

# Pulsars; evolution of stellar magnetism

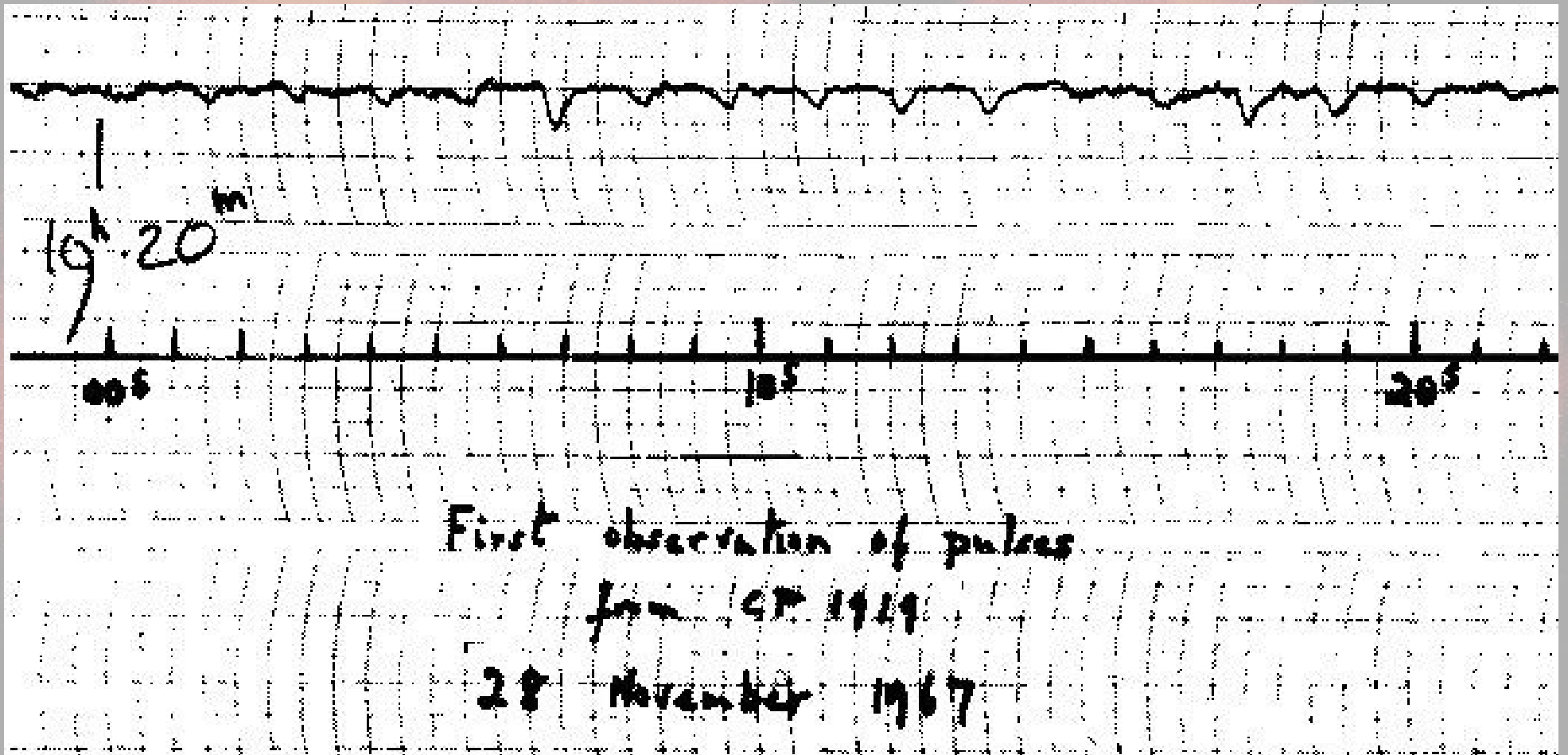


JDL

# Discovery of pulsars

- First pulsar discovered accidentally in radio study of scintillating (small angular diameter) radio sources by Jocelyn Bell and Tony Hewish
- First pulsar had periodic repetitive radio pulses,  $P = 1.3$  s
- Uncertainty at first about “clock”: rotation, pulsation, orbital motion
- Short period requires very *small* clock – a white dwarf or neutron star (e.g. shortest orbital period for double white dwarf is of order seconds)
- Several more soon found, various periods, all of a few sec

# Discovery of CP 1919+21



# Crab Nebula pulsar

- Discovery of Crab Nebula pulsar provided important clues
  - association with a known supernova (1054)
  - short period of 0.033 sec ruled out all white dwarf models:
    - if we guess that clock is rotation and require that equatorial velocity  $v$  is no more than Keplerian,  $P = 2\pi R/v$  satisfies  $4\pi^2 R^3 / P^2 < GM \Rightarrow \rho > 3\pi / GP^2 \sim 10^{11} \text{ gm/cm}^3$ , much higher than density of white dwarf ( $10^6 \text{ gm/cm}^3$ )
  - therefore clock must be a neutron star
  - pulse period soon found to be slowing down ( $4 \times 10^{-13} \text{ s/s}$ )
  - presence of pulsar at centre of bright nebula with no visible energy source suggests pulsar is strongly magnetised neutron star that is slowing down by radiating low-frequency EM waves

# Rotationally powered emission region in Crab Nebula

- Composite image of supernova remnant from SN 1054 explosion
- Pulsar is blue star at centre, powering EM radiation from nebula – a macrowave oven
- X-ray – blue  
Visible – green  
Radio - red





# Energy loss from a pulsar

- Suppose that a pulsar is basically a *rapidly rotating magnetic neutron star* which loses rotational energy by EM radiation

- Radiated energy given by Larmor formula,

$P_{rad} = 2 (d^2 m / dt^2)^2 / 3c^3$  where  $m = B_{\perp} R^3$  is the perpendicular component of the magnetic moment of the field in the star

- If  $m = m_0 \exp(-i\omega t)$  then  $d^2 m / dt^2 = -\omega^2 m$  so

$$P_{rad} = 2 (\omega^2 m)^2 / 3c^3 = 2 (B_{\perp} R^3)^2 (2\pi / P)^4 / 3c^3$$

- This power is taken from rotational energy, and is radiated as very low-frequency EM waves:

- $dE_{rot} / dt = d(I\omega^2 / 2) / dt = d(2 \pi^2 I / P^2) / dt = -4\pi^2 I P \dot{P} / P^3 = -P_{rad}$

where  $P \dot{P} = dP / dt$  and  $I \sim 2 MR^2 / 5$

- With known  $I$ , and measured  $P$  and  $P \dot{P}$ , we can solve for  $B_{\perp}$ !

# Finally, field strength of a pulsar

- Solving the energy loss equation for the field  $B$  required to supply the radiative energy loss from rotational deceleration

$$B \sim (3c^3 I / 8\pi^2 R^6)^{1/2} (P \dot{P})^{1/2}$$

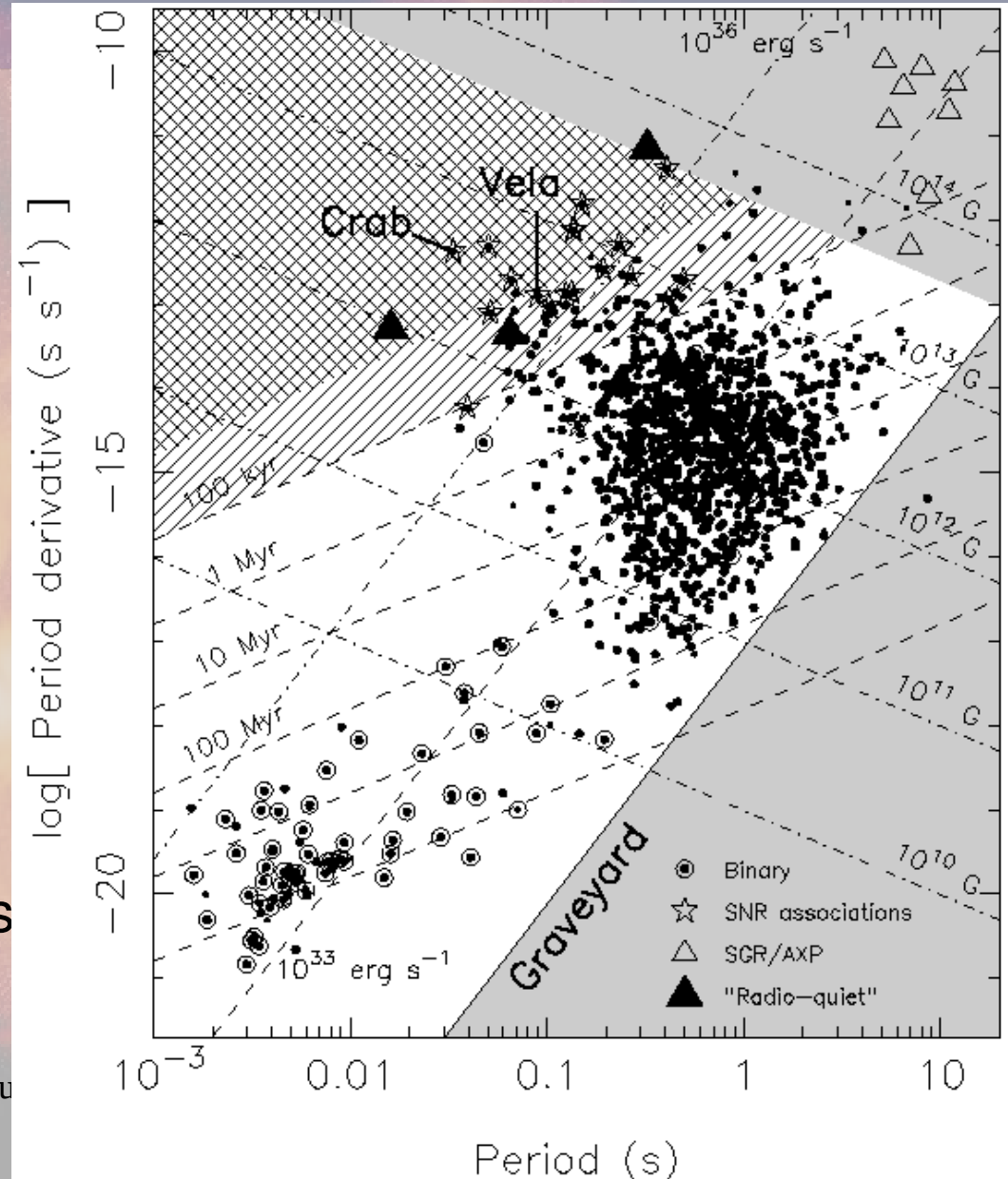
- Using values for the Crab pulsar,  $B \sim 4 \times 10^{12}$  G
- This value is typical for many pulsars
- Assuming that the field  $B$  is approximately constant in time, solving for  $P \dot{P} = P dP/dt$ , writing  $P dP = \text{const} \times dt$ , and integrating from  $t = 0$ , we find predicted evolution of  $P(t)$ :

$$[P^2 - P_0^2]/2 = 8\pi^2 R^6 B^2 / 3c^3 I t = (P \dot{P}) t.$$

If  $P_0$  is much smaller than  $P$  and can be neglected, solving for  $t$  leads to an estimated age of  $t = P/(2 \dot{P})$

# The P-Pdot diagram

- The  $P$ - $\dot{P}$  diagram provides important insight into pulsar evolution
- If  $B$  stays constant, pulsars should evolve along lines of constant  $B$ , to greater and greater ages and steadily smaller energy loss rates
- Distribution of pulsars shows that this is too simple: field decay may occur.
- Pulsar field seem to be fossils



Taken from "Handbook of Pulsar Astronomy" by Lorimer & Kramer



# The Lives of the Pulsars

- Most current pulsars were formed in core-collapse SN explosions with fields around 1 TG, and evolve (perhaps with slow field decay), converting rotational energy into VLF radiation and thus slowing down, until after a few hundred Myr they no longer make radio beams
- Some pulsars (often “millisecond pulsars”) are formed in interacting binary systems – when fresh material and angular momentum are dropped on a pre-existing neutron star, it is spun up and is able to pulse again even with a much reduced field of order 100 MG
- A few pulsars form (perhaps from massive stars with extremely large fields on MS) with  $>100$  TG fields, and have emission powered by energy release of magnetic decay

# Overview of evolution of stellar magnetic fields

- We have a good general picture of stellar evolution
  - $\sim 1 M_{\odot}$ : ISM  $\rightarrow$  T Tau  $\rightarrow$  MS  $\rightarrow$  RG  $\rightarrow$  HB  $\rightarrow$  AGB  $\rightarrow$  PN  $\rightarrow$  WD
  - $\sim 10 M_{\odot}$ : ISM  $\rightarrow$  HAeBe  $\rightarrow$  MS  $\rightarrow$  RSG  $\rightarrow$  SN  $\rightarrow$  NS
  - (And don't forget that evolution in close binaries can be very different)
- How do magnetic fields evolve during this stellar evolution?
- We have basically two different kinds of questions
  - How do fields evolve *during* a given evolution stage, such as main sequence or neutron star phases, and
  - How do fields evolve *between* phases we know something about, through still uncharted phases such as the red giant?
- We now have some answers to the first type of question, but very little to the second

# Star formation and pre-main sequence

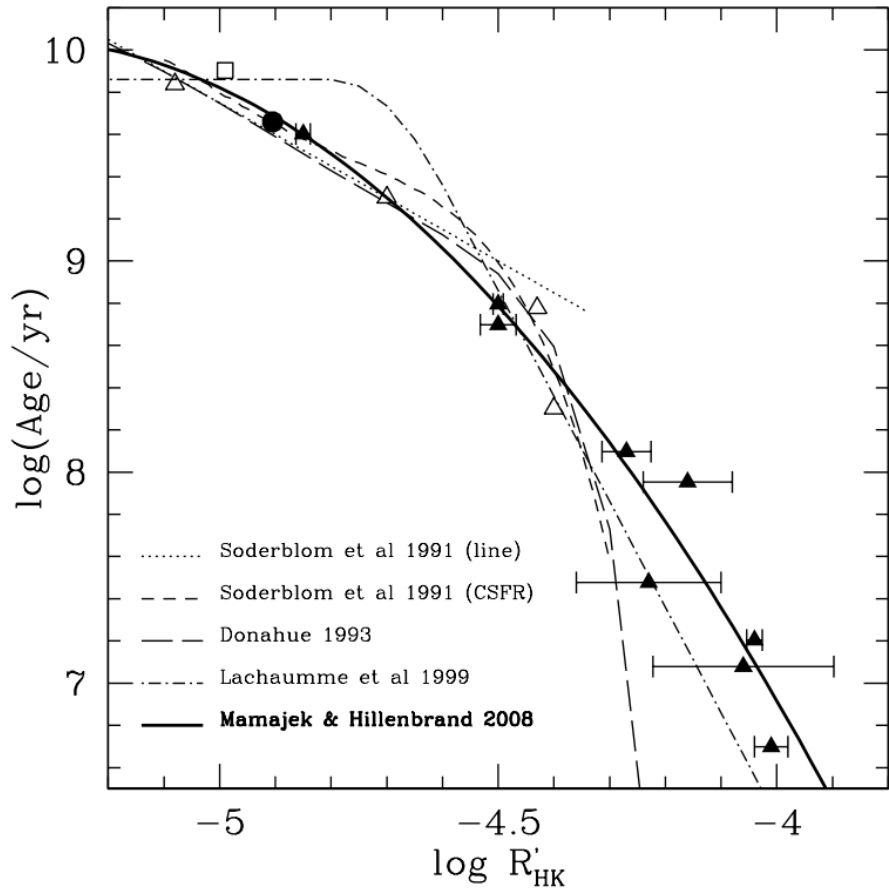
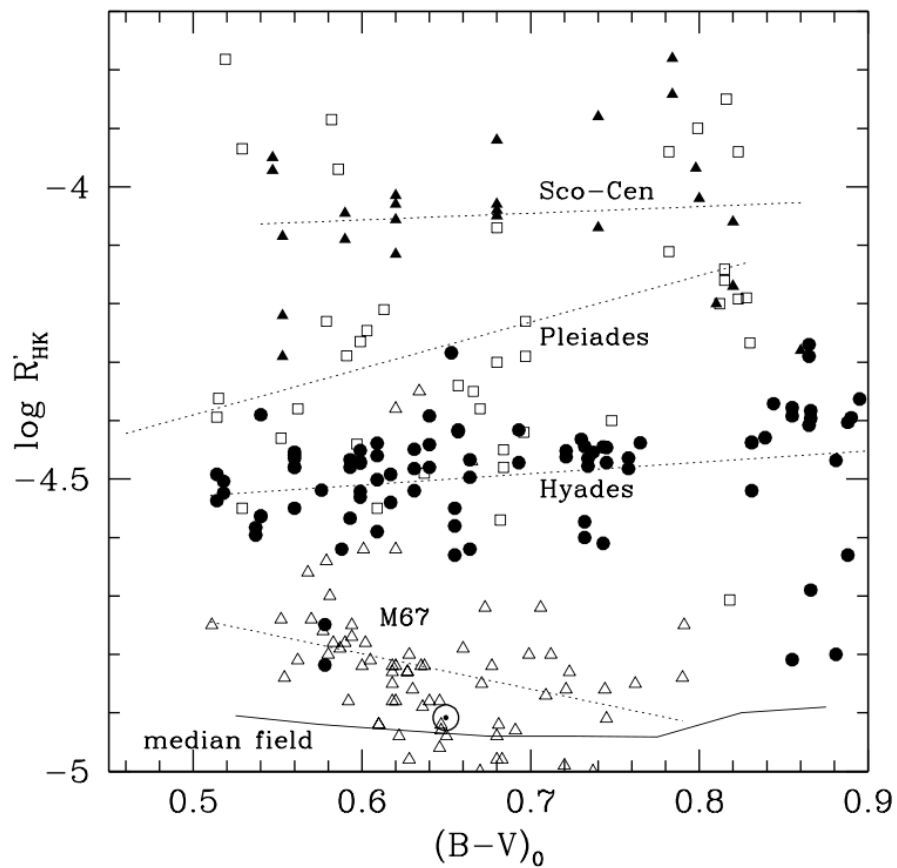
- We know fields of  $\mu\text{G}$  to  $\text{mG}$  are present in ISM, where they have energy density similar to the values for kinetic and gravitational energy densities
- If fully retained as fossil, this flux would give  $\sim 100$  MG on MS, so much flux must be lost, greatly reducing importance of fields
- Theory tells us that fields transfer angular momentum and this is probably the main way that protostars lose enough angular momentum to contract to stellar dimensions
- But little is known about field nature or evolution until the pre-main sequence (T Tau and Herbig AeBe) phase
- Probably the fields of T Tau stars are dynamos.
- Fields in more massive PMS stars could be due to proto-star dynamos, or fossil remnants, or more complex processes....

# Field nature and evolution of *low-mass* stars during main sequence

- Fields seem to be present generally in PMS stage – T Tau stars usually have fields of  $\sim 1 - 3$  kG that control accretion from disk
- During MS we cannot detect fields directly yet except in fairly active stars, but  $\sim$ all stars show activity indirectly through chromosphere (visible in Ca II K line) and X-ray emission
- Level of activity increases with decreasing rotation period
- Loss of angular momentum through wind and mass ejections causes rotation to slow during MS, so field – and activity -- declines
- This is so predictable that it can be used to determine stellar ages (gyro-chronology)
- Such fields are clearly produced by dynamo action, although details of dynamo are still quite obscure



# H-K line emission, and presumably B, declines with age in low mass stars

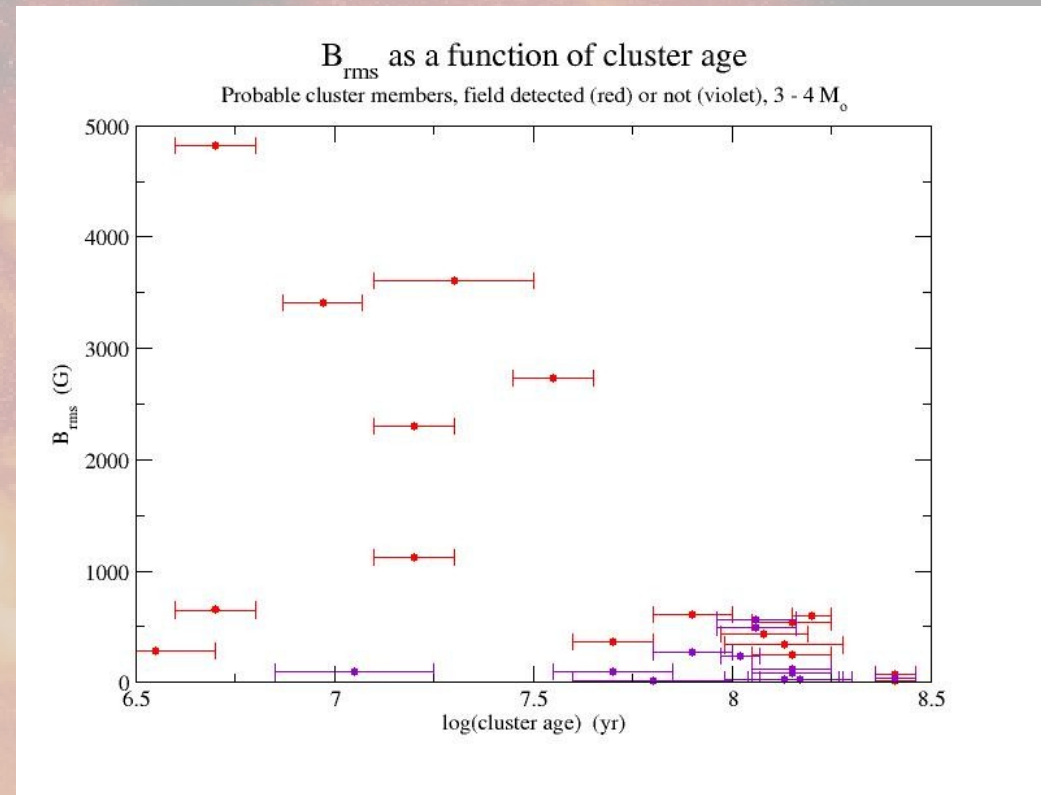


# Field nature and evolution in *massive* stars during main sequence phase

- Fields seem to be present at immediate pre-main sequence
- Only a few % of O, B, A stars are magnetic; fraction declines sharply below  $T_{\text{eff}} \sim 10\,000\text{ K}$ , vanishes below  $7\,000\text{ K}$ . Why?
- Fields sometimes present in only one star of SB. *No* fields found in SBs with periods below 3 d. Not obvious that fossil origin can explain all these features. Hint of binary origin or connection??
- Fields associated with 10x (or more) deficiency in angular momentum (slow rotators), perhaps due to loss of rotation through stellar wind in PMS phase
- $|B|$  is not correlated with  $1/(\text{rotation period})$  or depth of surface convection: unlikely to be current dynamo. Probably in fossil phase
- Field and flux both decline during MS with time scale somewhat shorter than main sequence time scale over  $\times 2$  range of mass

# Evolution of field strength during main sequence phase of Ap stars

- Stefano Bagnulo & I have obtained first sample of magnetic stars of known ages spanning full MS lifetime, by observing magnetic Ap stars in associations and clusters
- A typical result is at right. We see that field strength in this mass range seems to decline after an age of about 40 Myr  $\sim 0.2 \times (\text{MS life})$
- Decay rather fast to be Ohmic, but slow for instability...  $\Rightarrow ??$



# Fields evolution through giant phases towards magnetic white dwarfs

- During MS life of massive star, it is usually assumed that field is excluded from convective core
- However, perhaps enough radiative zone remains to anchor a fossil field even with red giant's deep envelope convection – one such star (EK Eri) seems to have been discovered
- Most giants known to have fields are in close binary systems (RS CVn, FK Com) and are forced to rotate rapidly by tidal coupling – hence they have dynamo fields based on rotation and convection
- Very weak field has been found in one single subgiant (beta Gem): not known if this is dynamo or fossil
- Global picture of field evolution through giant phase(s) still far from clear
- Recall Tout contention that WD fields may only arise in binaries



# Evolution of white dwarf fields

- Once a single white dwarf is formed, its evolution is simply cooling. For typical WD ( $0.6 M_{\odot}$ ), cooling times are
  - $10^7$  yr:  $T_{\text{eff}} \sim 40\,000$  K, field decay modest during cooling
  - $10^8$  yr:  $T_{\text{eff}} \sim 20\,000$  K, ditto
  - $10^9$  yr:  $T_{\text{eff}} \sim 10\,000$  K, ditto
  - $3 \times 10^9$  yr:  $T_{\text{eff}} \sim 6\,000$  K, and cooling time longer than field decay time
- Thus for *fossil evolution* from start of WD stage, expect constant magnetic fraction for all but coolest WDs, where fraction should decline
- However, convection zones exist in non-degenerate outer layers of WD, so dynamo action might be possible, even though rotation velocities are *very slow* ( $< \sim 10$  km/s)
- Valyavin & Fabrika (1990s) report that frequency of fields *increases* as  $T_{\text{eff}}$  declines – clearly not expected fossil behaviour.
- And we have seen that neutron star fields may decay as fossils....

# Finally ... overview

- Two families (or phases?) of magnetic fields: fossils and dynamos
- Fossil fields
  - Upper main sequence (and some Herbig AeBe stars), white dwarfs, neutron stars
  - Field strength unrelated, or inversely related, to rotation rate
  - Fairly simple global field structure
  - Field structure is static or evolves slowly over many years
  - Associated chemical peculiarity may occur, due to vertical diffusion (gravity vs radiative acceleration) which requires suppression of competing mixing phenomena: internal mixing weak due to slow rotation, atmospheric mixing weak due to field stabilisation
  - Close binary frequency is very strange (no Ap systems with  $P < 3$  d)

# Overview 2

- Current dynamo fields
  - Lower main sequence stars & active red giants (usually binary)
  - Field strength directly related to rotation rate and presence of deep convection zone
  - Field structure normally rather complex, like solar field
  - Field structure usually changes within a few rotation periods
  - Associated phenomena (chromospheric emission lines, e.g. in Ca II lines, starspots, and X-ray emission) seem to be intrinsically linked to (powered by) presence and variability of dynamo field, and are stronger with more rapid rotation
  - Phenomena closely connected with binarity, since rapid rotation is required and this may be enforced by close companion
  - As a single star loses mass, angular momentum and field both decline

# Overview 3

- One hypothesis is that these main types are independent:
- Fossil fields are left in some stars from formation, and persist until collapsed state (WD, NS) because of long decay time
  - Statistics roughly right for WDs but probably not for NSs
  - Leave binarity anomalies unexplained
- Dynamo fields appears when physics (rotation, convection, shear) can drive dynamo, otherwise not
- Alternative 1: dynamo fields can persist into fossil phase (e.g. PMS dynamo leads to MS fossil, giant dynamo leads to WD or NS fossil)
- Alternative 2: dynamo fields are produced *only* (or mainly, or sometimes) in certain types of binaries (e.g. common-envelope systems) and then appear in resulting system (cataclysmic variable such as AM Her) or even in a single (merged) star



# Thanks for your attention