Studying weak magnetic fields in white dwarf stars with ESPaDOnS

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White dwarfs

- White dwarfs are end state of stellar evolution for ~95% of stars.
- During red giant and asymptotic giant branch evolution, star loses much mass and collapses.
- Tiny, degenerate core survives as dense metal-like body of $M \sim M_{SUN}$, $R \sim R_{EARTH}$ that simply cools slowly : a white dwarf (WD)
- WDs potentially carry (conceal?) many clues about prior evolution ! Magnetism is one clue.

Why are magnetic fields important in stellar physics ?

- Magnetic fields alter spectral lines, greatly change pulsation modes, and produce « activity ». Fields strongly affect interpretation of observations
- A magnetic field can stabilise a stellar atmosphere and substantially alter its physical structure (e.g. by supressing convection, or by Lorentz forces)
- Fields greatly affect transport of angular momentum and mixing – during accretion or mass loss phases, and inside the star at any time

A bit of history

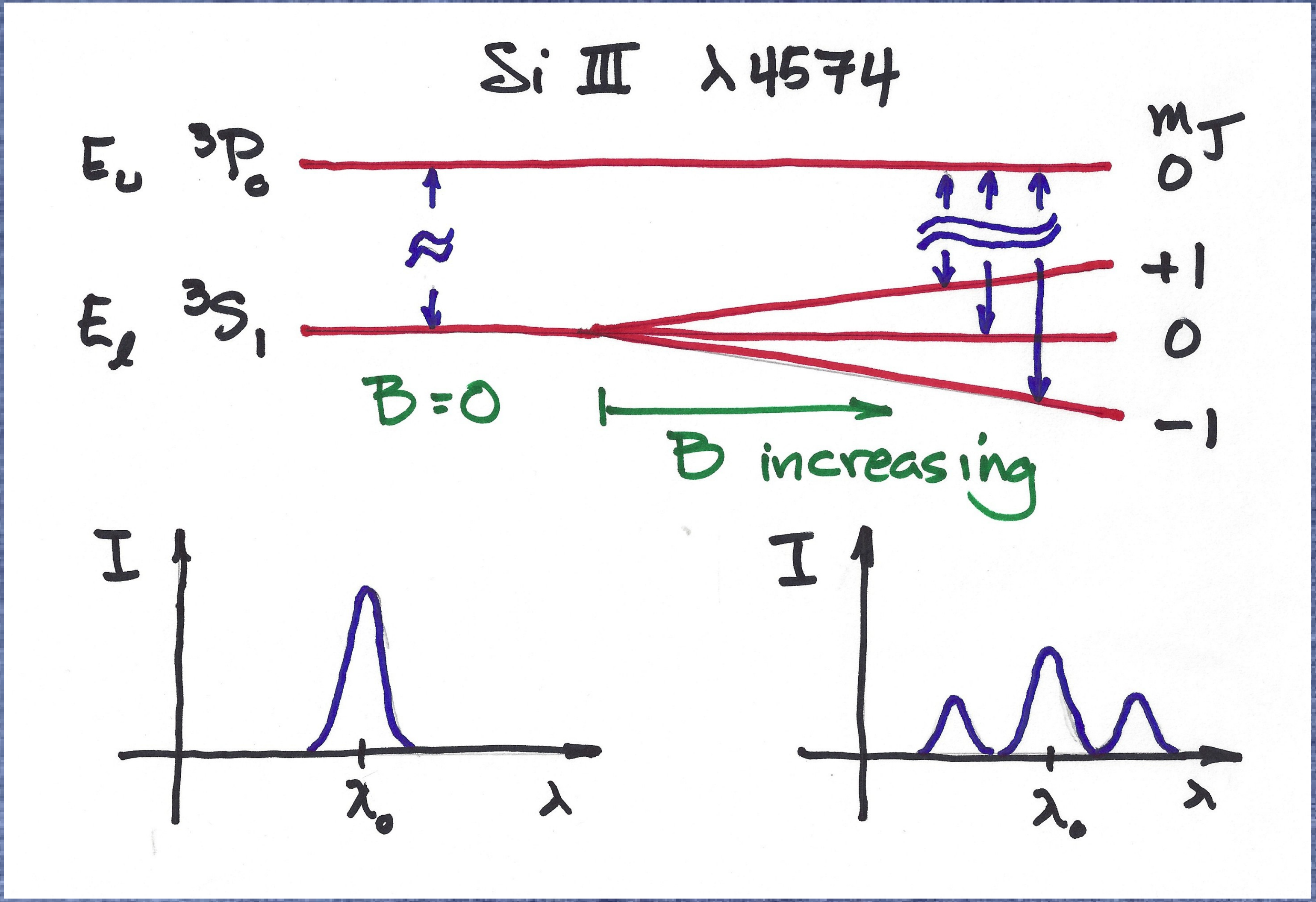
- 1947 : Horace Babcock discovered a kG magnetic field in a main sequence A star. Further fields were found in other such stars.
- In 1964 L. Woltjer suggested that magnetic flux conservation from main sequence to neutron stars could yield $B \sim 10^{12}$ G.
- Discovery of pulsars in 1967, with $B \sim 10^{12}$ G, gave credibilty to idea of flux conservation. Would white dwarfs have $B \sim 10^{6}$ G ?

How are magnetic fields detected and measured ?

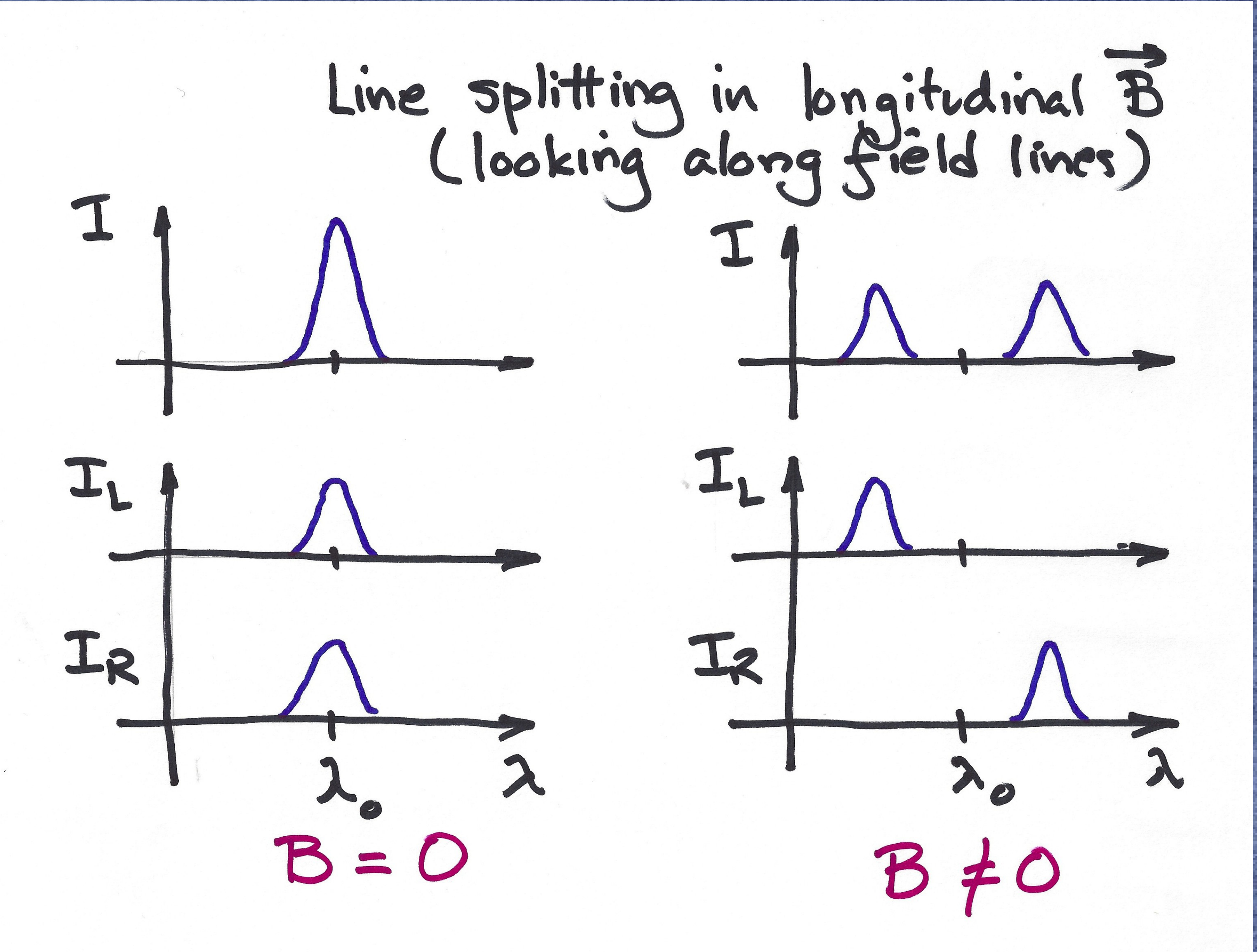
- To detect most stellar magnetic fields, we use the **Zeeman effect**. In many hot stars, this is the **only** detectable symptom of a field.
- Zeeman effect splits a single spectral line into multiple components, separated in wavelength and polarised
- Components are separated by roughly

$$\Delta\lambda(A) \sim 5\ 10^{-13}\ B(G)\ \lambda^{2}(A)\ \sim 13\ A/MG$$

Zeeman effect in the intensity spectrum



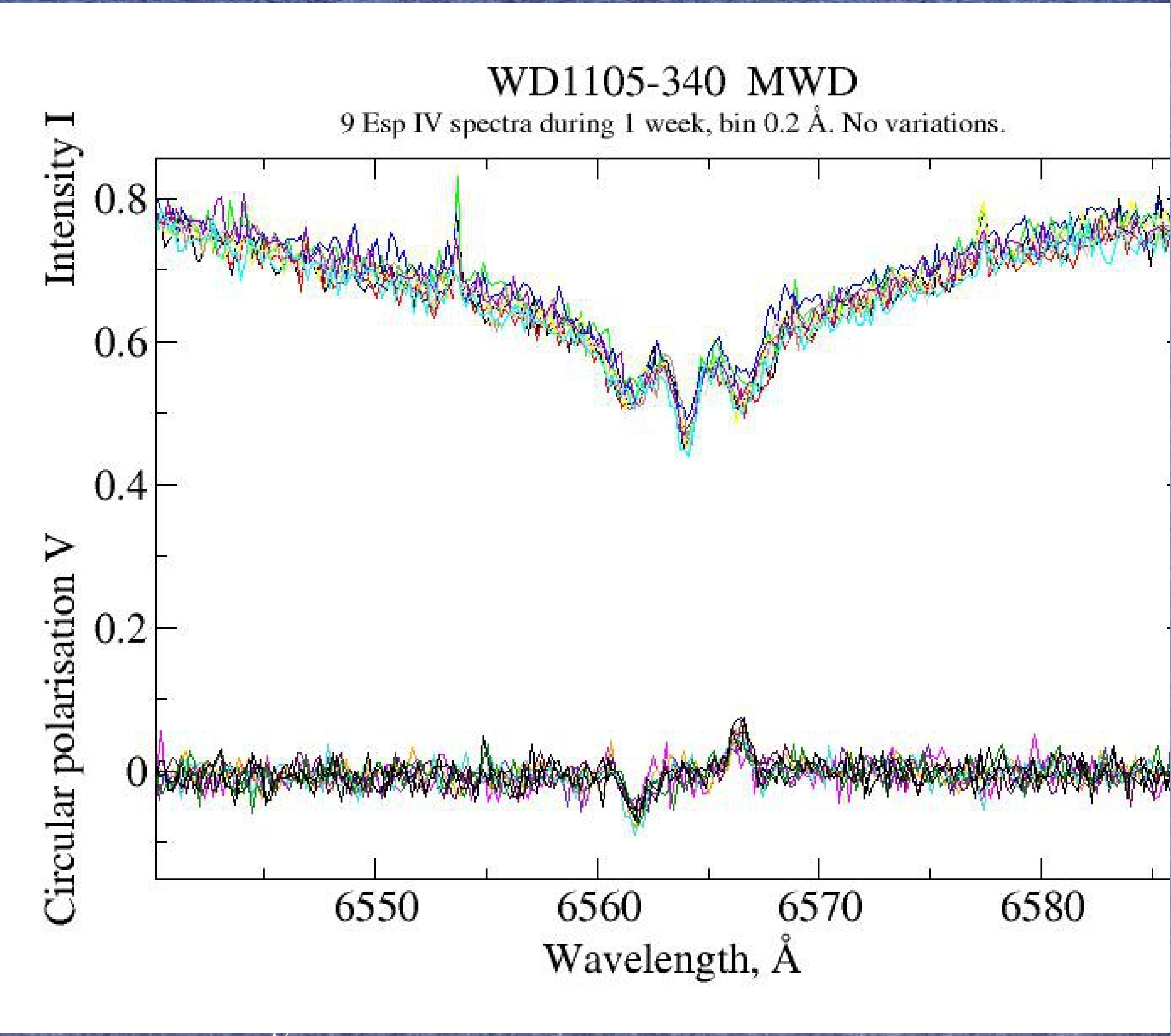
Zeeman effect also leads to line circular polarisation



Zeeman splitting and polarisation

- Clear Zeeman splitting and polarisation in ESPaDOnS spectrum of WD1105-340
- <|B|> ~ 120 kG

  <Bz> ~ - 30 kG



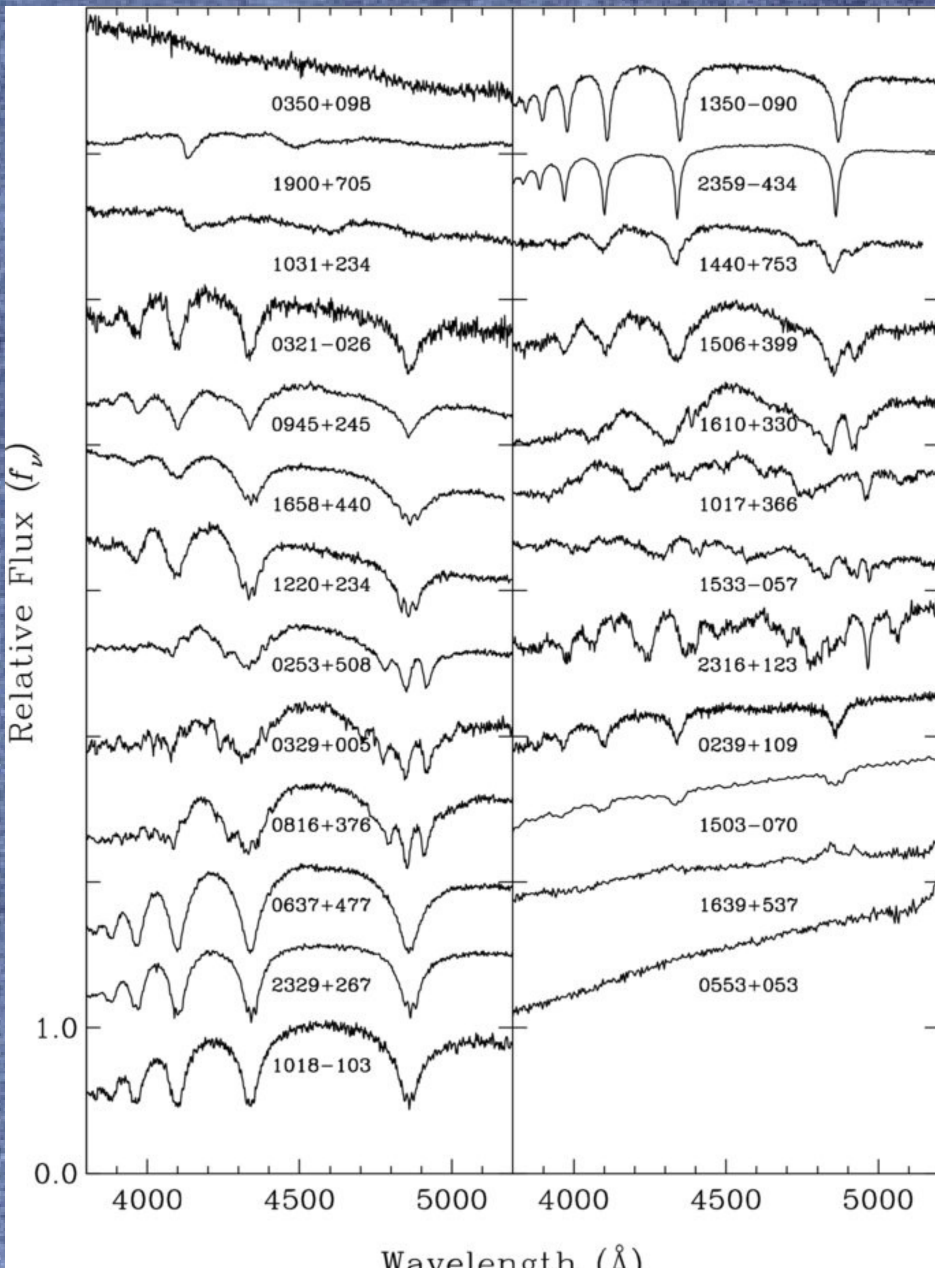
History (2) : Search for WD fields

- B >~ 5 MG fields should produce easily seen Zeeman splitting of >~50 A
- Among ~200 WDs known in 1970, **no Zeeman splitting noted** => fields are rare/absent, or small, or «unrecognisable», or buried...
- First really sensitive survey using polarimetry gave NO detections (Angel & Landstreet 1970)
- Jim Kemp searched for **continuum** circular polarisation. I proposed Grw+70 8247....

Megagauss magnetic fields !

- Circular polarisation found in Grw+70 8247. Interpreted as resulting from field of B~10^7 G (now known to be 3 10^8 G) (Kemp+ 70)
- Further searches during next 30 yr, for polarisation or Zeeman splitting, discovered ~1 or 2 new MWD/yr, often exotic, puzzling objects, with 1 < B < 1000 MG.
- In 1990s first evidence found of fields below 1 MG (Schmidt+Smith 94, Koester+ 98)

Survey field detections



- Most of ~600 MWDs now known are from single low-resolution I spectra (e.g. Gianninas et al 11, SDSS)
- R~2000 and S/N~10 => lower limit to field detection is ~2 MG. Easy detection 2-80 MG Upper limit ~ 10^9 G ?

Stellar magnetism in context

- We now have magnetic field detections in (some) stars in all major phases in HR diagram!!
  - PMS stars: T Taus (dynamo) and a few Herbig AeBe stars (fossil)
  - Main sequence (MS): rapidly rotating low mass stars (dynamo) ; small fraction of O, B, A (Ap/Bp) stars (fossil)
  - Giant stars: a few Ap descendant(?) fields, weak dynamo fields in both red giant & AGB stars
  - Some white dwarfs have MGauss fossil fields. Neutron stars are formed with TGauss fossil fields

Global evolution of fields

- From observational evidence that (some) fields occur in most major evolution stages, we look to theory to interpret the observed evolution
- Low mass stars : current dynamos occur at most stages until final collapse to white dwarf. But why **are a few % of WDs left with huge fossil fields ? (are these the descendants of low mass stars?)**
- In more massive stars, situation is very strange! T Tau (dynamo) -> Herbig (fossil) -> MS (fossil) -> RG, AGB (dynamo) -> white dwarf or neutron star (fossil). **This complex evolution is far from understood.**

How to make progress ?

- **Theorists** model single star magnetic evolution (Mathis, Brun, Brathwaite, etc). Others consider MWD formation channels through binary common envelope phases (Tout 08, Wickramasinghe et al 14, etc)
- **Observers/modellers** can provide (1) distribution of MWD field strengths as function of WD mass, age, chemistry, etc, and (2) detailed models of individual stars

The super-weak field regime

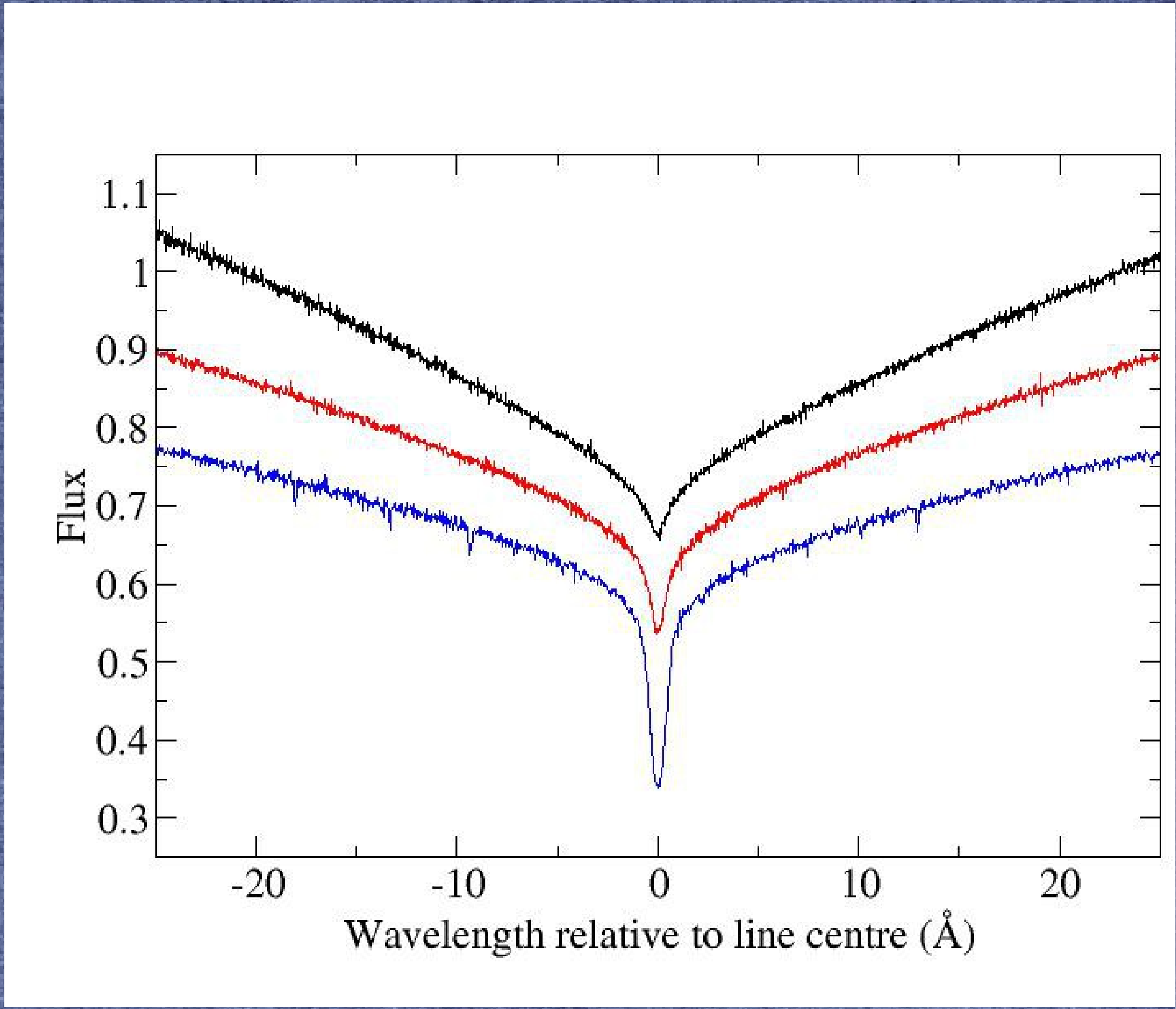
- Very few MWDs are known with fields below ~2 MG. Is deficit real, or observational limit ?
- Stefano Bagnulo and I have been studying the super-weak field regime – to find more MWDs in this range, and model them
- We are exploring all available avenues to search for and characterise such stars … how can we get the **smallest measurement uncertainties** ?

High precision WD field measures

- Measuring small <|B|> depends on resolution. $R \sim 10^3$ detects ~1 MG, $R \sim 5\ 10^4$ detects 30 kG
- Small <Bz> requires spectropolarimetry, resolution and aperture. Best precision now : 85 G (40 Eri B : ESPaDOnS : Landstreet+15)
- Facility spectropolarimeters in visible : ESPaDOnS (V<15, no continuum measures, but resolve Halpha core), ESO FORS (low R but big mirror), WHT ISIS (intermediate)

Why is resolution useful for WDs ?

- Hγ, Hβ, Hα in DA WD 40 Eri B
- Clearly Hα offers a potentially very useful line for WD polarimetry and intensity spectroscopy

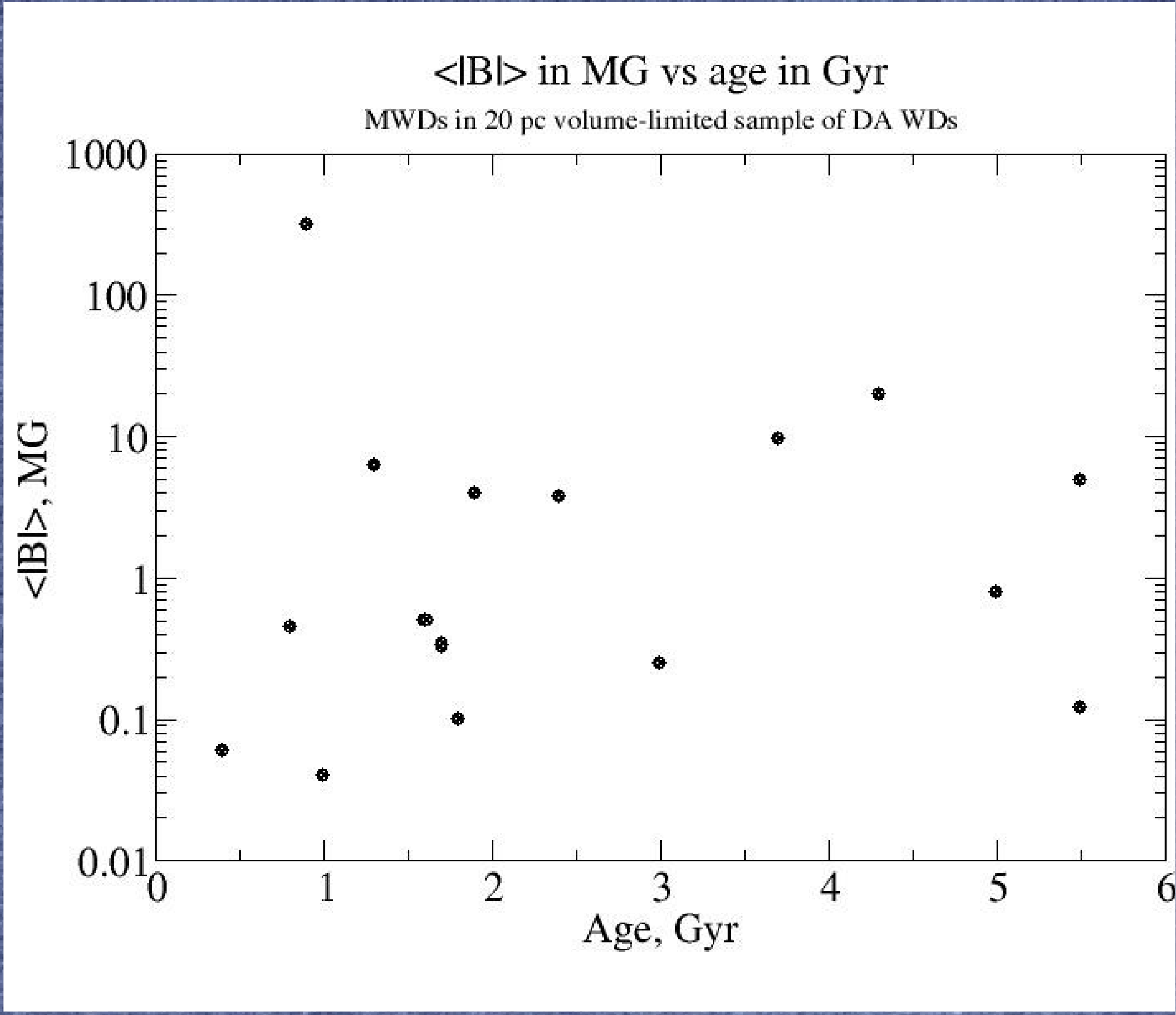


20-pc volume-limited survey

- A volume limited WD sample contains a fossil record of 95% of completed local stellar evolution (mostly of B-A-F stars)
- We are surveying 20-pc volume for weakest fields. Among H-rich WDs, we find *20%* have fields with <|B|> > few kG, *more than half with <|B|> < 1 MG.*
- Too large a fraction to be produced by flux conservation from magnetic Ap-Bp stars

Field evolution with age ?

- On upper MS, fossil fields decline strongly in ~10^8 yr (Landstreet+08)
- No such evolution in fossil fields of magnetic DAs even over 5 10^9 yr



Conclusions

- WDs have important clues about WD formation channels. One clue is magnetism (3 kG < <|B|> < 1 TG)
- Tiny number (~25) known with <|B|> < 1 MG
- ESPaDOnS powerful for finding new weak-field WDs
- Survey of DA stars in 20 pc volume shows that about 20% are magnetic, too many to be due to flux conservation from upper main sequence magnetic stars. Close binary merger origin ? Or … ?
- Unlike magnetic Ap/Bp stars, magnetic WDs show no sign of field decay even over 5 Gyr

Thank you for your interest