Milliseccond Pulsars
P-P-Dot Diagram (Again)

- A rotating neutron star lies at a high voltage relative to infinity.
- If the voltage is too low, no pulsar: **DEATH LINE**

\[ \dot{E} = I \Omega \dot{\Omega} = -4\pi \dot{P} P^{-3} \]
\[ \dot{\phi} \sim \frac{\Omega^2 R^3 B_p}{2c^2} \]
\[ 4 \times 10^{20} \dot{P}^{1/2} P^{-3/2} V \]
How to get a millisecond pulsar?

- A normal pulsar will spin down due to dipole radiation and join the pulsar graveyard.
- To become a millisecond pulsar,
  - The neutron star must be spun up to a millisecond period
A Clue

- Many (but not all) millisecond pulsars are in binaries.
- Accretion can spin up a neutron star.
- A neutron star only has to accrete a little matter to get spun up to a millisecond period (Problem 1).
Spinning up the neutron star

Let’s assume that the disk can spin up the neutron star as long as some portion of it is rotating faster that the neutron star, so the critical frequency is

$$\Omega^2 r_A^3 = GM$$
Rebirth

- If the star accretes at the Eddington rate, the star ends up along the BIRTH LINE (Problem 2)
- $\tau = t_H$
But that’s not all.

- If a typical neutron star got spun up like this, it would end up with a one-second period (Why?)
But that’s not all.

- If a typical neutron star got spun up like this, it would end up with a one-second period (Why?)
- If the magnetic field started out at $\sim 10^{10}\text{G}$, then you would end up with a millisecond pulsar.
How to get a millisecond pulsar?

- A normal pulsar will spin down due to dipole radiation and join the pulsar graveyard.
- To become a millisecond pulsar,
  - The neutron star must be spun up to a millisecond period, and
  - The magnetic field must go away.
- There aren't enough neutron stars born with such low fields.
Magnetic Field and Plasma

- MHD: in magnetohydrodynamics with infinite conductivity the magnetic flux passing through a parcel of plasma is conserved: “Flux Freezing”

- A corollary is that the flux is conserved.

- So MHD can move the field but can’t destroy it.
First, move the field.

- Accreted material piles at the magnetic poles.
- Gravity makes the material spread out over the surface of the star, dragging the magnetic field with it.
- Like combing down a cowlick.
Second, get rid of the field.

- Once the accretion stops the field may pop up again.
- We have assume that the conductivity is infinite. Because it is finite, the magnetic field can move relative to the plasma and pop out.
- Also the resistance can dissipate the currents that anchor the field.
To summarize...

- People try to understand the formation of millisecond pulsars through binary evolution models and population synthesis.
- Only a small fraction of high-mass stars in binaries end up as millisecond pulsars.
An Alternative

Perhaps, we have misread the clue that millisecond pulsars are in binaries.

White dwarfs are often in binaries and could accrete material and collapse to form a neutron star.

\[
L \propto MR^2/P, \quad P_{WD} = P_{NS} \left( \frac{R_{WD}}{R_{NS}} \right)^2 \approx 1000\text{s}
\]

\[
\Phi \propto BR^2, \quad B_{WD} = B_{NS} \left( \frac{R_{NS}}{R_{WD}} \right)^2 \approx 10^4\text{G}
\]
Accretion Induced Collapse of a White Dwarf

- Accreting white dwarfs are thought to result in Type Ia supernovae or have novae which cause their mass to decrease.
- Another option is that they collapse to a NS.
- Could help to explain a potential excess of MSPs relative to LMXBs in GCs.
Many but not all millisecond pulsars are in binaries. How do the rest dump their partners?

- Lose them through interactions with other stars (important in GCs)
- Vaporize them

The Black Widow Pulsar
Where are the MSPs?
MSPs are hard to find.

- The pulse of a millisecond pulsar is on for a large fraction of the pulsar period.
- The dispersion of the plasma requires a narrow bandwidth to find the pulsar at all.
Where to find millisecond pulsars?

- Need lots of binary stars.
- LMXB epoch can last a billion years.
- Do you want to dump the companion?
Collapsed Globular Clusters

- Hubble and Chandra images of the globular cluster 47 Tucanae
What can MSPs tell us? (1)

- Binary pulsars: tests of general relativity
  - The orbit of the Hulse-Taylor binary pulsar shrinks by 3.2 mm each orbit due to the emission of gravitational radiation.
  - In relativistic binaries the mass of both stars can be determined accurately.
What can MSPs tell us? (2)

Two binary pulsars

- Pulsars in binaries give hints to the formation of millisecond pulsars.

- The MSP has a lower mass companion in a circular orbit.
What can MSPs tell us? (3)
What can MSPs tell us? (4)

- Millisecond pulsars are as stable as Earthbound atomic clocks but they are across the Galaxy.
- Passing gravitational waves will change the arrival times mimicking timing noise.
- Many MSPs form a timing array.
What can MSPs tell us? (5)

- How fast can a neutron star spin?
  - The neutron star equation of state
    - Smaller neutron stars have larger maximal spin rates.
    - The quest for the submillisecond pulsar.
  - The viscosity of neutron-star interiors
    - If the interiors of neutron stars were inviscid, a rotating neutron star would emit gravitational radiation through the r-mode instability.