Origin of Magnetic Fields in Neutron Stars

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QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

High Field Magnetic White Dwarfs (isolated)

Number: ~ 150

Field: ~ 10^6 - 10^9 G

Incidence of Magnetism (HFMWDs): ~15%

Mean Mass: 0.95 M_0 - significantly higher than 0.58 M_0 for all WDs

Rotation: Evidence for spin period to increase with field strength.
(Note: observed spin period is essentially birth spin period)

Neutron Stars (isolated)

Number: $\sim$ 1,500

Field: $\sim 10^{10}$ - $10^{14\text{-}15}$ G

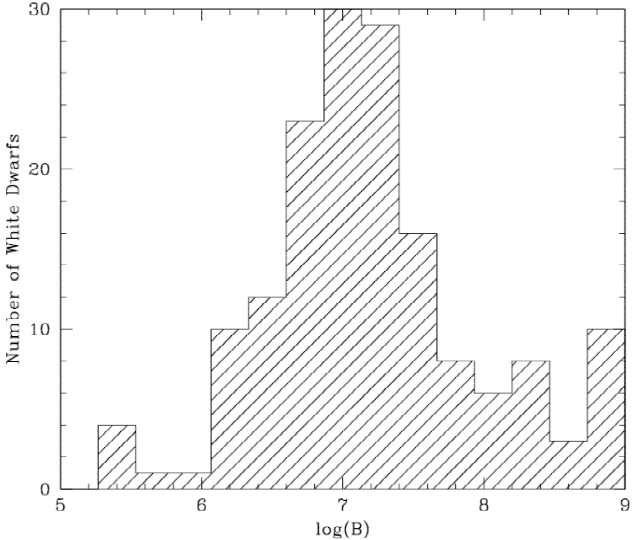
Incidence of Magnetism: 100% ?

Mean Mass: $\sim 1.35\ M_0$

Rotation: Milli-seconds - seconds.
(Observed periods are not the birth periods)

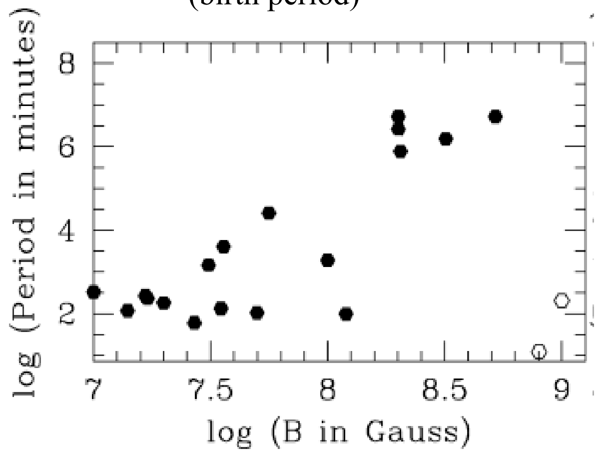
Properties of the magnetic white dwarfs

Field distribution



Period distribution

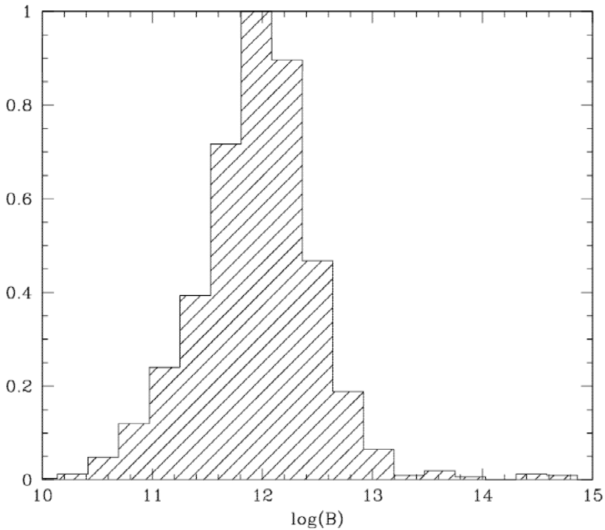
(birth period)



Ferrario & Wickramasinghe (2004)

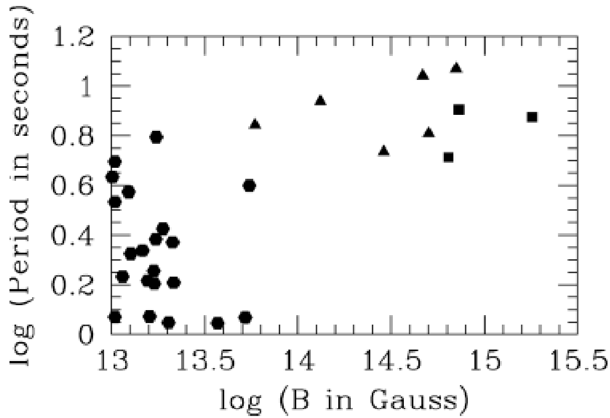
Properties of the neutron stars

Field distribution



Period distribution

(not birth period)



Ferrario & Wickramasinghe (2004)

Progenitors of the HFMWDs

• Prior to 2003: Magnetic Ap and Bp stars had measured fields in the range B(MS) ~ 2,000 - 30,000 G. Lower limit was believed to be real.

• 2003-2005: Surveys with improved sensitivity suggest that **essentially all chemically peculiar Ap and Bp stars** are likely to be magnetic with fields extending down to a few 100 G - the new observational limit.

Field range for Ap and Bp stars likely to be ~ 200 - 30,000 G
A plausible scenario: Chemical peculiarity may draw attention only to the **tip of the field distribution**. Magnetism may be more widespread on the MS extending also to the non chemically peculiar stars (Auriere et al. 2003).

A fossil origin for fields in compact stars

• Magnetic fluxes of main sequence stars, magnetic white dwarfs, and neutron stars are all of the same order of magnitude

$$\Phi \approx 10^{27} \text{ G cm}^2$$

at the top end of their field distributions (Ruderman 1972)

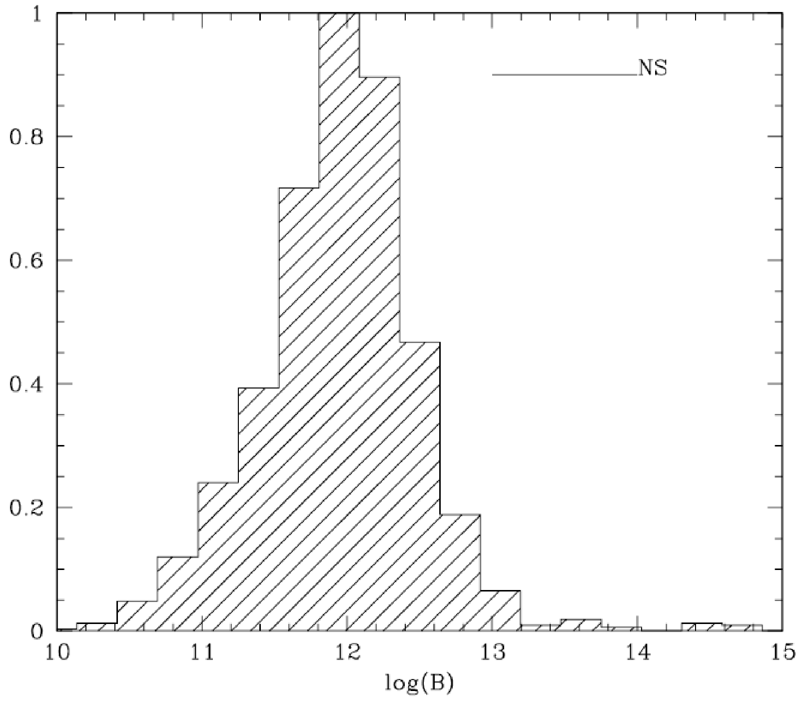
• Under flux conservation:

$B(\mathrm{MS}) \sim 200 - 30{,}000$ G $\longrightarrow$ B (WD) $\sim 10^6 - 10^9$ G

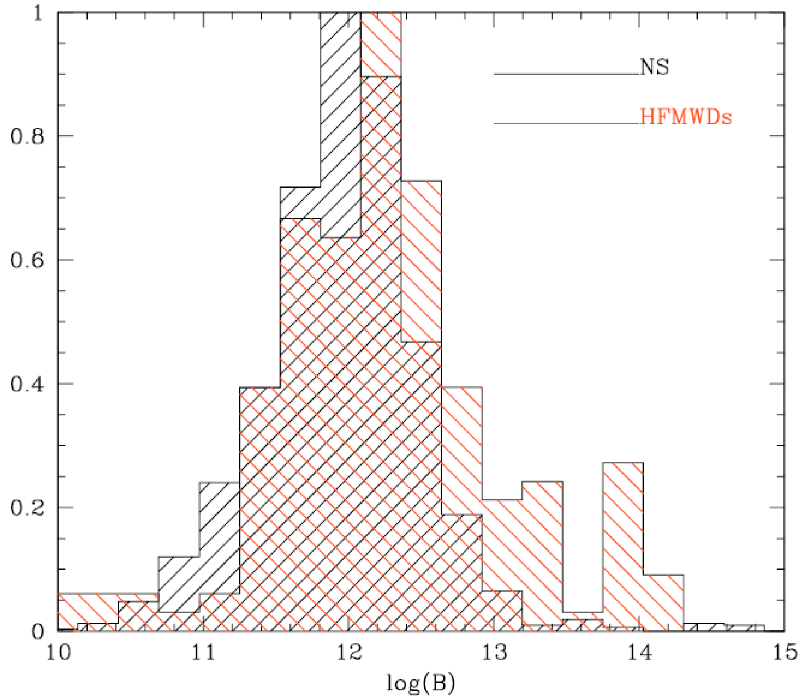
$\longrightarrow$ B (NS) $\sim 10^{11} - 10^{15}$ G

A strong case can therefore be made for a fossil origin of fields at least in the **medium to high field** end of the field distributions

Field comparison in compact stars



Field comparison in compact stars



Recent developments

Population synthesis calculations of highly magnetic white dwarfs have demonstrated that

- the field distribution
- the higher than average mass
- the incidence of magnetism

can **all** be explained if their fields are of **fossil origin** from the main sequence with the progenitors being

- the chemically peculiar magnetic Ap and Bp stars
- a subset of B stars with lower fields (10 -100 G) below the current limit of detectability (Wickramasinghe & Ferrario 2005)

Percentage distribution of Ap/Bp stars (currently observed)

Johnson (2004)

At spectral type F0 and earlier stars have radiative envelopes and 10% are strongly magnetic exhibiting large scale dipolar-type fields - possibly of fossil origin.

Highest ordered field for NS progenitor on MS: Theta Orion C (spectral type O4-O6: 1,100 G - Donati et al. 2002)

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TIFF (Uncompressed) decompressor
are needed to see this picture.

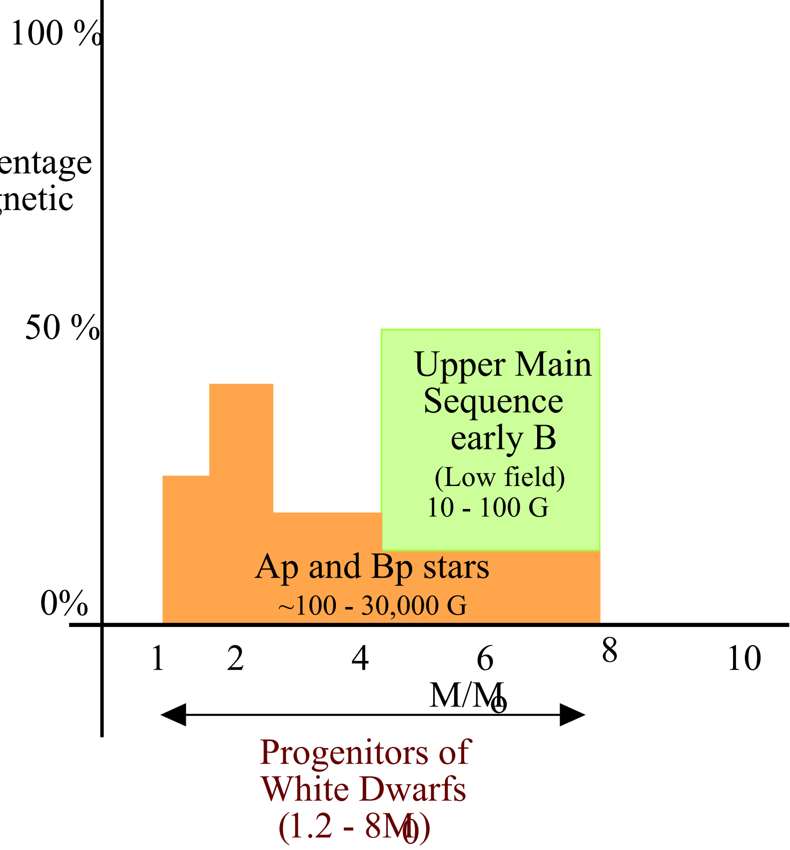
Convective
Envelopes

O8 B2 B8 A5 F0
G0
$23M_O$ $9M_O$ $3.8M_O$ $2M_O$ $1.6M_O$

Magnetism on Main Sequence (theoretical prediction)

- 50% magnetism in B-type stars required to explain higher than average mass of HFMWDs (Wickramasinghe & Ferrario 2005).

- Fossil origin also explains the observed field distribution of HFMWDs

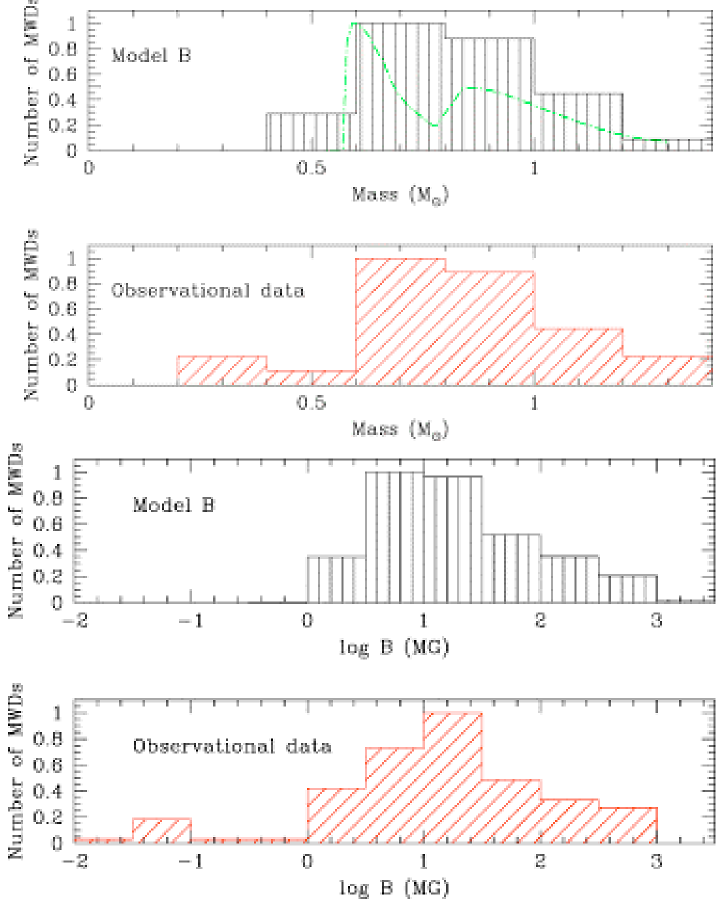


Results of population synthesis model for White Dwarfs

Mass distribution of MWDs

Field distribution of MWDs

(Wickramasinghe & Ferrario 2005)



Birth magnetic flux

For the modelling of the white dwarf and neutron star populations, we assume that the fields of the progenitor stars are determined by the magnetic flux that is entrapped in the star as it starts its MS evolution. Time scale for accretion of matter exceeds the time-scale of pre-main sequence contraction for $M > 2\ M_0$. The more massive stars can therefore continue to accrete mass (and magnetic flux) **after** they have developed a radiative envelope (Tout, Livio &Bonnell 1999).

Furthermore, stars with ($M > 10\ M_0$) - progenitors of the neutron stars - **do not go through a fully convective Hayashi phase** during which magnetic flux may be dissipated. A fossil origin of fields is therefore even more plausible for such stars. Thus assuming that they form from a constant density cloud:

$$\text{Magnetic flux } \Phi \propto B_{ISM} M^{2/3}$$

(Tout, Wickramasinghe & Ferrario 2004)

Population Synthesis Model for Neutron Stars

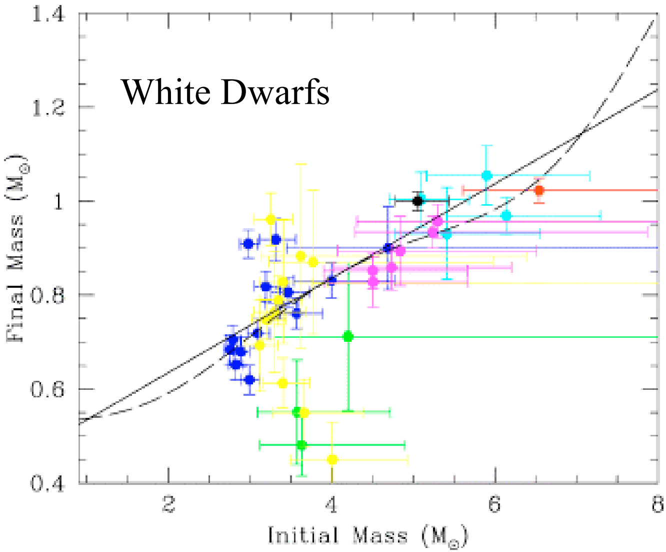
• Constant star formation rate (Boissier & Prantzos 1999) as a function of galactic radius, and a Saltpeter initial mass function.

• We specify an initial - final mass relationship for NS (Timms, Woosley & Weaver 1996), and move the stars in the galactic potential of Kuijken & Gilmore (1989) assuming the kick velocity distribution of Lorimer et al. (1997).

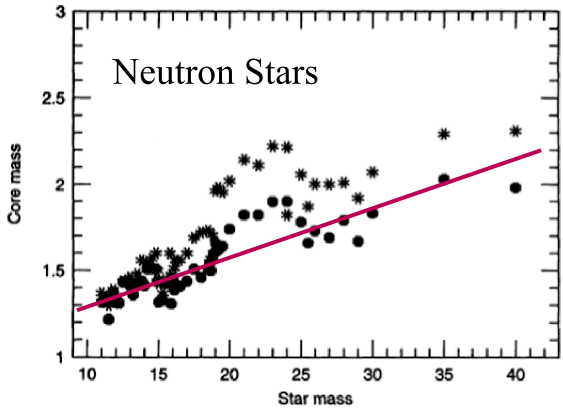
• Mean magnetic flux on the MS satisfies: $\Phi_m \propto M^{2/3}$ (Tout et al. 2004) and the flux is distributed as a Gaussian in the logarithm about this mean with dispersion $\sigma_{\log \Phi_m}$

• We assume that the birth period depends on the birth magnetic field, and parametrise this relationship as $P_0 = aB + b$

The initial-final mass relationship (input)



Open cluster data: Pleiades, NGC2516, M35, Praesepe, Hyades, NGC3532, M37, Sirius
(Ferrario et al. 2005)



Filled circles: iron core masses
Open stars: iron core + O-burning shell
(Timms, Woosley & Weaver 1996)

Magnetic field and initial period distribution (input)

- We used a gaussian distribution in the logarithm of the magnetic flux

$$\log \phi_m = 25.1 + \frac{2}{3}\log\left(\frac{M_i}{M_0}\right) \quad \text{with} \quad \sigma_{\log \phi_m} = 0.5 \quad \Rightarrow B_{NS} = \frac{\phi}{\pi R_{NS}^{\ 2}}$$

Where R_{NS} is given by the mass-radius relationship of Douchin & Haensel (2001).

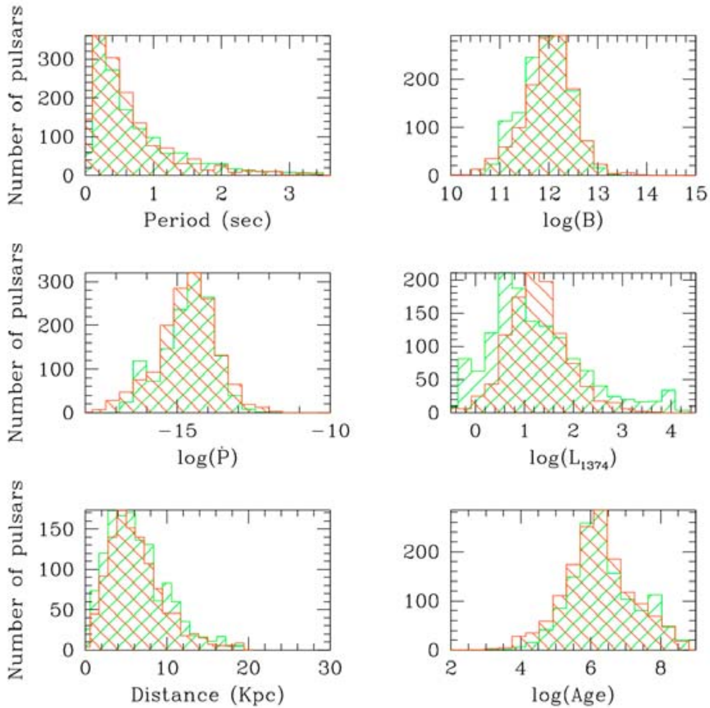
- We used the mean Birth Period - Magnetic Field relationship

$$P_0(\text{sec}) = a\left(\frac{B}{10^{12}}\right) + b \quad \text{with} \;\; a = 0.01 \text{ and } b = 0.15$$

and distributed the birth period about this mean using a gaussian.

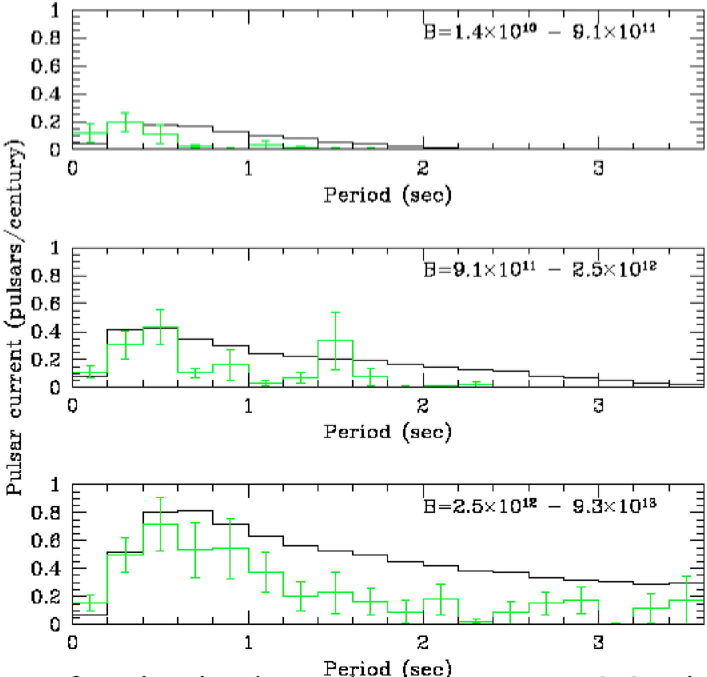
- We compare our theoretical predictions with the ~800 pulsars from the Parkes MBS (Manchester et al. 2001).

Model predictions and observations (preliminary results)



Data in red, model in green (Ferrario & Wickramasinghe, 2005, in preparation)

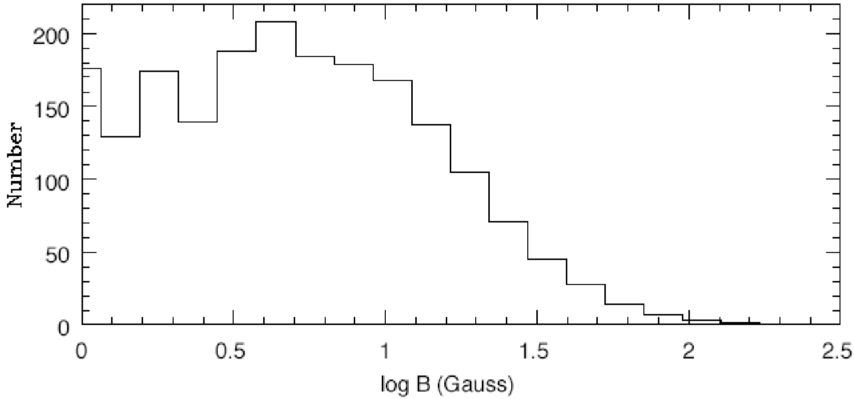
Model prediction for pulsar current (preliminary results)



Data (in green) from Vranesevic et al. (2004) Model (in black) from Ferrario & Wickramasinghe (2005, in preparation)

Clear evidence for rise in the pulsar current at 0.2 s in the HF and MF bins. These indicate a field dependent birth period.

Inferred magnetic field distribution on Main Sequence



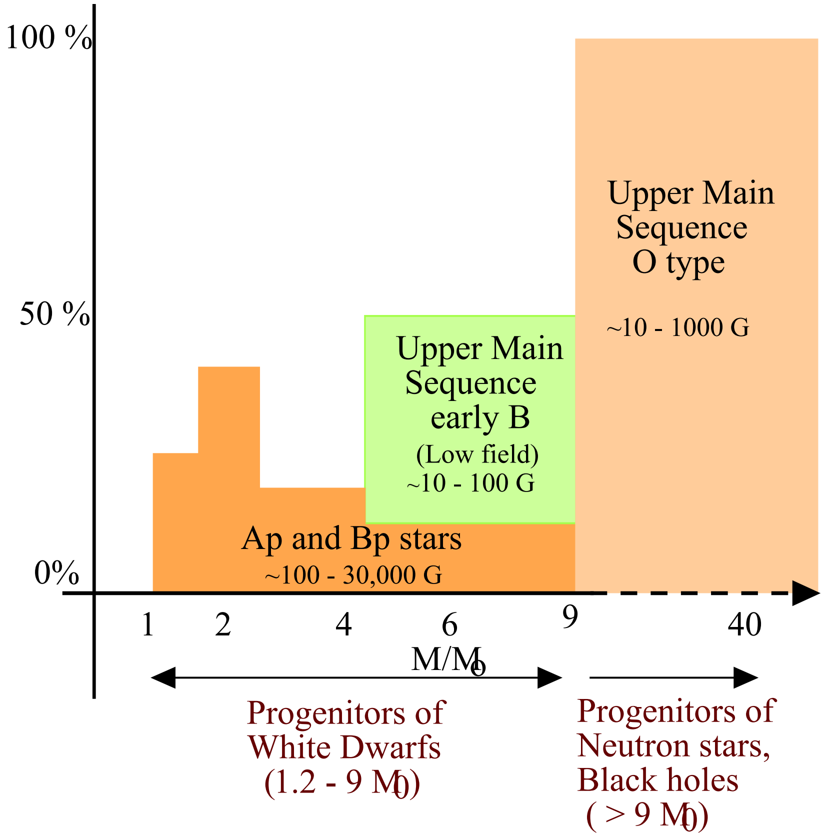
• Surface magnetic fields below ~ 200 Gauss are currently not directly observable.

• Indirect evidence for fields from Chandra observations of wind variability in massive hot stars (e.g. Waldron & Cassinelli 2001, Wade 2001)

Main Sequence Field Distribution

- required for fossil origin of White Dwarf and Neutron star fields

• Magnetars from the high mass high field end of distribution



Conclusions

• A fossil origin for the fields provides a natural explanation for the wide range of fields observed in neutron stars and magnetic white dwarfs in terms of different initial conditions in the star forming region.

• In the case of the HFMWDs, the distribution of magnetic fields required for the progenitor stars to explain the observed incidence, and field distribution is generally consistent with what is observed for the chemically peculiar Ap and Bp stars, but requires also a significant fraction of early B stars to be magnetic at a level below current detectability (<100 G).

• We have shown that with a similar model, we can also explain the observed incidence and field distribution of magnetism in neutron stars. For the neutron stars, the progenitors (mainly O stars) must be magnetic with mean fields at a level well below current polarimetric detectability.

• The pulsar currents show that the birth spin period depends on the magnetic field, with the higher field objects being preferentially born as slower rotators. The presence of a fossil magnetic field must facilitate the outward transport of angular momentum during stellar evolution to the compact star phase.

• The birthrate that we calculate is consistent with current estimates of the star formation rate as a function of the galacto-centric radius.

• On the fossil field hypothesis of Tout, Wickramasinghe, Ferrario (2004), the higher field neutron stars originate preferentially from higher mass progenitors, and so we would expect **the high field neutron stars (such as the magnetars) also to be more massive** - as it is observed for the high field magnetic white dwarfs.