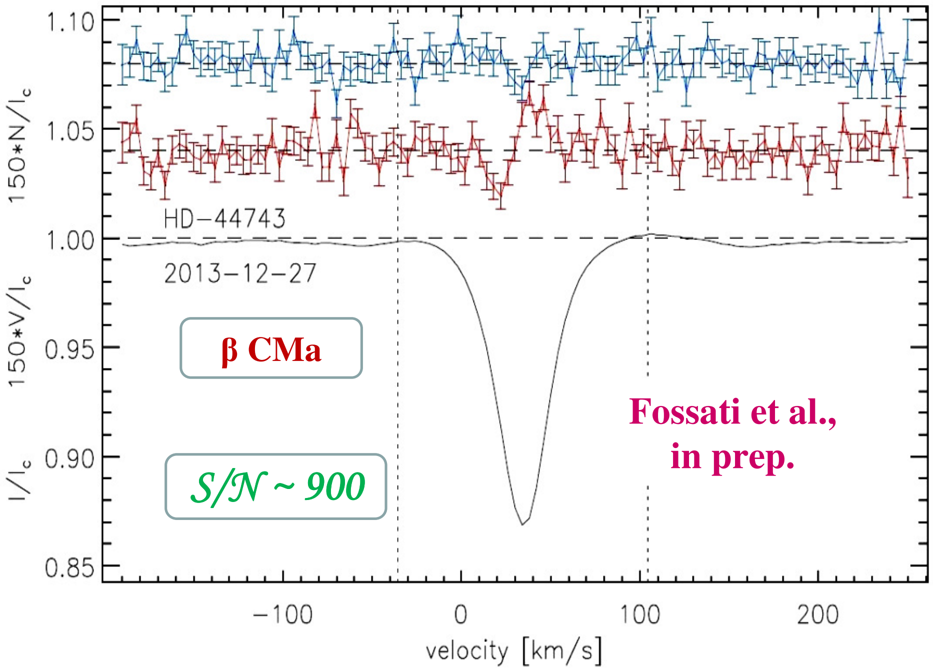


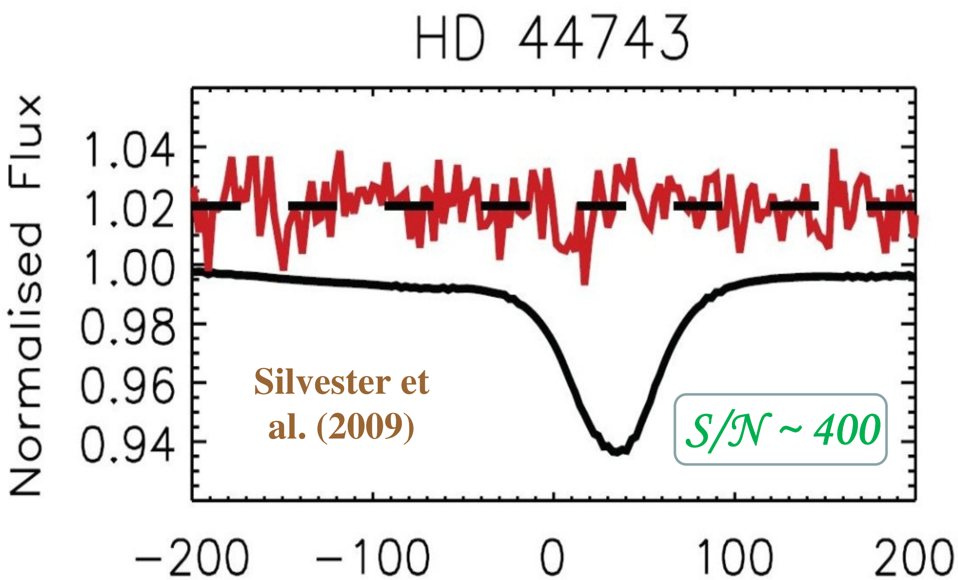
Detection of weak fields in early B-type stars

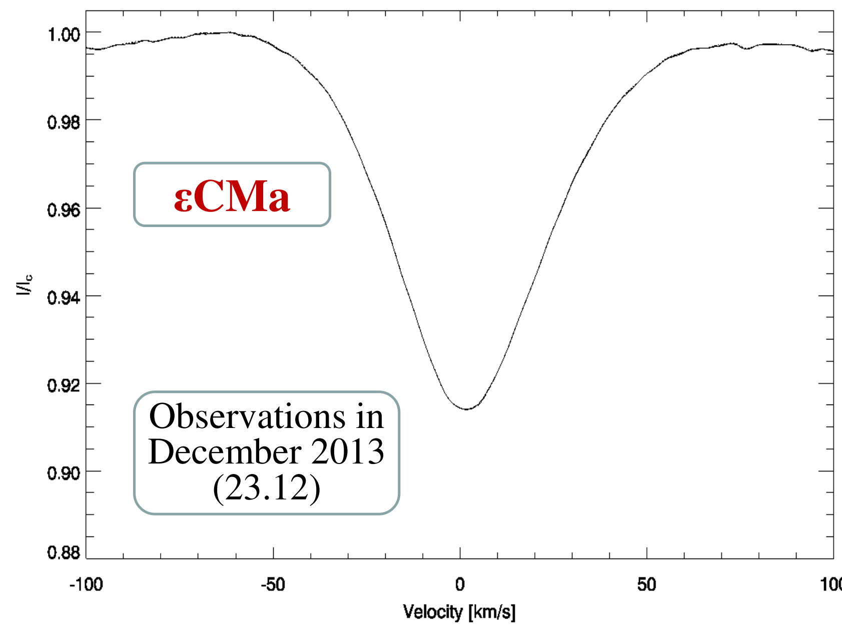




Detection of weak fields in early B-type stars



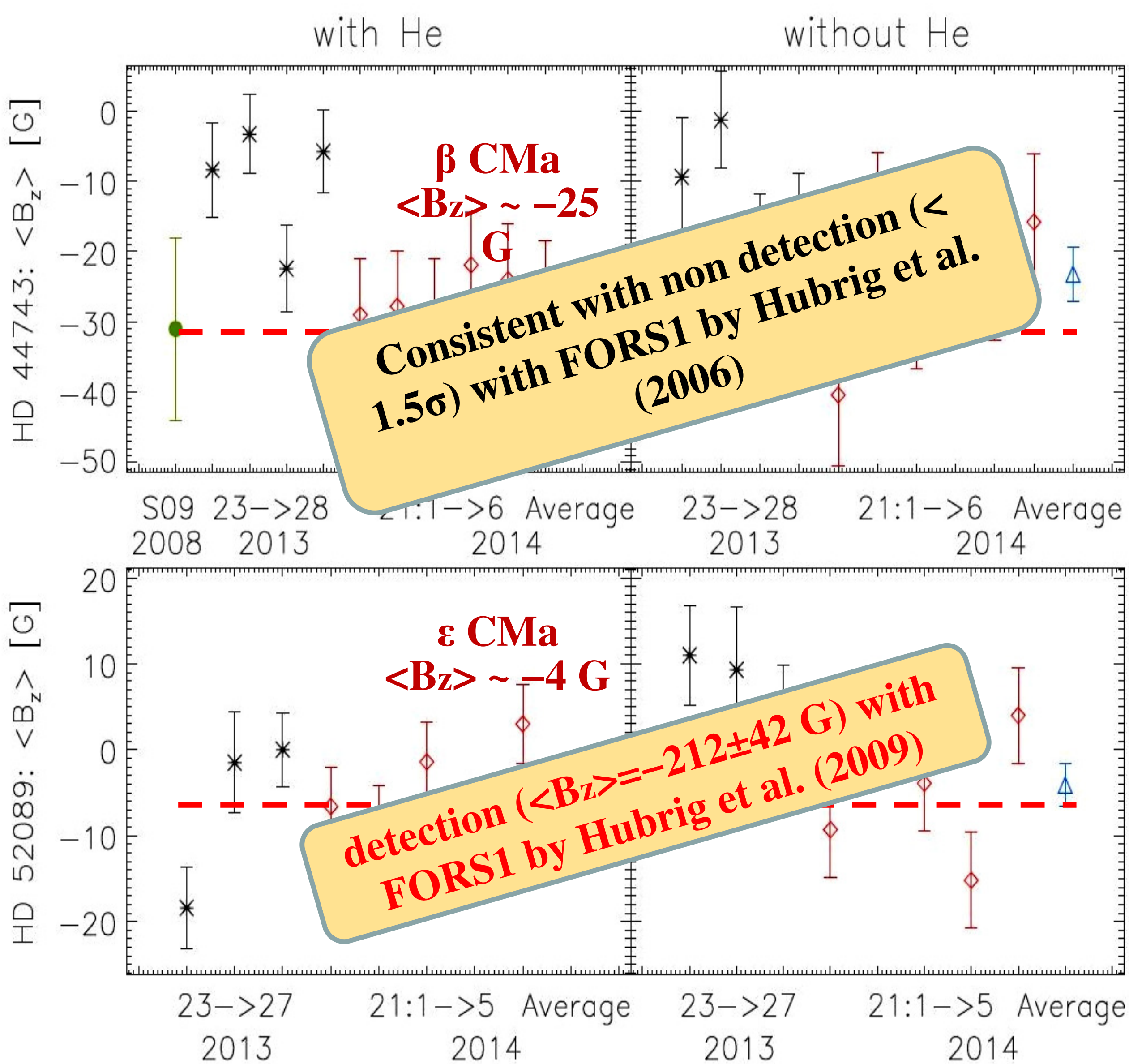




No variability is detected

Detection of weak fields in early B-type stars

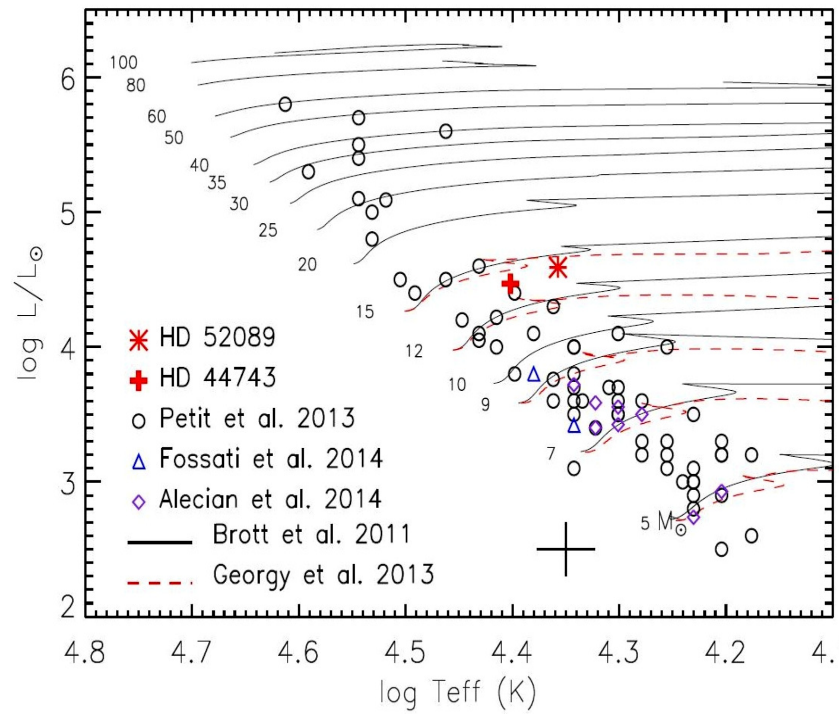
Silvester et al. (2009)
BOB December 2013
BOB April 2014
Average BOB April 2014



Detection of weak fields in early B-type stars

Output of spectral synthesis with DETAIL/SURFACE and Geneva evolutionary tracks (Irrgang et al. 2014)

	β CMa	ε CMa
Teff [K]	25230±510	22770±470
logg	3.66±0.10	3.38±0.10
vsin*i* [km s^{-1}]	27±2	< 9
M [Msun]	13.7±1.5	14.0±1.2
R [Rsun]	9.1±1.3	12.7±1.9
Age [Myrs]	~12.0	~12.0
Nitrogen	Normal	Mildly enriched



Seismic study of β CMa (Mazumdar et al. 2006)

P_{rot} = 18.6±3.3 days: *i* = 61 (+29−15) degrees

Not seen pole-on

No field variations during 5 days (one third of rotation period):

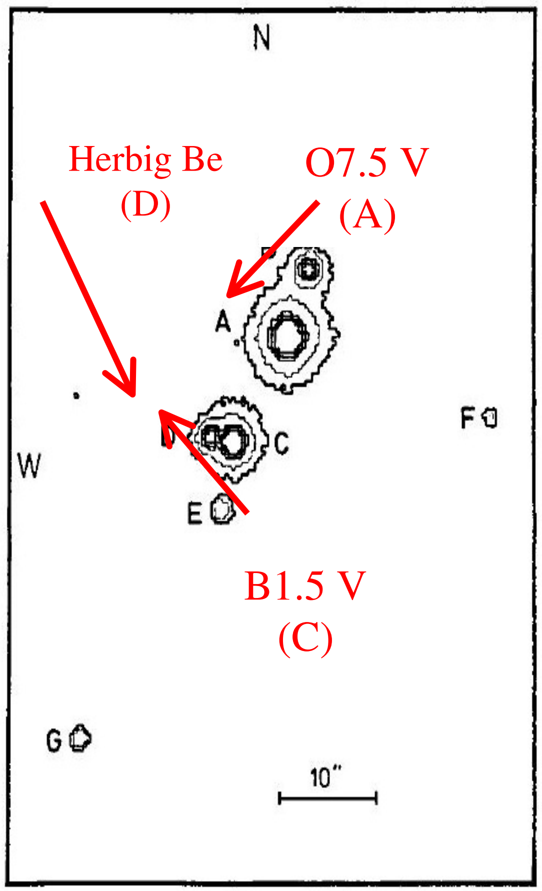
Magnetic field axis likely nearly aligned with rotation axis

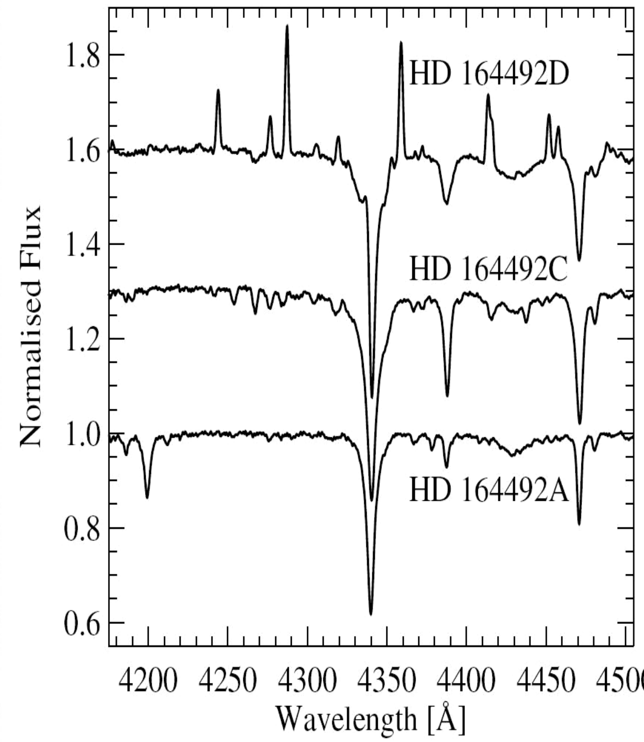
A young, magnetic binary in the Trifid Nebula

The Trifid Nebula is one of the youngest star forming regions.

Seven components identified in the central system HD 164492 (Kohoutek et al. 1999).

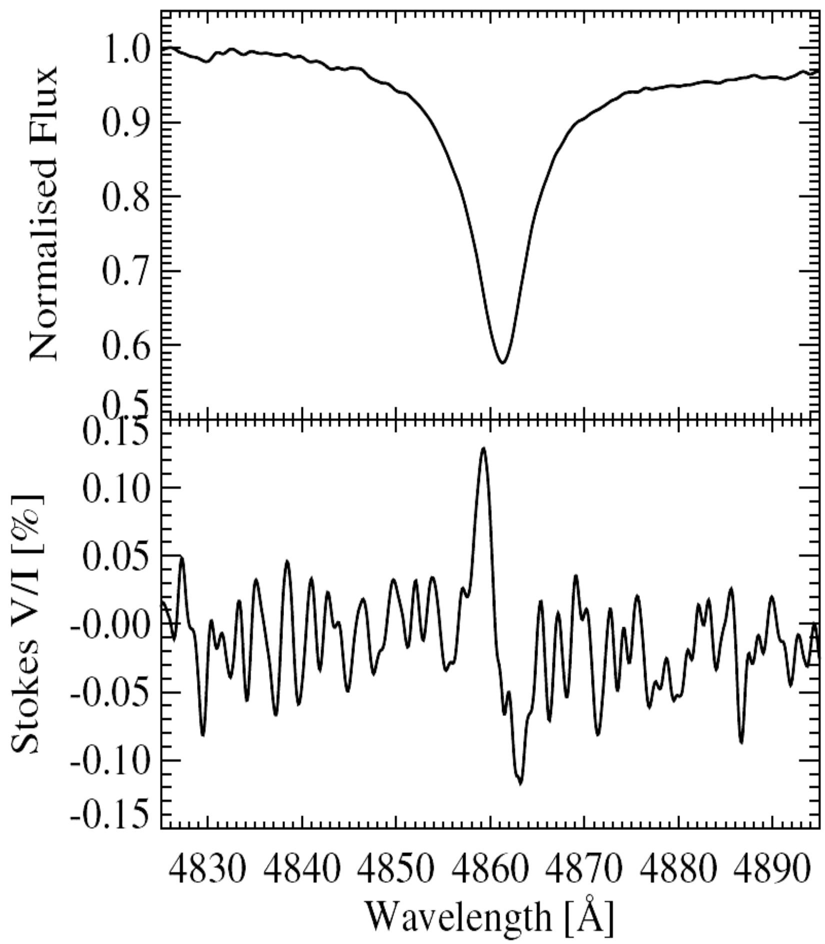
The three brightest components were observed: A, C, and D.





Hubrig et al. (2014)

A young, magnetic binary in the Trifid Nebula



Hubrig et al. (2014)

Clear magnetic signal in the FORS2 V/I spectrum of HD 164492C obtained on 2013 April 9.

Two fully independent (and consistent) magnetic field determinations:

Bonn:

$\langle B_z\rangle_{all} = 523 \pm 37$ G

$\langle B_z\rangle_{hyd} = 600 \pm 54$ G

Potsdam:

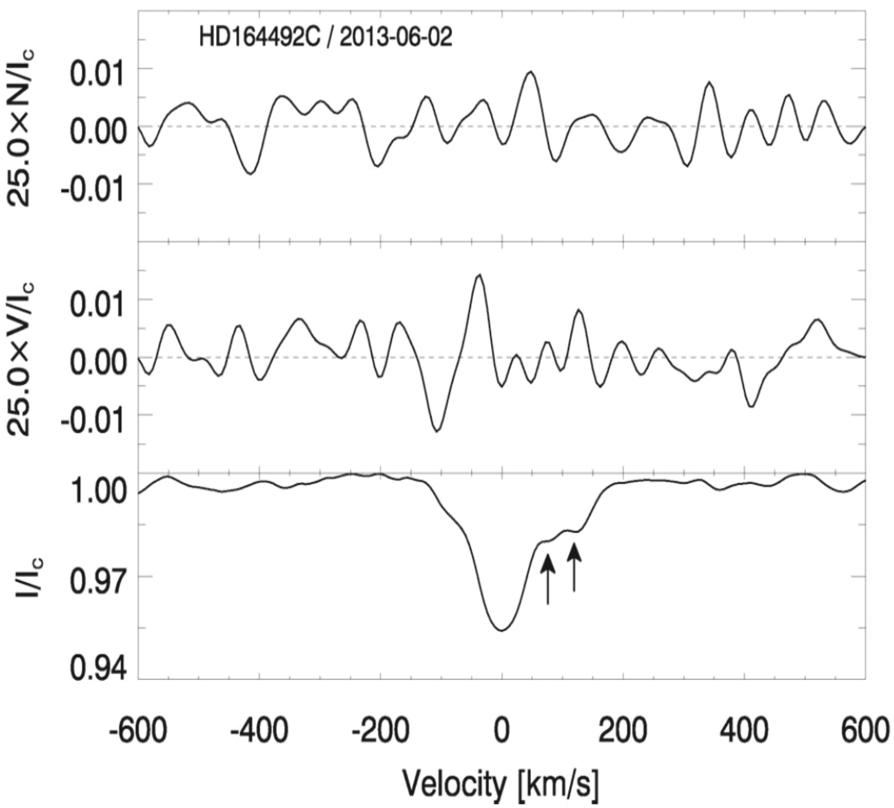
$\langle B_z\rangle_{all} = 472 \pm 44$ G

$\langle B_z\rangle_{hyd} = 576 \pm 60$ G

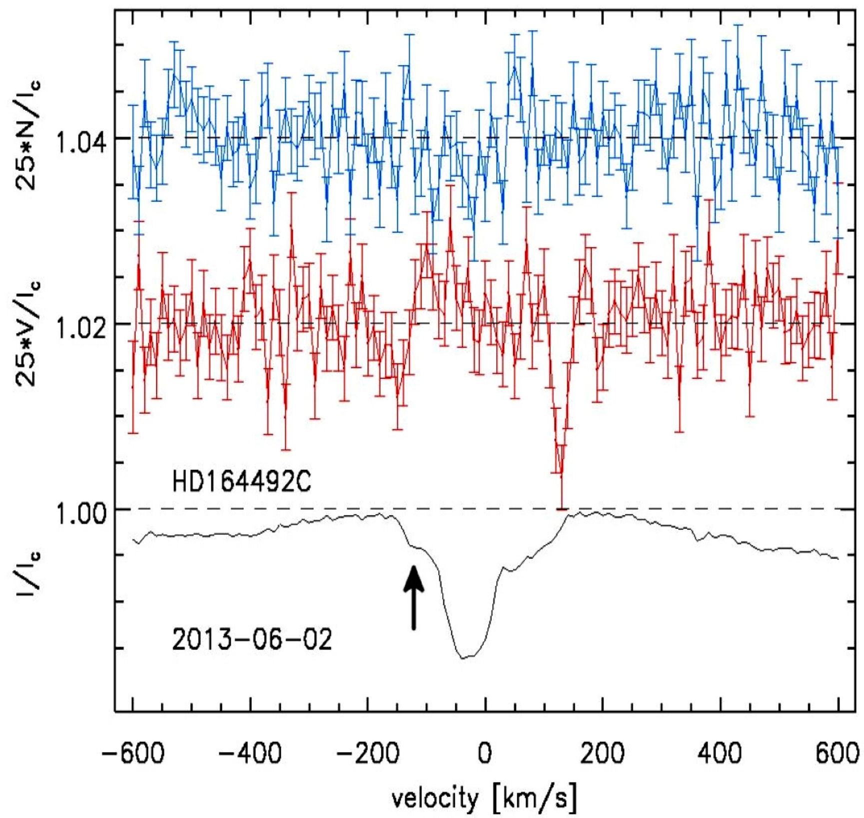
A young, magnetic binary in the Trifid Nebula

Is HD 164492C actually a multiple system?

SVD – only Si III lines



LSD – no He I lines



Hubrig et al. (2014)

CPD −57 3509: A σ Ori E analogue?

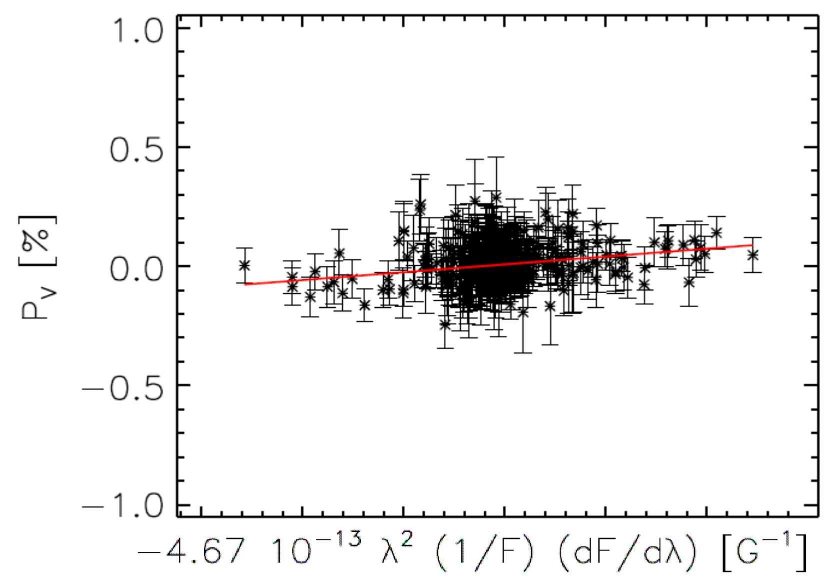
B1V D

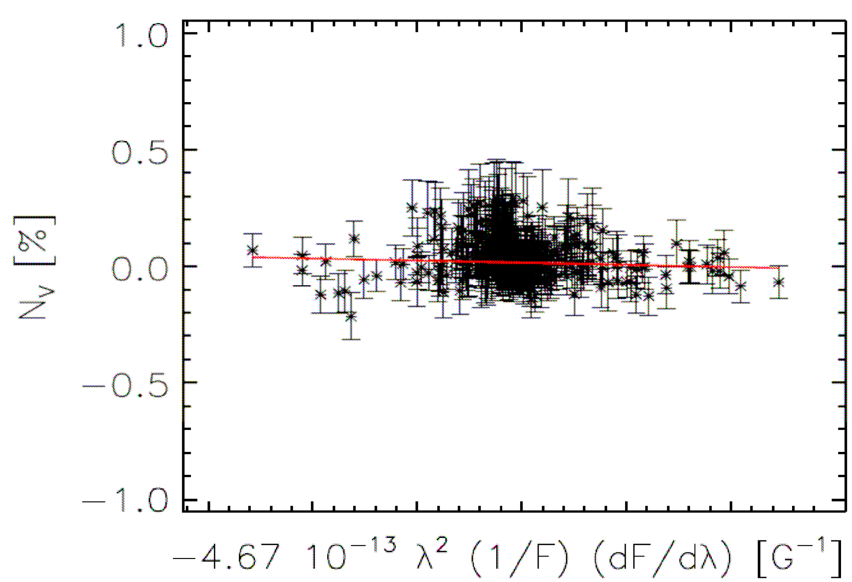
V=10.7

FORS2 observations

High consistency of measurements

			Hydrogen lines		All lines	
			V	N	V	N
No detection	06 02 2014	Bonn	-356±127	-362±122	-144±78	-39±78
		Potsdam	-287±126	-372±138	-39±76	-75±82
Detection	07 02 2014	Bonn	660±120	-120±107	711±62	68±60
		Potsdam	694±108	-116±104	618±61	16±62
No detection	01 06 2014	Bonn	-71±75	-53±75	40±46	-51±47
		Potsdam	-19±71	-28±86	87±54	-45±59
Detection	02 06 2014	Bonn	1050±93	-85±61	943±43	2±39
		Potsdam	979±68	-108±77	920±48	2±50





CPD –57 3509: A σ Ori E analogue?

FORS2 observations

		Hydrogen lines		All lines		
		V	N	V	N	
06 02 2014	Bonn	-356±127	-362±122	-144±78	-39±78	No detection
	Potsdam	-287±126	-372±138	-39±76	-75±82	
07 02 2014	Bonn	660±120	-120±107	711±62	68±60	Detection
	Potsdam	694±108	-116±104	618±61	16±62	
01 06 2014	Bonn	-71±75	-53±75	40±46	-51±47	No detection
	Potsdam	-19±71	-28±86	87±54	-45±59	
02 06 2014	Bonn	1050±93	-85±61	943±43	2±39	Detection
	Potsdam	979±68	-108±77	920±48	2±50	

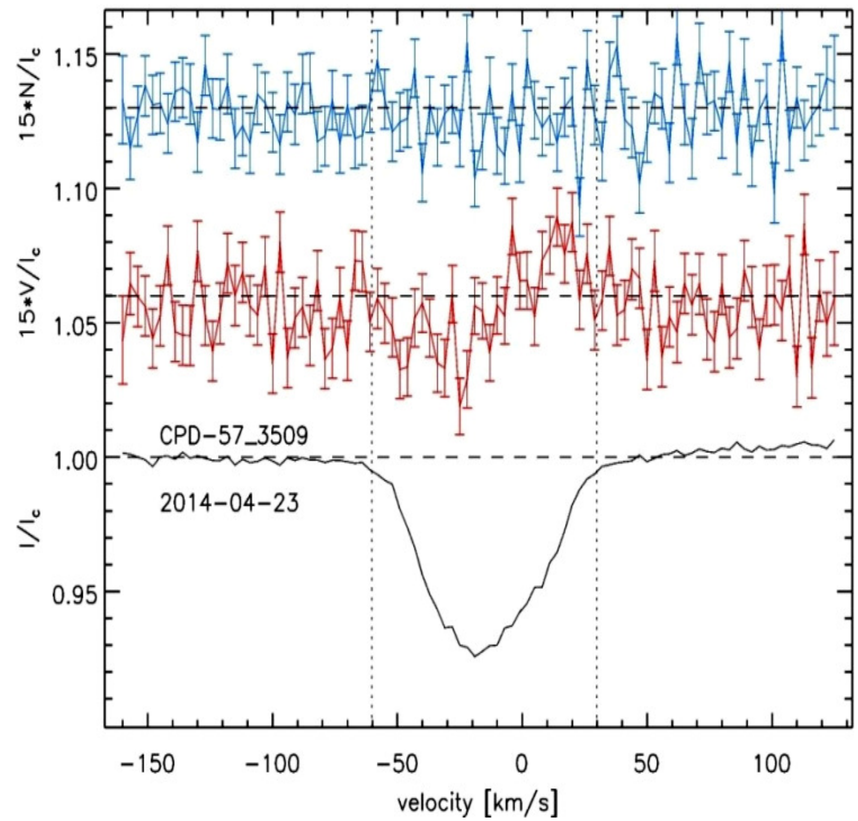
Strong, daily variations of the field

CPD −57 3509: A σ Ori E analogue?

HARPS observations

ND: FAP > 10^{-3} MD: 10^{-5} < FAP < 10^{-3} DD: FAP < 10^{-5}

		V		N	
23 04 2014	Bonn	**-557±73**	**DD**	**76±72**	**ND**
	Potsdam	**-492±78**	**DD**	**-59±59**	**ND**



CPD –57 3509: A σ Ori E analogue?

FORS2 observations

			Hydrogen lines		All lines	
			V	N	V	N
No detection	06 02 2014	Bonn	-356±127	-362±122	[illegible]	-39±78
		Potsdam	-287±126	-372±[illegible]	[illegible]	-75±82
Detection	07 02 2014	Bonn	660±120	[illegible]	[illegible]±62	68±60
		Potsdam	694±1[illegible]	[illegible]	618±61	16±62
No detection	01 06 2014	Bonn	[illegible]	[illegible]	40±46	-51±47
		Potsda[illegible]	[illegible]	[illegible]28±86	87±54	-45±59
Detection	02 06 2014	B[illegible]	[illegible]	-85±61	943±43	2±39
		[illegible]	[illegible]9±68	-108±77	920±48	2±50

Dipolar field > 3.1 kG

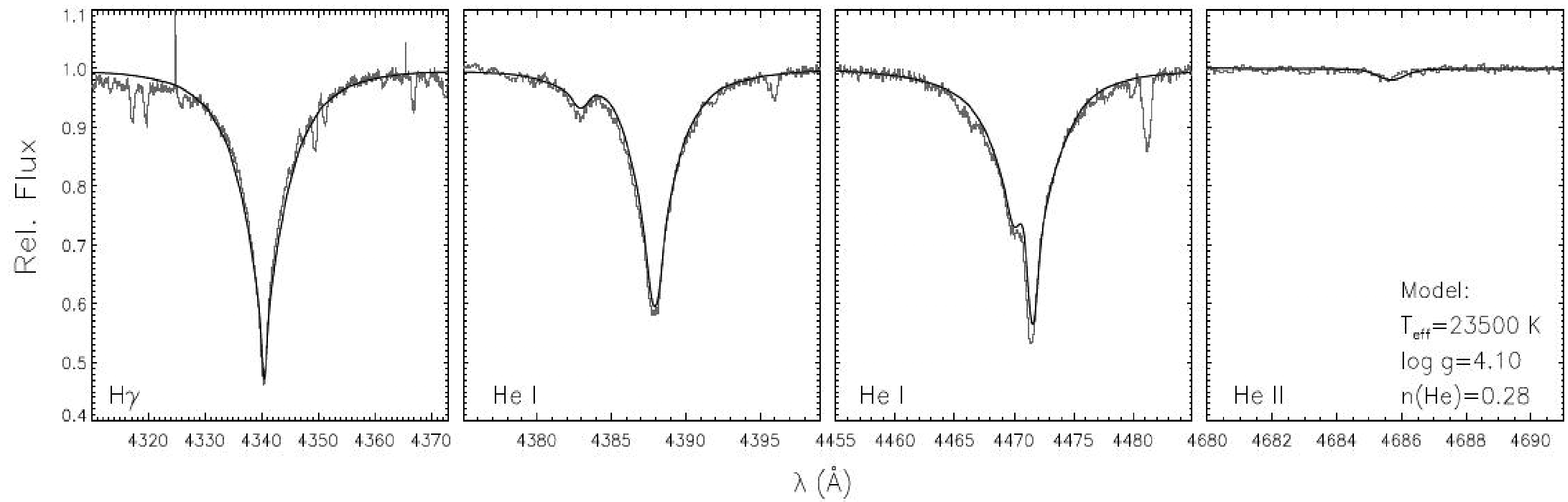
CPD –57 3509: A σ Ori E analogue?

Star in NGC 3293 (cluster age ~10 Myrs)

Output of spectral synthesis with DETAIL/SURFACE

Teff ~ 23500 K logg ~ 4.1

vsini ~ 35 km s^{-1} **He/H ~ 0.28**



Star evolved throughout ~30% of its main-sequence lifetime

One of the most evolved He-rich stars with a tight age estimate

Will provide constraints on the evolution of stars with magnetically-confined stellar winds

Still unclear whether CPD –57 3509 is a σ Ori E analogue (e.g., X-ray properties unknown)

Conclusions

- Observations of ~100 OB stars carried out so far with both FORS2 and HARPS.
- Only very few targets in common with MiMeS.
- About fifteen nights remaining. Will be mainly devoted to confirm marginal detections and to characterize field properties for new magnetic stars.
- Consistent detections using completely different reduction and analysis techniques.
- Confirmation that the occurrence of fields above the detectability threshold (~100-200 G) is low in massive stars. *However, exact estimation of incidence rate still pending (may be revised upwards).*
- Discovery of a young, massive magnetic binary in the Trifid Nebula (Hubrig et al. 2014). Unclear at this stage whether only one or more components are magnetic.
- Indications for intrinsically weak fields (B_d ~ 150 G) in early B-type stars.

  Much stronger case for β CMa.

  No evidence in massive stars for the "magnetic desert" found in intermediate-mass stars (e.g., Aurière et al. 2007). Evidence for field decay?

  Strong Dipolar field (>3.1 kG) of CPD-57 3509 (Ori E analogue?)