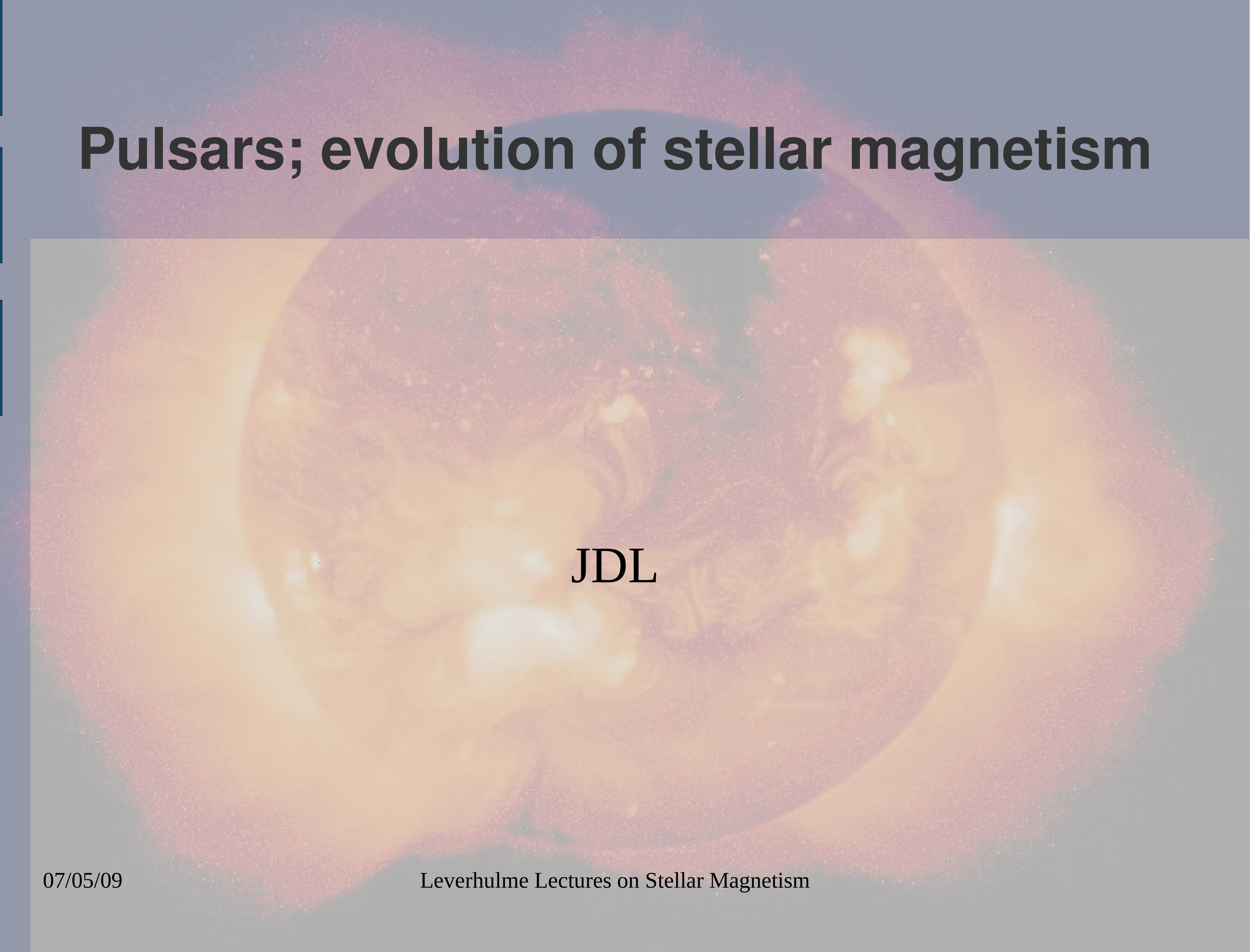
Pulsars; evolution of stellar magnetism

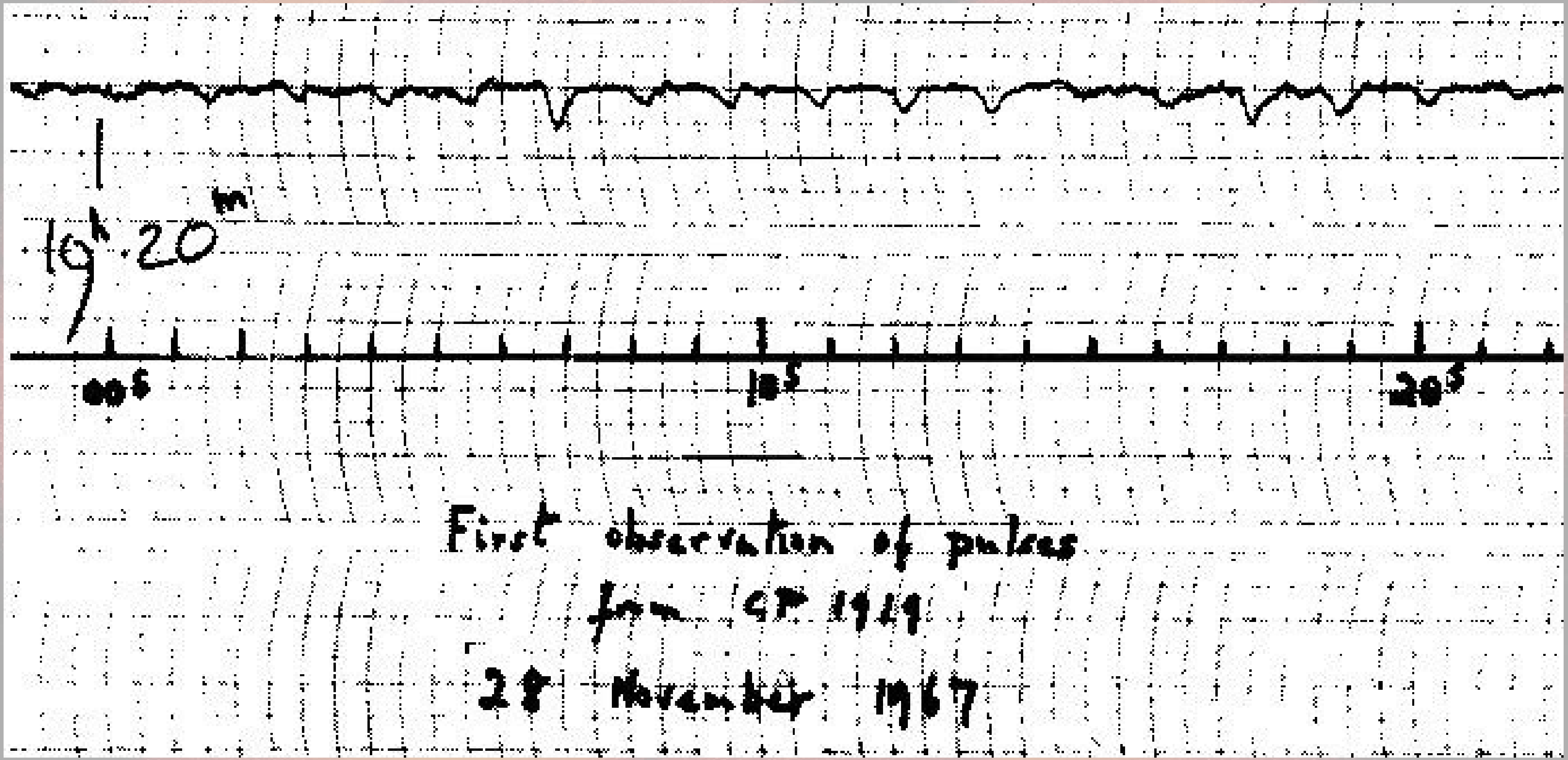


JDL

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



First observation of pulses
from CP 1919
28 November 1967

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 $4\pi^2 R^3 / P^2 < GM \Rightarrow \rho > 3\pi / GP^2 \sim 10^{11}$ gm/cm^3, much higher than density of white dwarf (10^6 gm/cm^3)
  - therefore clock must be a neutron star
  - pulse period soon found to be slowing down (4 x 10^{-13} 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, $P_{rad} = 2\,(d^2m\,/dt^2)^2\,/\,3c^3$ 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 $d^2m\,/\,dt^2 = -\omega^2 m$ 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:
- $$dE_{rot}\,/dt = d(I\omega^2/2)\,/dt = d(2\,\pi^2 I\,/P^2)\,/dt = -4\pi^2 I\,Pdot\,/P^3 = -P_{rad}$$

  where $Pdot = dP/dt$ and $I \sim 2\,MR^2/5$
- With known *I*, and measured *P* and *Pdot*, we can solve for $B_\perp$*!*

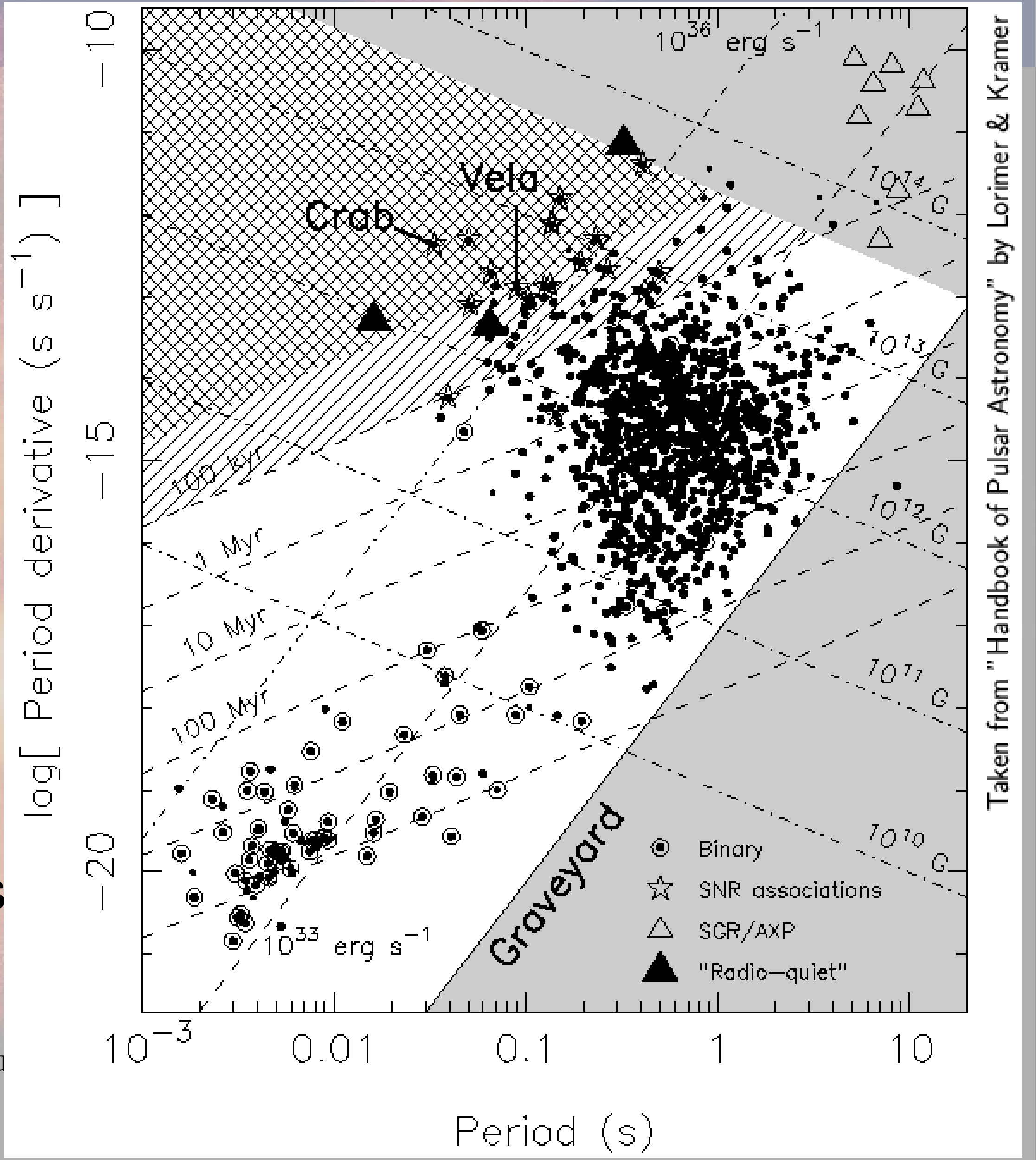
Finally, field strength of a pulsar

- Solving the energy loss equation for the field B required to supply the radiative energy loss from rotational deceleration
  $B \sim (3c^3 I / 8\pi^2 R^6)^{1/2} (P\ Pdot)^{1/2}$
- 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 $P\ Pdot = P\ dP/dt$, writing $P\ dP = const \times dt$, and integrating from $t = 0$, we find predicted evolution of $P(t)$:
  $[P^2 - P_0^{\ 2}]/2 = 8\pi^2 R^6 B^2 / 3c^3 I\ t = (P\ Pdot)\ t.$

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

The P-Pdot diagram

- The *P-Pdot* 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
  - ~1 M_0: ISM -> T Tau -> MS -> RG -> HB -> AGB -> PN -> WD
  - ~10 M_0: ISM -> HAeBe -> MS -> RSG -> SN -> 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

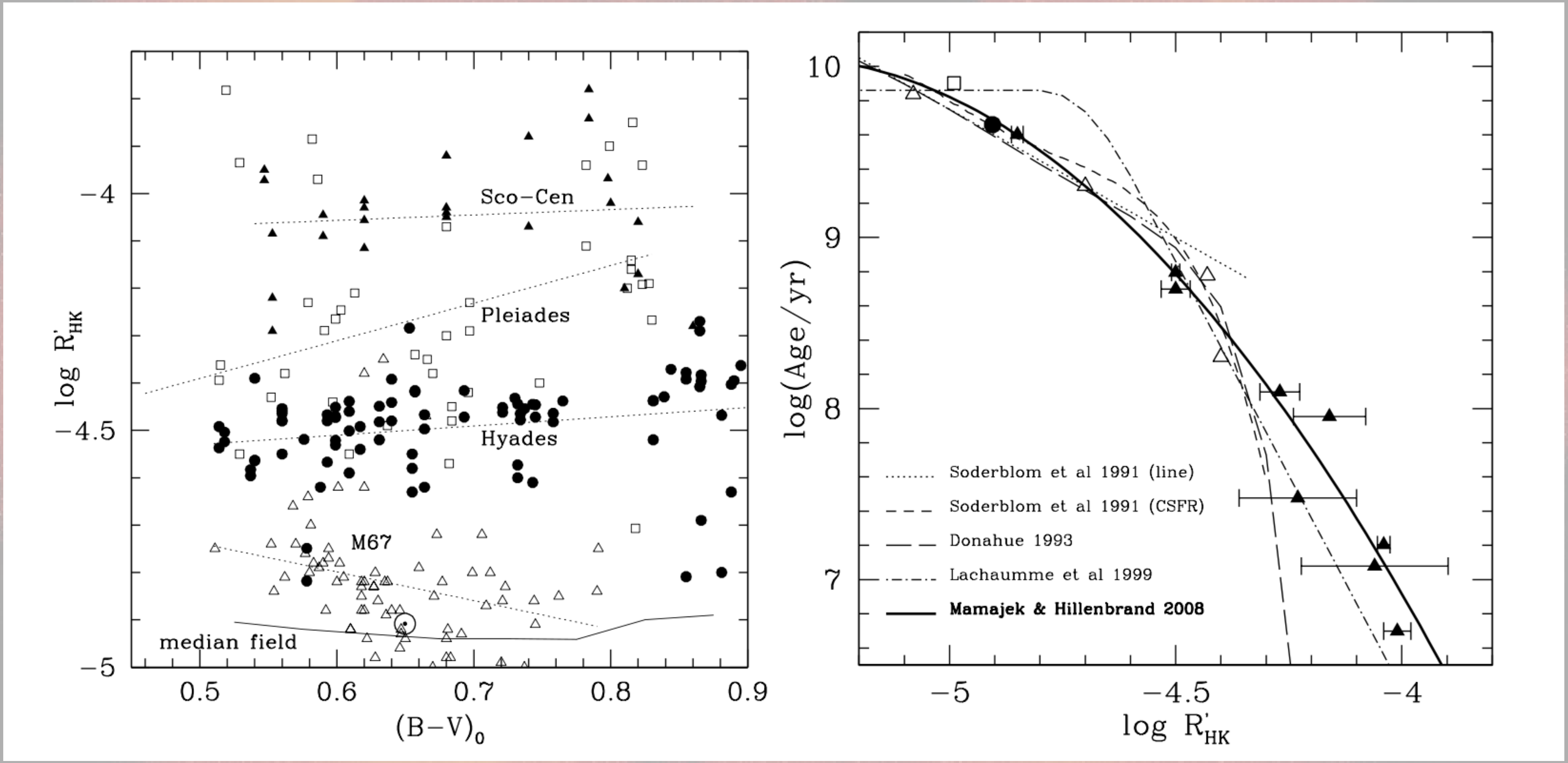
Star formation and pre-main sequence

- We know fields of μG to 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 ~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 ~ 1 – 3 kG that control accretion from disk
- During MS we cannot detect fields directly yet except in fairly active stars, but ~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

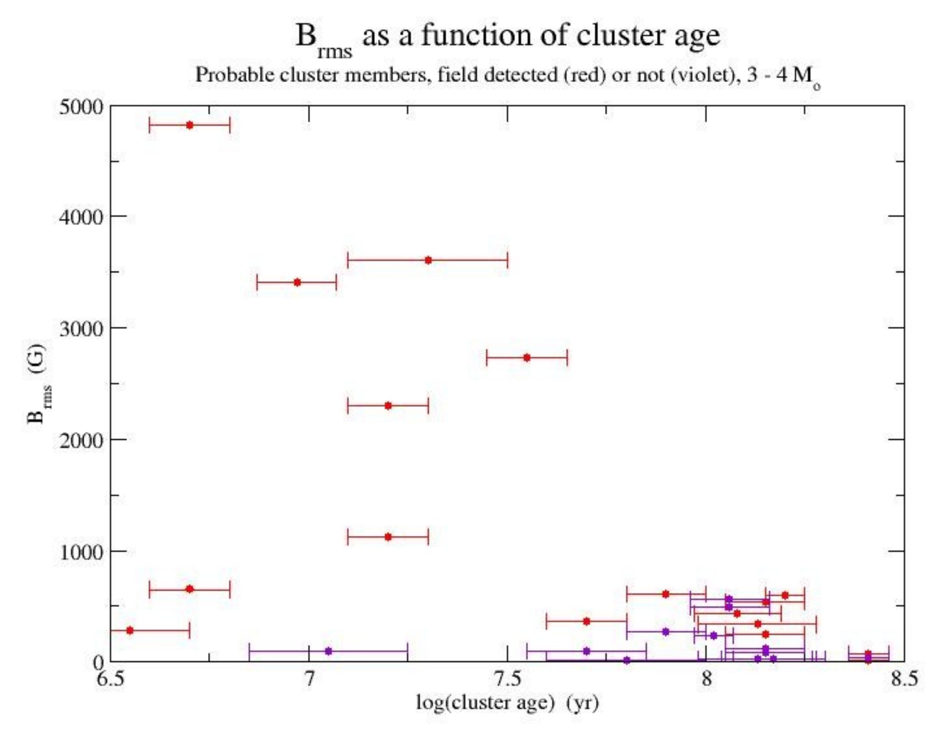


Field nature and evolution in *massive* stars during main sequence phase

- 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_{eff} ~ 10 000 K, vanishes below 7 000 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/(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 x2 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 Aps 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 ~ 0.2x(MS life)
- Decay rather fast to be Ohmic, but slow for instability... => ??



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_0), cooling times are
  - 10^7 yr: Teff ~ 40 000 K, field decay modest during cooling
  - 10^8 yr: Teff ~ 20 000 K, ditto
  - 10^9 yr: Teff ~ 10 000 K, ditto
  - 3×10^9 yr: Teff ~ 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 (<~ 10 km/s)
- Valyavin & Fabrika (1990s) report that frequency of fields *increases* as Teff 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