

Why are there so few magnetic  
A (and B and O) stars?

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and a cast of thousands...

# Context

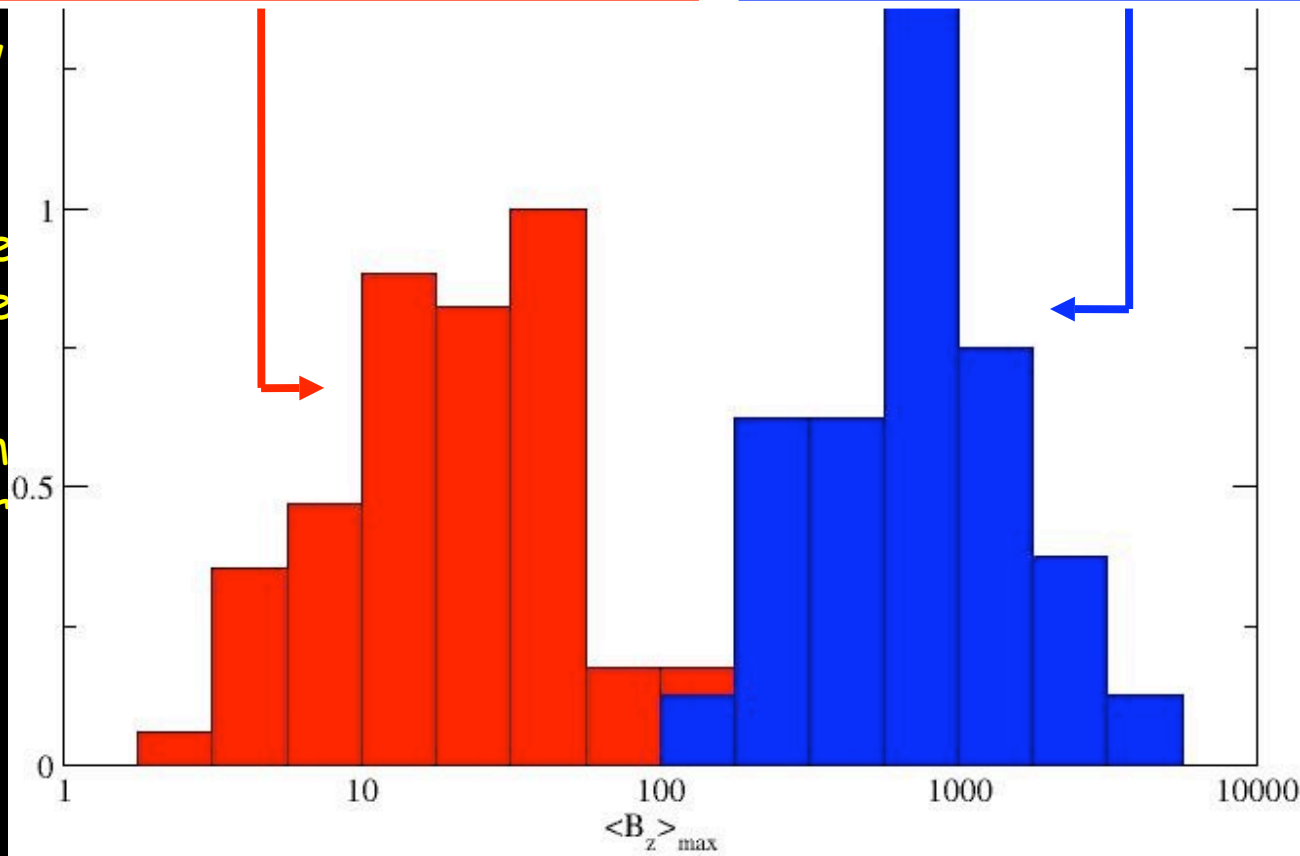
- Physics of magnetic fields in stars with  $M > 1.5$  solar
  - Strong
  - Organised, with evidence for smaller-scale structures
  - Stable, long-lived
  - No strong correlation with period, age or mass
  - Associated with slow rotation and chemical peculiarity
  - Rare
- Open questions:
  - Field origin
  - Field evolution
  - Role of rotation

# Magnetic dichotomy

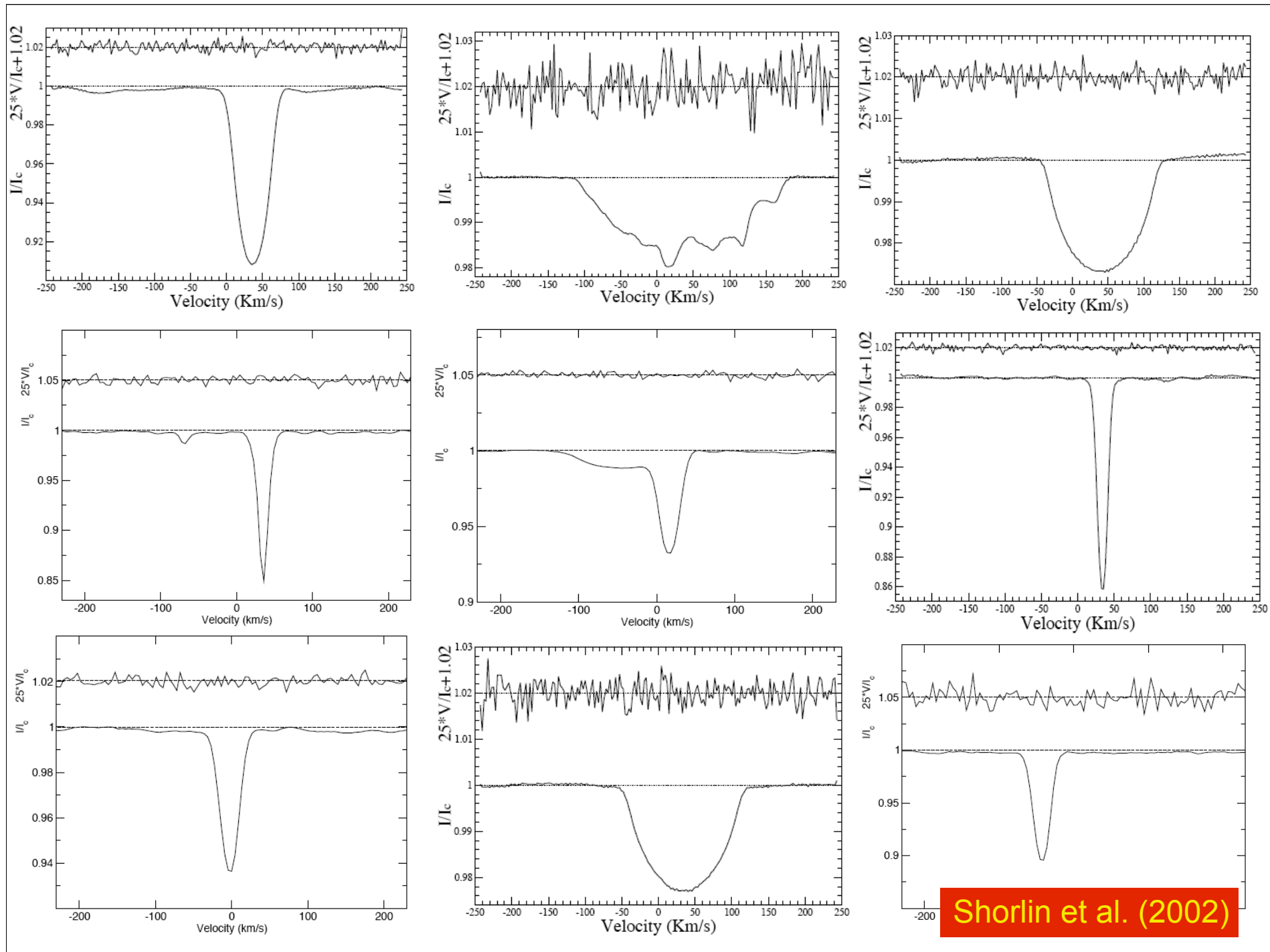
Non-Ap stars - ALL null results  
(~95%)

Ap stars - ALL detections  
(~5%)

- A few oblique
- In the detected
- The magnetic field to their



Ap stars")  
due



Shorlin et al. (2002)

# Weak magnetic fields in Ap stars

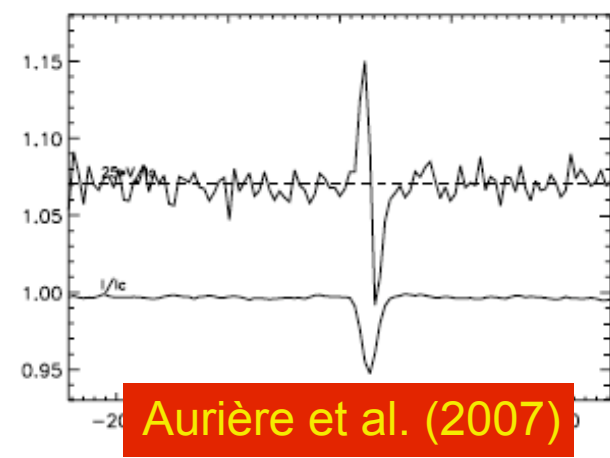
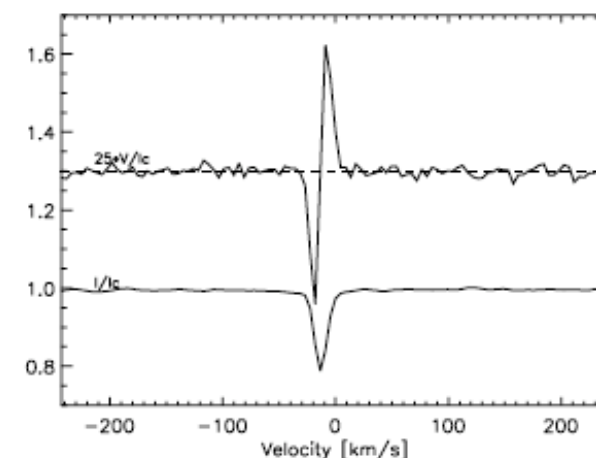
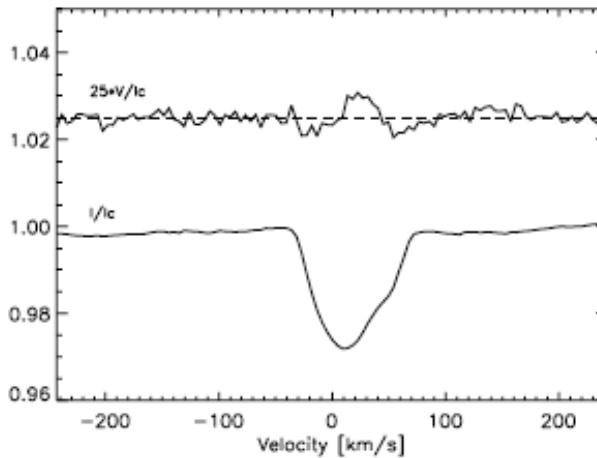
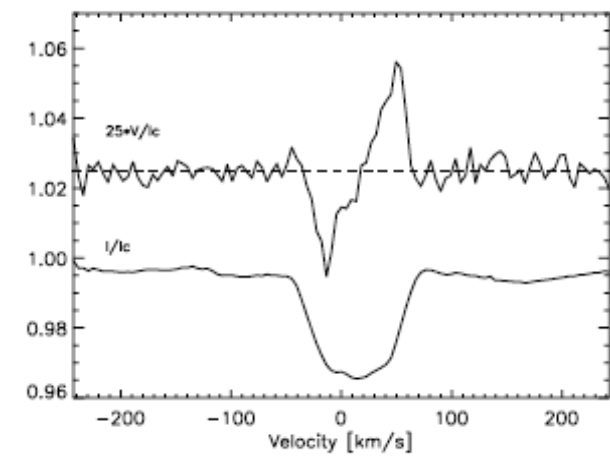
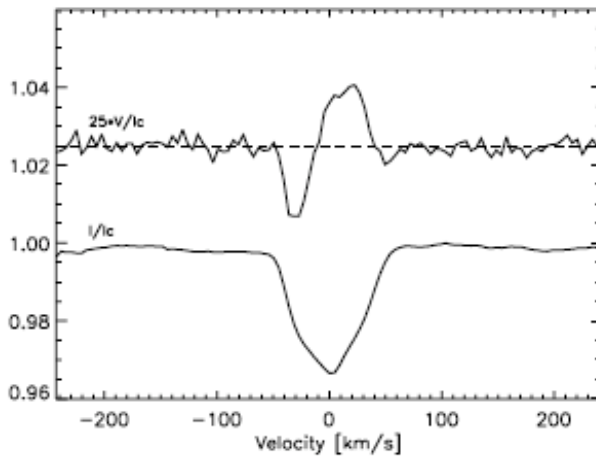
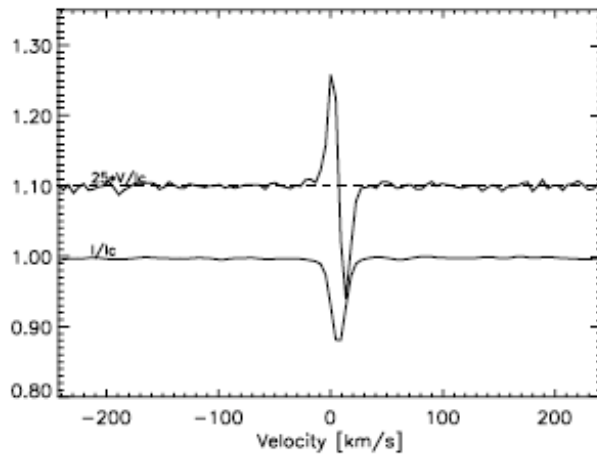
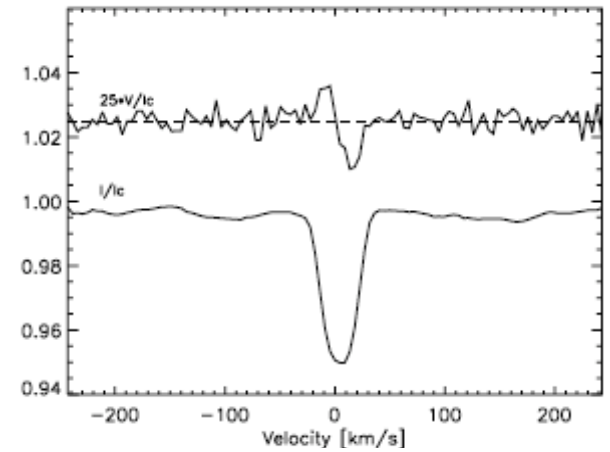
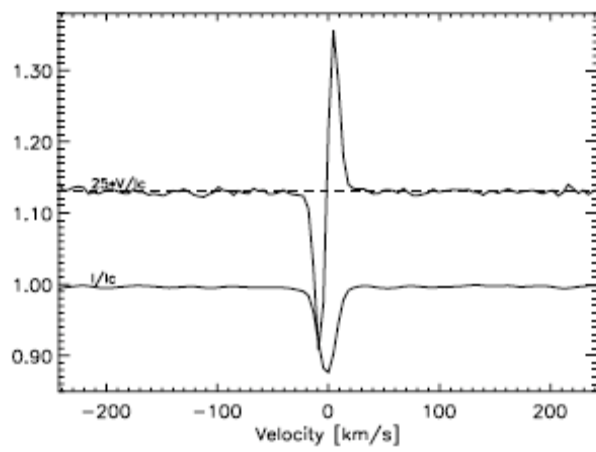
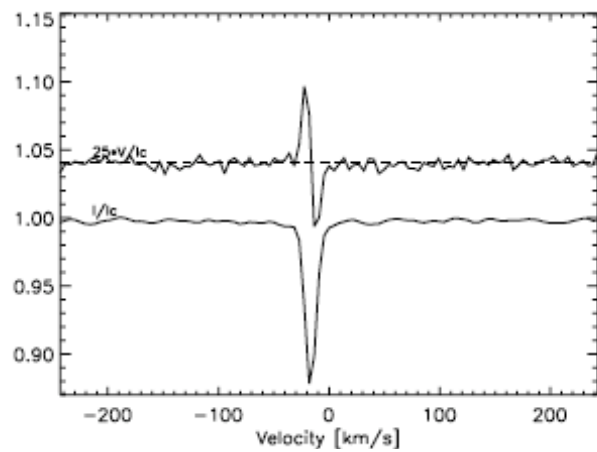
- What are the magnetic properties of Ap stars with very weak fields?
- What is the field strength distribution of intermediate-mass stars?
- Survey of weak-field Ap stars (Aurière et al. 2007)
  - MuSiCoS spectropolarimeter at Pic du Midi observatory
  - Twenty-eight spectroscopically-identified Ap stars
    - Undetected / uncertain longitudinal magnetic fields
  - Ten observing runs from 2001 - 2006
  - Twenty-five observers
  - Two hundred and eighty-two Stokes V spectra

# Targets: Ap stars with weak or undetected magnetic fields

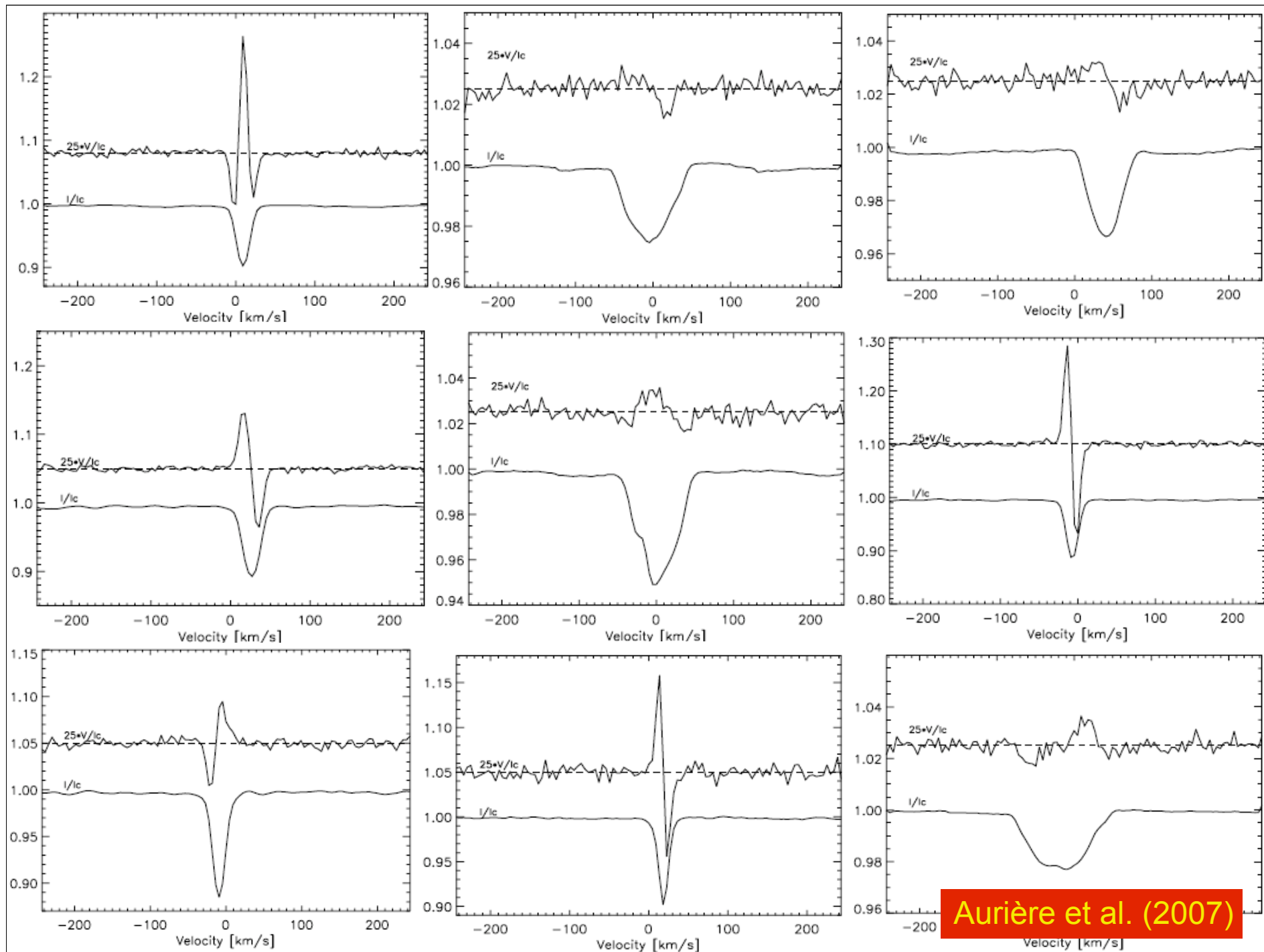
ID	HD	$m_V$	Spec Type	$T_{\text{eff}}$ (K)	$\log L$ ( $L_{\odot}$ )	$R$ ( $R_{\odot}$ )	Mask (kK)	#	Det. level	$ B_{\ell} ^{\text{max}} \pm \sigma$ (G)	$z$	$B_d^{\text{min},3,3}$ (G)
HN And	8441	6.7	A2p	$9060 \pm 300$	$1.90 \pm 0.16$	$3.6 \pm 0.9$	9	8	8d	$157 \pm 18$	8.7	399
43 Cas	10221	5.5	A0sp	$10660 \pm 350$	$2.11 \pm 0.09$	$3.3 \pm 0.7$	11	10	8d	$148 \pm 34$	4.3	264
$\iota$ Cas	15089	4.5	A5p	$8360 \pm 275$	$1.38 \pm 0.05$	$2.3 \pm 0.4$	9	12	12d	$486 \pm 23$	20.8	1452
	15144	5.8	A6Vsp	$8480 \pm 280$	$1.21 \pm 0.07$	$1.9 \pm 0.3$	9	6	6d	$631 \pm 15$	42.0	1983
21 Per	18296	5.0	B9p	$9360 \pm 310$	$2.08 \pm 0.11$	$4.2 \pm 1.0$	10	2	2d	$213 \pm 20$	10.6	571
9 Tau	22374	6.7	A2p	$8390 \pm 275$	$1.48 \pm 0.13$	$2.6 \pm 0.7$	9	2	2d	$523 \pm 24$	21.7	1568
56 Tau	27309	5.3	A0sp	$12730 \pm 420$	$2.06 \pm 0.08$	$2.2 \pm 0.4$	12	12	12d	$804 \pm 50$	16.1	2323
11 Ori	32549	4.7	A0sp	$10220 \pm 335$	$2.35 \pm 0.12$	$4.7 \pm 1.2$	11	11	1d3m	$186 \pm 39$	4.7	356
	22650	5.4	B9sp	$11090 \pm 300$	$2.11 \pm 0.07$	$2.7 \pm 0.5$	12	18	2m3d	$91 \pm 18$	5.0	237
							10	2	2d	$766 \pm 119$	6.4	1742
137 Tau							11	8	3d1m	$216 \pm 59$	3.6	323
							9	3	1d1m	$528 \pm 38$	13.8	1492
							11	8	8d	$628 \pm 25$	25.1	1907
15 Cnc							10	16	1d4m	$325 \pm 47$	6.9	762
3 Hya							10	13	13d	$427 \pm 16$	27.4	1304
45 Leo	90669	6.0	A0sp	$10250 \pm 335$	$1.78 \pm 0.10$	$2.5 \pm 0.5$	11	10	10d	$541 \pm 23$	23.5	1634
	94427	7.3	A5	$7250 \pm 240$	$1.05 \pm 0.11$	$2.1 \pm 0.5$	8	8	8d	$356 \pm 41$	8.6	904
EP Uma	96707	6.0	F0sp	$7780 \pm 255$	$1.54 \pm 0.08$	$3.2 \pm 0.6$	8	21	7d7m	$69 \pm 33$	2.3	128
65 Uma	103498	6.9	A1spe	$9220 \pm 300$	$2.06 \pm 0.20$	$4.2 \pm 1.5$	9	14	12d1m	$169 \pm 19$	8.9	432
21 Com	108945	5.4	A2pvar	$8870 \pm 290$	$1.72 \pm 0.09$	$3.1 \pm 0.6$	9	13	12d1m	$234 \pm 54$	4.3	416
$\omega$ Her	148112	4.6	B9p	$9330 \pm 305$	$1.86 \pm 0.08$	$3.2 \pm 0.6$	10	12	11d	$204 \pm 21$	9.7	535
45 Her	151525	5.2	B9p	$9380 \pm 310$	$2.18 \pm 0.13$	$4.7 \pm 1.2$	11	14	2d3m	$146 \pm 38$	3.8	231
	171586	6.4	A2pvar	$8760 \pm 290$	$1.37 \pm 0.10$	$2.1 \pm 0.5$	10	5	5d	$375 \pm 56$	6.6	868
	171782	7.8	A0p	$9660 \pm 315$	$1.76 \pm 0.30$	$2.7 \pm 1.3$	10	6	2d1m	$333 \pm 78$	4.2	584
19 Lyr	179527	5.9	B9sp	$10370 \pm 340$	$2.63 \pm 0.16$	$6.4 \pm 1.9$	11	11	8d2m	$156 \pm 46$	3.4	211
4 Cyg	183056	5.1	B9sp	$11710 \pm 385$	$2.69 \pm 0.11$	$5.3 \pm 1.2$	12	13	13d	$290 \pm 42$	6.9	680
	204411	5.3	A6pe	$8750 \pm 290$	$1.97 \pm 0.07$	$4.2 \pm 0.8$	9	12	12d	$88 \pm 14$	6.0	198
$\kappa$ Psc	220825	4.9	A0p	$9450 \pm 310$	$1.40 \pm 0.05$	$1.9 \pm 0.3$	10	12	12d	$312 \pm 25$	12.8	865

d = "definite detection"

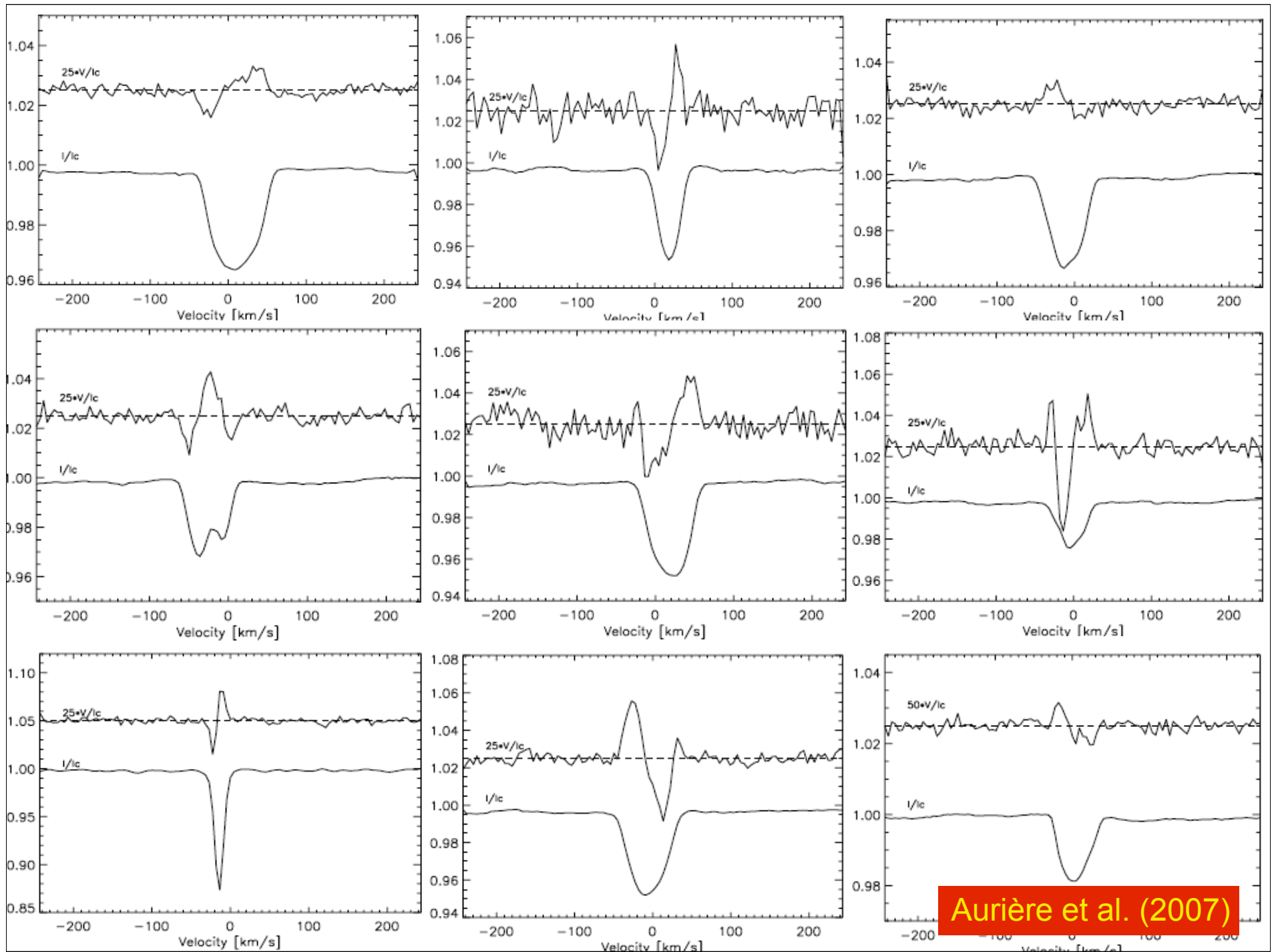
m = "marginal detection"



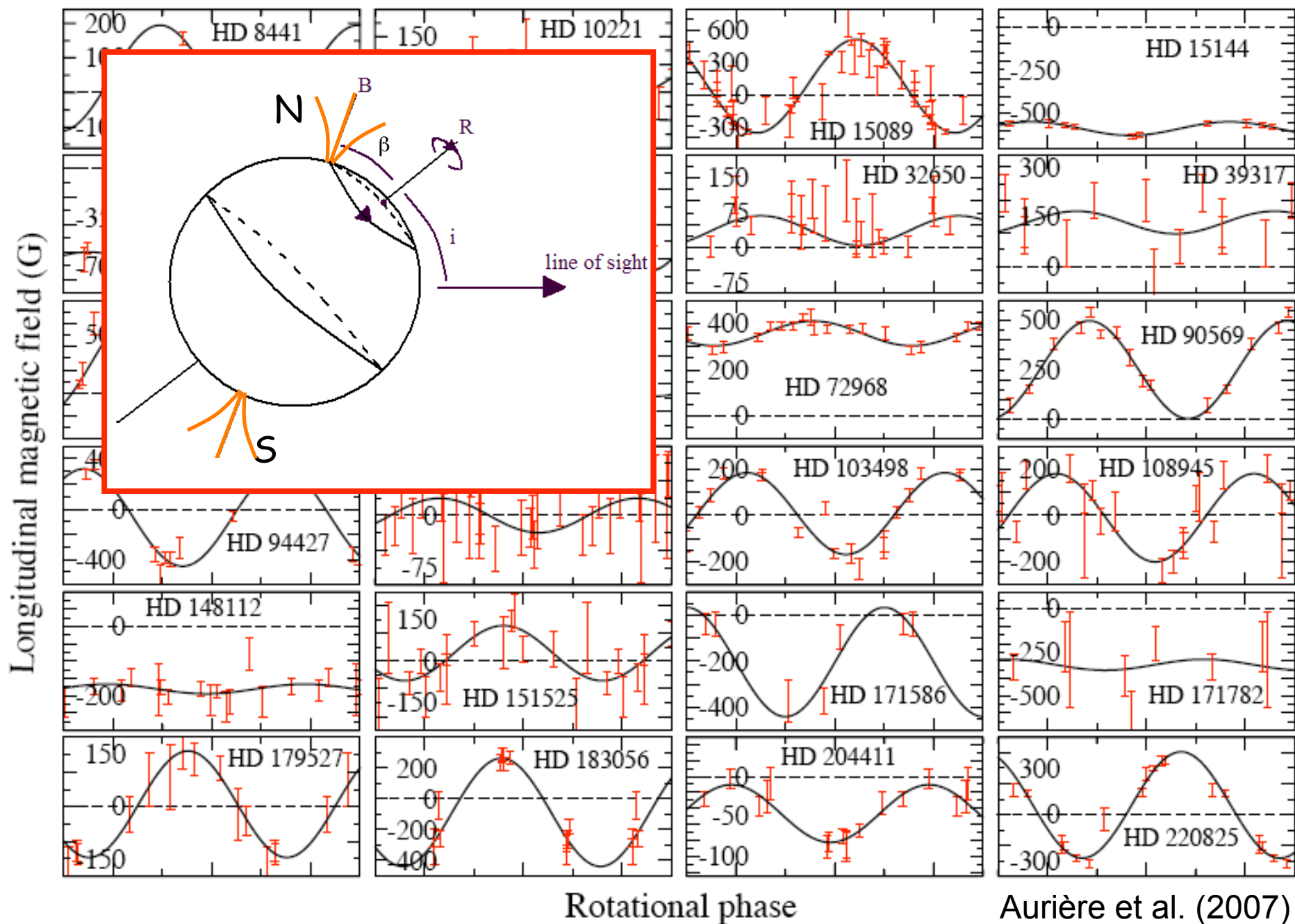
Aurière et al. (2007)



Aurière et al. (2007)



Aurière et al. (2007)



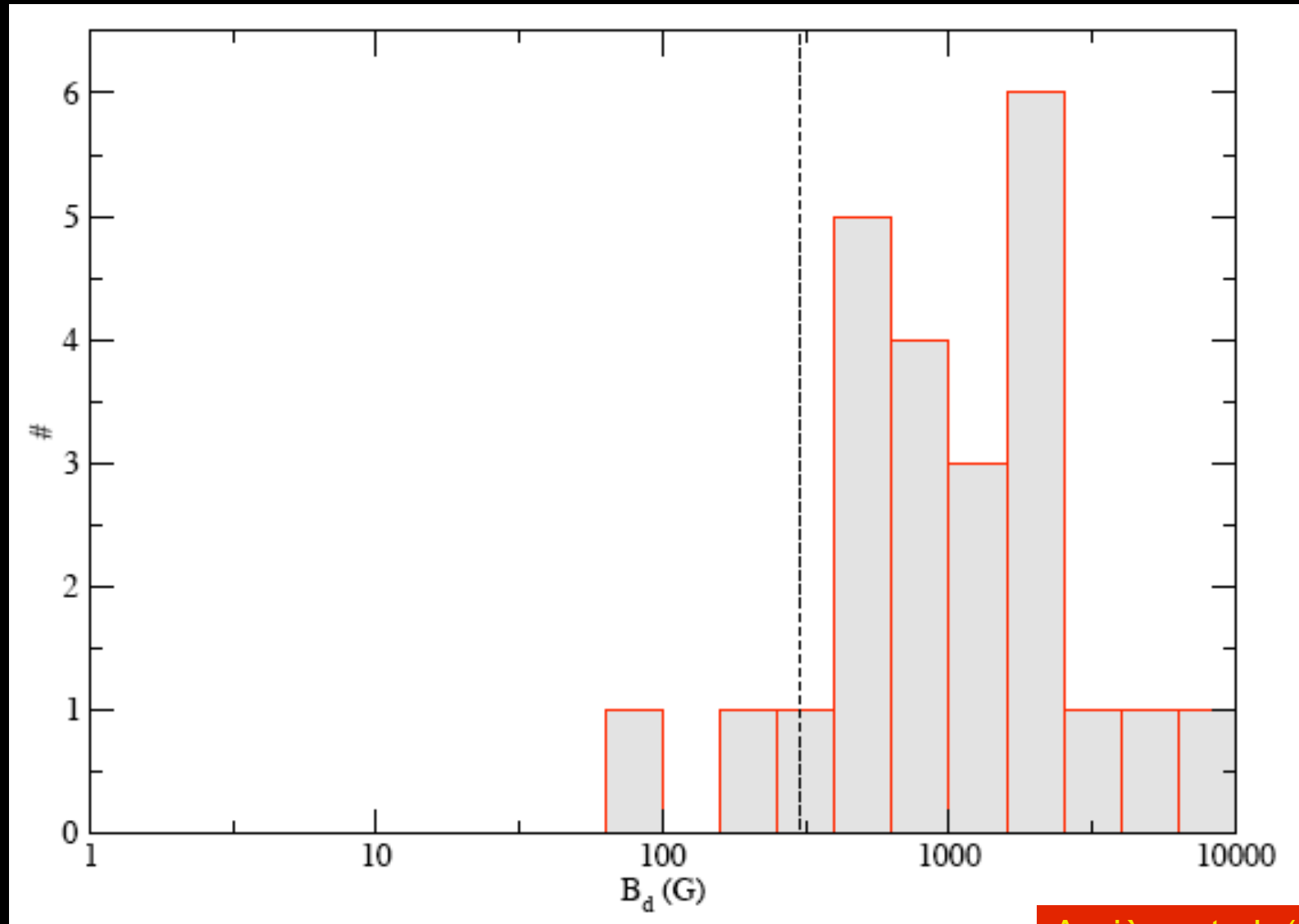
# Results

star	Period (d)	$v \sin i$ (km/s)	$\chi_0^2$	$\chi_1^2$	$\chi_2^2$	$\chi_{lim}^2$	$i$ ( $^\circ$ )	$\beta$ ( $^\circ$ )	$B_d$ (G)	$B_d^{min}$ (G)	$B_d^{max}$ (G)
8441	69.2	2	13.71	6.69	1.75	3.35	$49 \pm 33$	$73_{-61}^{+17}$	683	415	2931
10221	3.15459	24	5.90	1.81	1.56	2.71	$27 \pm 11$	$42_{-41}^{+38}$	375	195	1202
15089	1.74033	48	57.83	56.37	1.83	2.14	$45 \pm 11$	$80_{-12}^{+7}$	2031	1560	2999
15094	1.74033	48	57.83	56.37	1.83	2.14	$24 \pm 8$	$9_{-3}^{+6}$	2100	2007	2281
27094	1.74033	48	57.83	56.37	1.83	2.14	$53 \pm 17$	$5_{-5}^{+11}$	3673	2325	8022
32549	4.6393	47	7.19	8.96	1.75	2.75	$65 \pm 27$	$77_{-74}^{+11}$	546	312	28176
32650	2.7347	30	4.48	1.92	1.19	1.72	$37 \pm 12$	$45_{-30}^{+31}$	229	153	477
39317	2.6541	45	4.97	1.84	2.24	3.18	$36 \pm 12$	$20_{-20}^{+69}$	560	113	2252
43819	15.02	10	135.66	59.32	3.45	4.18	$63 \pm 66$	$42_{-42}^{+47}$	2488	2626	78367
68351	4.16	33	7.85	2.17	1.38	2.00	$28 \pm 37$	$46_{-41}^{+36}$	649	437	71486
72968	5.6525	16	360.16	4.51	1.22	2.03	$61 \pm 18$	$5_{-4}^{+7}$	2388	1451	6702
90569	1.04404	13	170.38	36.08	1.93	3.07	$9 \pm 4$	$81_{-7}^{+5}$	5157	2946	11284
94194	1.04404	13	170.38	36.08	1.93	3.07	$8 \pm 4$	$89_{-4}^{+1}$	8957	3806	25519
96196	1.04404	13	170.38	36.08	1.93	3.07	$53 \pm 16$	$90_{-90}^{+0}$	100	0	492
105458	19.859	19	29.49	29.71	0.99	7.44	$75 \pm 68$	$80_{-11}^{+10}$	600	572	6751
108945	2.01011	65	5.31	6.00	2.10	2.83	$57 \pm 18$	$85_{-61}^{+3}$	735	333	1509
148112	3.04296	44.5	40.67	0.93	0.95	1.73	$56 \pm 16$	$3_{-3}^{+11}$	1042	579	2370
151525	4.1164	35	2.74	2.86	0.97	1.70	$37 \pm 19$	$78_{-43}^{+11}$	545	208	1927
171586	2.1308	37	10.86	8.27	2.59	6.60	$48 \pm 19$	$46_{-40}^{+10}$	1422	716	4413
171782	4.4674	24	6.88	1.12	1.79	3.79	$51 \pm 51$	$5_{-5}^{+85}$	1651	213	22257276
179527	7.098	33	6.57	7.70	0.30	1.30	$74 \pm 32$	$81_{-34}^{+8}$	522	409	1233
183056	2.9919	26	25.02	28.74	1.59	2.32	$74 \pm 8$	$49_{-32}^{+37}$	1558	1172	3938
204411	4.8456	5.4	20.75	5.43	0.57	1.46	$7 \pm 5$	$81_{-12}^{+7}$	968	416	4509
220825	1.42539	38	78.54	90.05	2.29	3.18	$35 \pm 54$	$83_{-80}^{+7}$	1957	1141	21045

Dipole field intensity

Global field geometry

# Results



Aurière et al. (2007)

# Conclusions

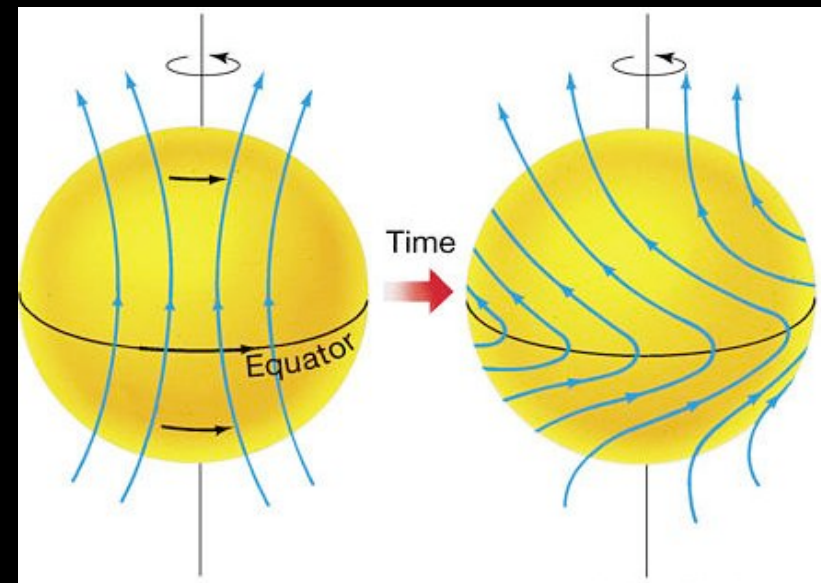
- The phenomenon of organised magnetism in intermediate-mass stars appears to disappear completely for dipole fields weaker than  $\sim 300$  G
- Ap stars and non-Ap stars differ qualitatively in their magnetic properties
- Fields aren't hiding somewhere!
  - We specifically chose Ap stars with the weakest fields
  - Non-Ap stars have been carefully searched for fields
- Studies of other samples yield similar conclusions (e.g. Power et al.)

# Interpretation

- We propose that the observed lower field threshold represents a critical field strength for stability of the large scale field against differential rotation.

- An weak initial large scale poloidal field is distorted by differential rotation.

- The resulting toroidal field is subject to various instabilities which result in its rapid decay.

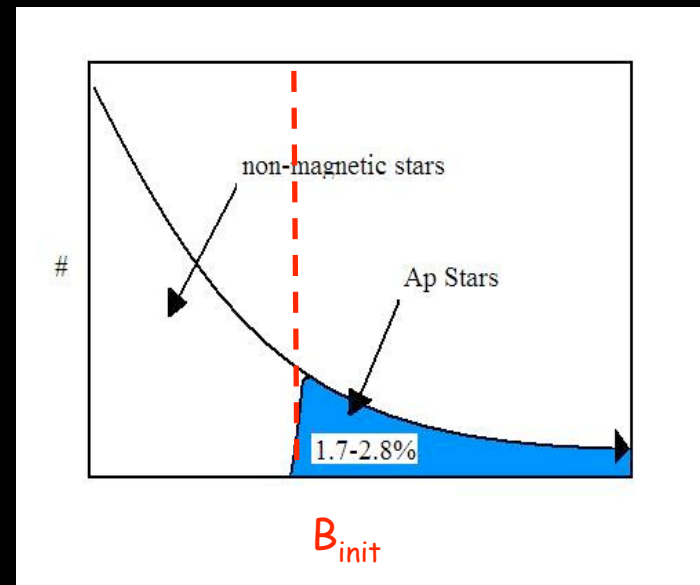


- The critical strength  $B_c$  of the initial field, above which it is stable against the winding effects of differential rotation, can be estimated by equating the winding and Alfvén timescales, giving:

$$B_c/B_{eq} \sim 2 P_{rot}^{-1} T_{eff}^{-1/2} R_* \sim 300 G$$

# Interpretation

- This scenario provides a possible physical foundation for the observed field threshold.
- It also provides a natural explanation for the magnetic dichotomy:
- For an initial magnetic field function increasing toward weak fields, most intermediate-mass stars would host fields weaker than  $B_c$ , and would therefore suffer field winding and decay. The small fraction of stars with strong initial fields ( $B_d > B_c$ ) would retain their fields and become "Ap stars".
- Clearly, this scenario requires elaboration via numerical modeling.



# Implications for B and O stars

- Ap-type peculiarities and variability constitute a near-perfect proxy discriminator of magnetic and non-magnetic A stars. Do any such discriminators exist for B and O stars?
- The model of Aurière et al. may also explain the even greater rarity of magnetic O and B stars:
  - For a main sequence B0p star (with  $T_{\text{eff}} = 31\,000\text{ K}$ ,  $R = 7.2 R_{\odot}$  and  $P = 2\text{ d}$ ),  $B_c \approx 7B_{\text{eq}} \sim 2\text{ kG}$ . With a substantially larger critical field strength, massive stars are substantially less likely to retain their magnetic fields.
  - Known massive stars with relatively weak magnetic fields are still in agreement with Eq. (8):  $\beta\text{ Cep}$ ;  $\tau\text{ Sco}$ ;  $\theta 1\text{ Ori C}$ ; HD 191612.
  - If the  $P_{\text{rot}}$  of  $\zeta\text{ Ori A}$  is correct, this star appears to violate Eq. (8).
- If correct, can this model aid in identifying magnetic stars? Can it guide us in our strategy and expectations for the MiMeS SC?