What remains ?

Type I SN – nothing

– thought to be detonation of white dwarf in close binary system

Type II SN – neutron star or black hole, depending on mass of remnant core.

Mass depends on mass loss both before SN and during explosion

Neutron star

Supported by neutron degeneracy pressure

at same ρ, this is less than e^- degeneracy pressure by $\frac{m_n}{m_e} \simeq 2000$.

Q

What are some possible explanations for an astronomical object which emits in the radio &/or optical

- regularly
- with periods ranging from 1ms to several seconds ?

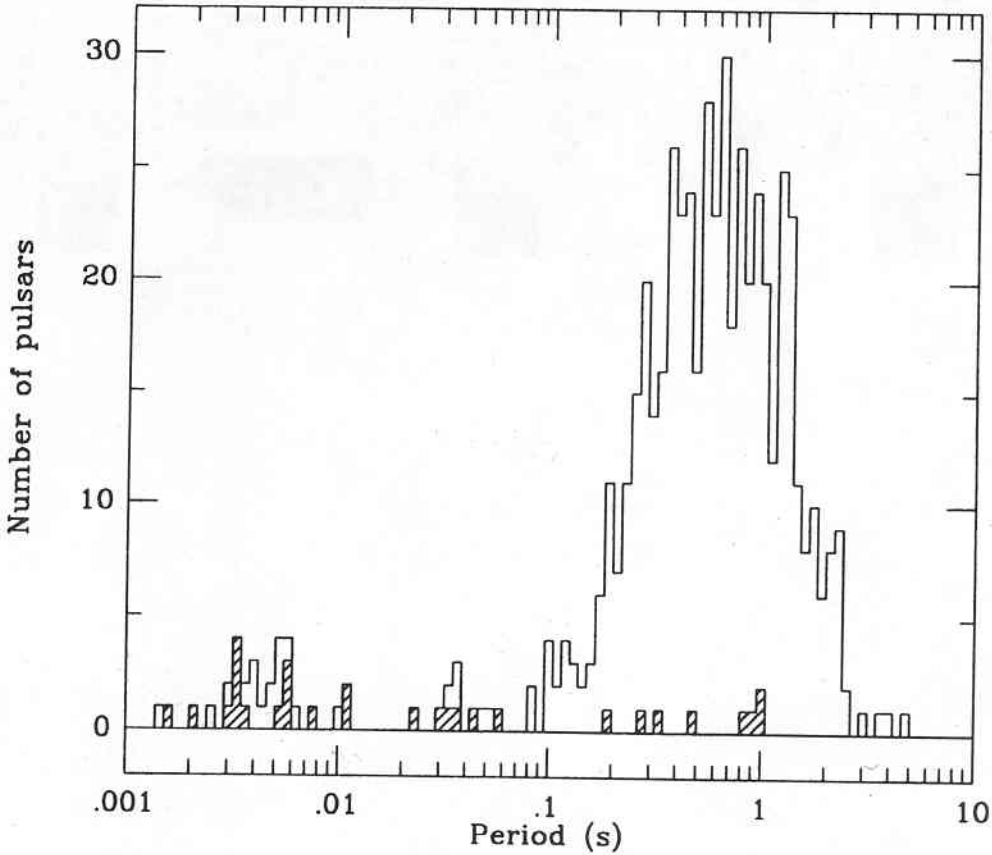

Figure 15.14 The distribution of periods for 558 pulsars. Binary pulsars are indicated by the shaded area, and the millisecond pulsars are on the left. The average period is about 0.8 s. (Figure from Taylor, Manchester, and Lyne, *Ap. J. Suppl.*, *88*, 529, 1993.)

Neutron stars

- Exceedingly collapsed : 1 solar mass inside a radius of ~15 km

- All neutrons : $p + e^- \rightarrow n + \nu$

- Possibility of very high rotation if angular momentum is conserved during collapse

$$J = I\omega$$

$$= \frac{2}{5} M R^2 \omega \quad \text{for a sphere}$$

Assume J conserved, no M lost :

$$R_\odot^2 \omega_\odot = R_{ns}^2 \omega_{ns}$$

$$\frac{\omega_{ns}}{\omega_\odot} = \frac{R_\odot^2}{R_{ns}^2} = \frac{(7\times10^{10})^2}{(1.5\times10^6)^2} = 2\times10^9$$

$$\omega = \frac{2\pi}{T} \Rightarrow \frac{T_{ns}}{T_\odot} = \frac{R_{ns}^2}{R_\odot^2} = \frac{1}{2\times10^9}$$

$$T_{ns} = \frac{30\times24\times3600}{2\times10^9} = 1.3\times10^{-3}\ s$$

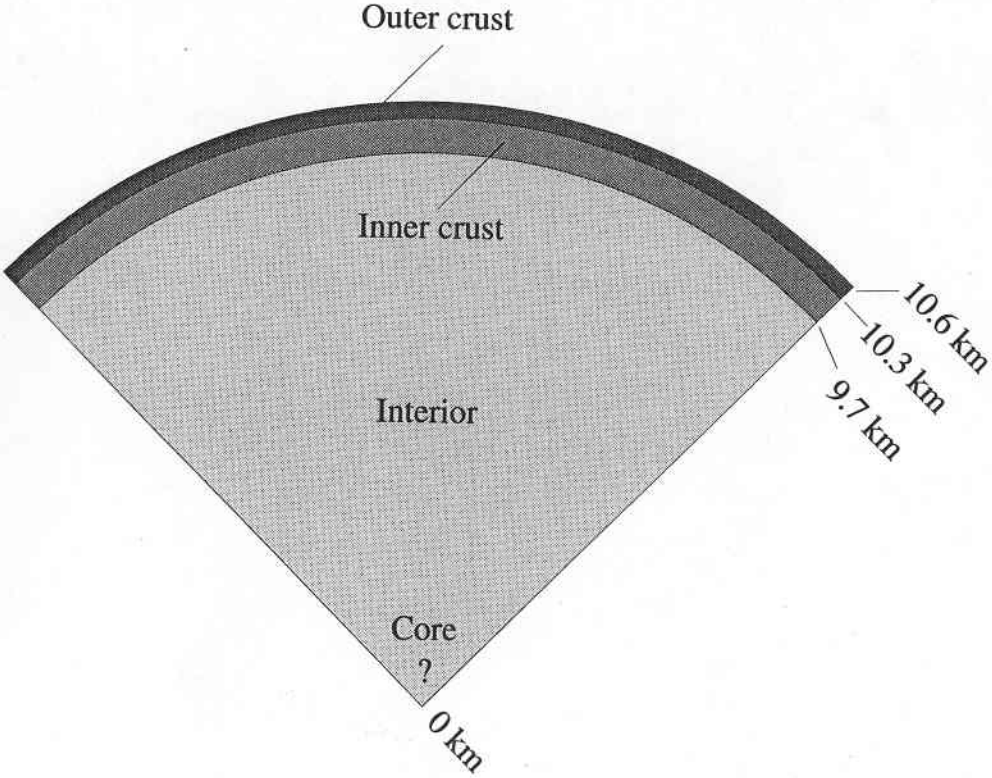

Figure 15.11 A 1.4 $M_\odot$ neutron star model.

see Carroll & Ostlie p603,4

Structure of neutron star

(poorly understood)
(weird .....)

10^{57} neutrons .....

density greater than atomic nucleus ....

- Outer crust : heavy nuclei & relativistic degenerate electrons ; nuclei become heavier towards bottom edge where we have neutron drip
- Inner crust : lattice of heavy nuclei (like Kr), free neutrons & rel. degenerate electrons
- Interior : mostly superfluid neutrons

[• core : may have a solid core of pions, etc]

Neutron stars : magnetic fields

Faraday's law $\oint E \cdot dl = -\frac{d\phi_B}{dt}$

ϕ_B is magnetic flux thru surface

E is electric field induced by change in flux

If there is some conductivity, a current will flow to oppose the change in magnetic flux.

So flux thru surface remains constant : "frozen in"

Flux $\propto$ magnetic field B

$\propto$ surface area

So $BR^2 = \text{constant}$.

So magnetic field $\propto \frac{1}{R^2}$

Start with magnetic field of Sun

Collapse to neutron star

$\Rightarrow$

magnetic field $\sim 2 \times 10^9 \times$ solar.

Gravitational acceleration on a neutron star:

$\sim 10^{11}$ times grav. acceleration on surface of Earth

$\boxed{Q}$ Could a spaceship land safely on the surface of a neutron star?

$\boxed{A}$ Tidal forces are extremely strong:

$$\frac{dg}{dr} = -2\frac{GM}{R^3}$$

$$= -1 \times 10^8 \text{ cm/s}^2/\text{cm}$$

for typical star

So spaceship, astronaut, etc would be pulled apart by tidal forces.

Escape speed from a neutron star can be $\sim 0.8c$!

(we need general relativity to calc. forces etc in such a strong grav. field)

Pulsar emission mechanism

Like the Earth, a pulsar's magnetic field is not aligned exactly with its rotation axis.

Emission mechanism not fully understood, but likely related to neutron star's strong magnetic field.

Charged particles spiral around magnetic field lines

→ synchrotron radiation

Pulsar works like a lighthouse: we only get a pulse when the beam sweeps past us.

Q If the 'lighthouse' theory for pulsar emission is correct, will there be pulsars we can never detect? Why?

A It depends on the opening angle of the beam of radiation, but yes ..... a given pulsar will be detected by only 20% of potential observers.

Q We find that all pulsars are slowing down (period increasing) What might cause this?
(think of Earth-Moon system)

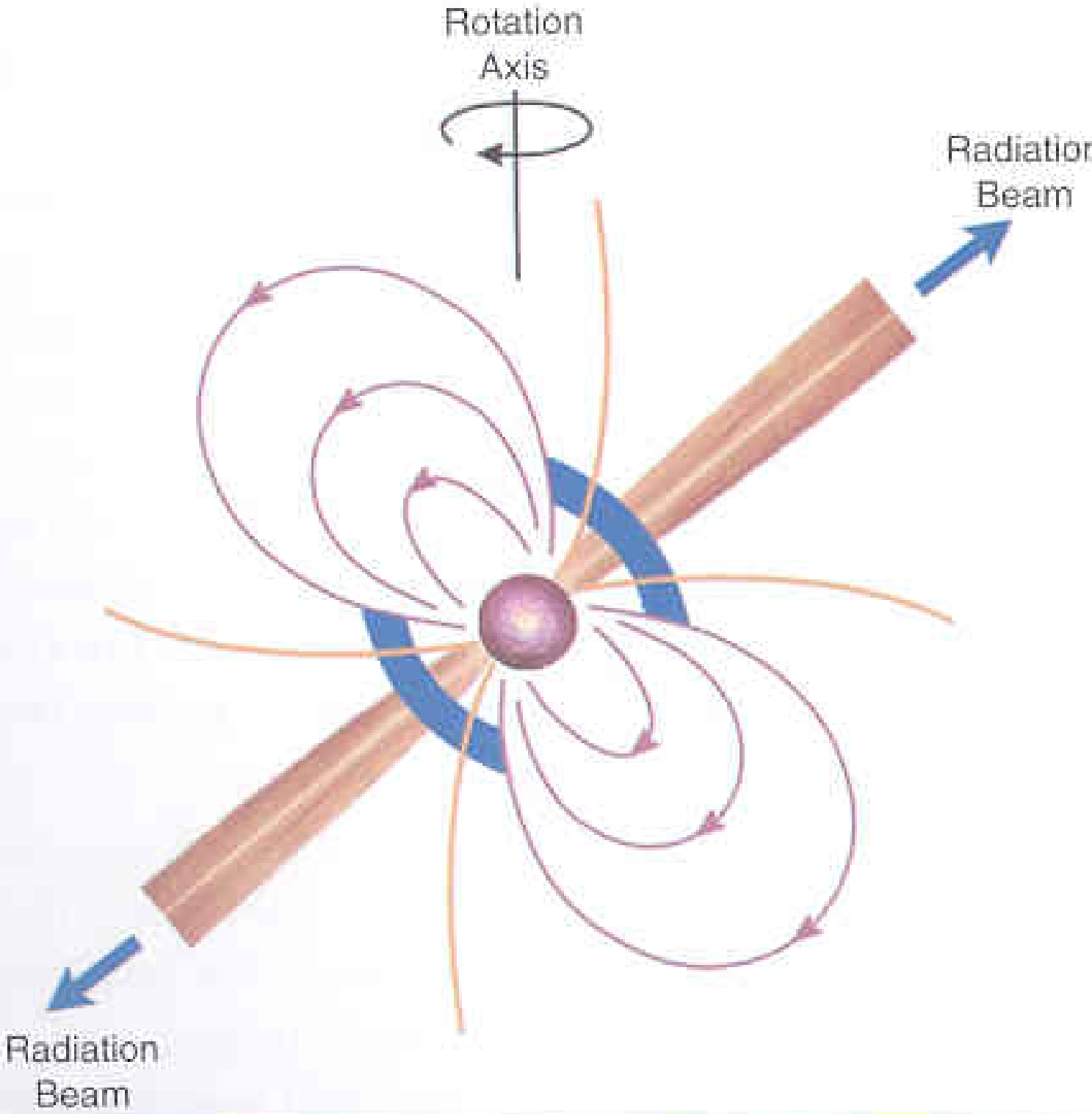

Fig 11.10. Role of a magnetic field in a pulsar emission mechanism. If the magnetic axis is not aligned with the rotation axis, then the magnetic axis can act like a searchlight beam. [NRAO/AUI/NSF]

A In a similar way to the Earth–Moon tidal evolution, the pulsar's energy output comes at the expense of its rotation, which slows.

The Crab nebula

Supernova remnant, SN observed in 1054.

We detect both radio & optical pulses (radio are much stronger as most synchrotron radiation comes out in radio)

Fig 11.11. The Crab Pulsar (NP 0532) in visible light. Each frame shows an image of the field at equally spaced points in the cycle. When the pulsar is on, it is the brightest object in the field. When it is off, we cannot see it. [NOAO/AURA/NSF]

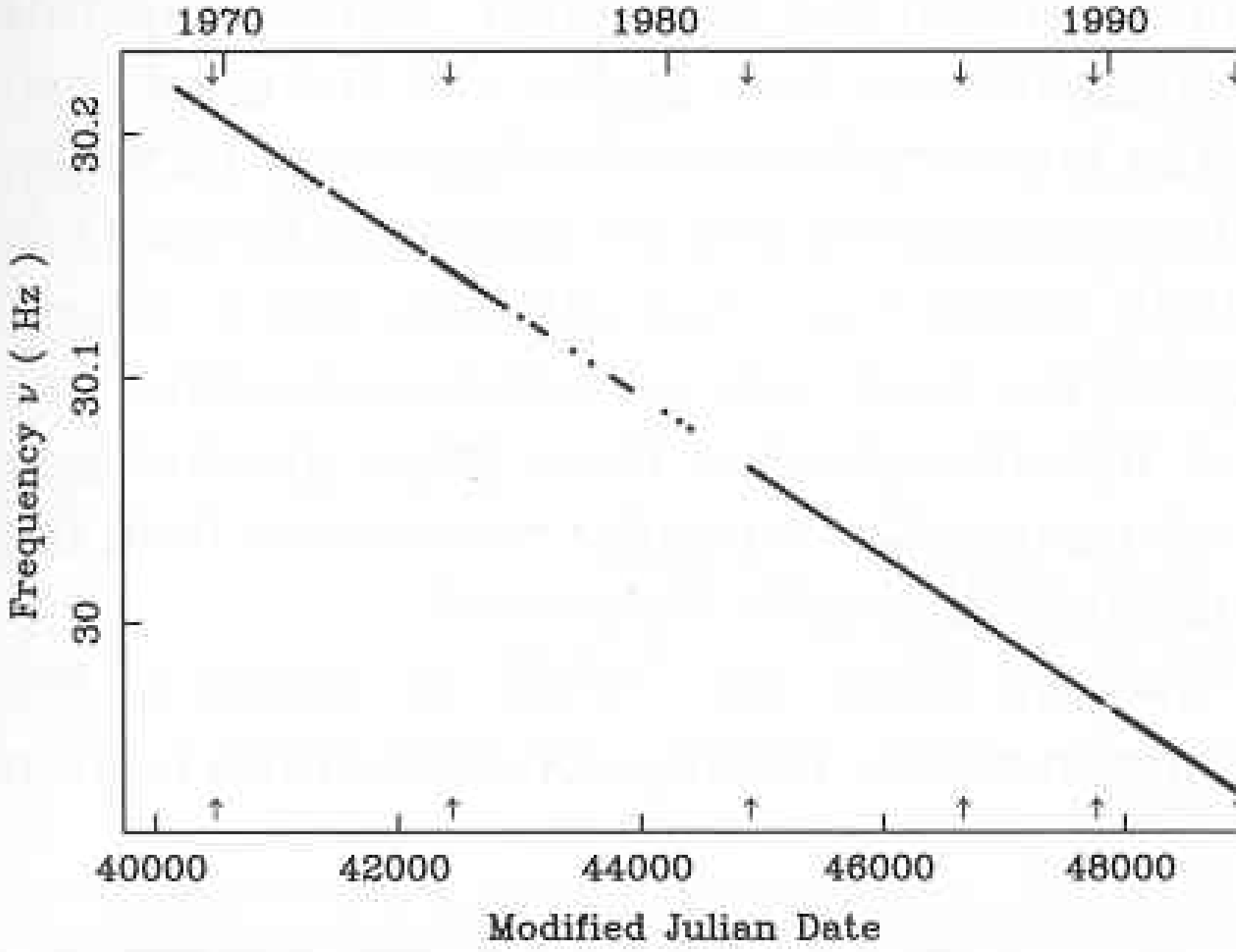

Fig 11.12. Period changes for the Crab pulsar. The general slowdown is clear. Glitches, brief period increases, are indicate by the locations of the arrows. [Michael Kramer/Lyne & Smith Pulsar Astronomy, 2nd edn, CUP]