SUPERNOVAE

These occur when a massive star explodes (or when two white dwarf stars merge)

For a short time, their brightness rivals that of their host galaxy

If we can use these as distance indicators, we can see out a significant fraction of the visible universe

SUPERNOVAE (type II)

Final stage of evolution of massive stars

* note mass loss can be large before this *

Burning of successively higher Z nuclei

Onion - like structure

Core contracts after each fuel exhausted,
heats up, next fuel ignites ......
until Fe is reached

* Fusion reactions after Fe peak <u>need</u> energy & do not release it *

Fe core collapses

$^{56}Fe + \gamma \rightarrow 13\,^{4}He + 4n$ (uses energy)

- Fe nuclei disintegrate to α particles & neutrons (takes energy, further collapses)

- High densities allow reverse β decay

$$e^- + p \rightarrow n + \nu$$

(support from degenerate e^- removed)

(ν's carry away lots of energy)

- Core implodes (what good is electron degeneracy without electrons?)

- Pressure is eventually so great that core 'bounces'

o Neutrino pressure important! (usually, mean free path is more than a light year of lead)

- Outer layers of star are pushed outward & lost to ISM (interstellar medium)

- Enormous energy output, can rival total luminosity of galaxy

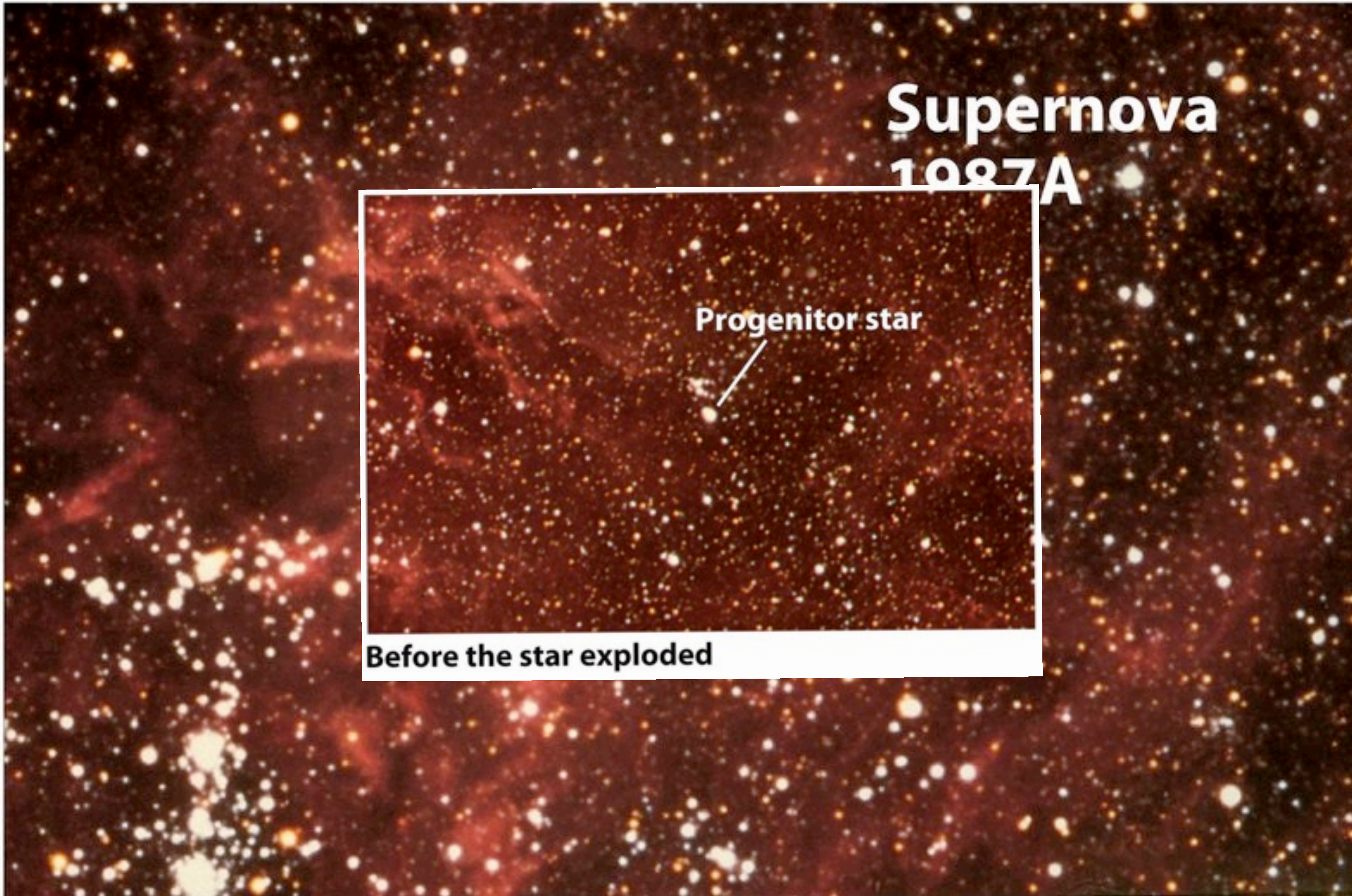
.... mostly in neutrinos

Explosion

- As a result of the energy deposited by neutrinos (and rotation and magnetic fields?), a shock wave moves out through the star ejecting everything external to the neutron star. In some cases – quite massive stars – the ejection may be inefficient, and matter may fall back forming a black hole. In some cases the outgoing shock may never form. When successful about 10^{51}erg is deposited in the ejecta giving them a speed of 1000's of km/s.

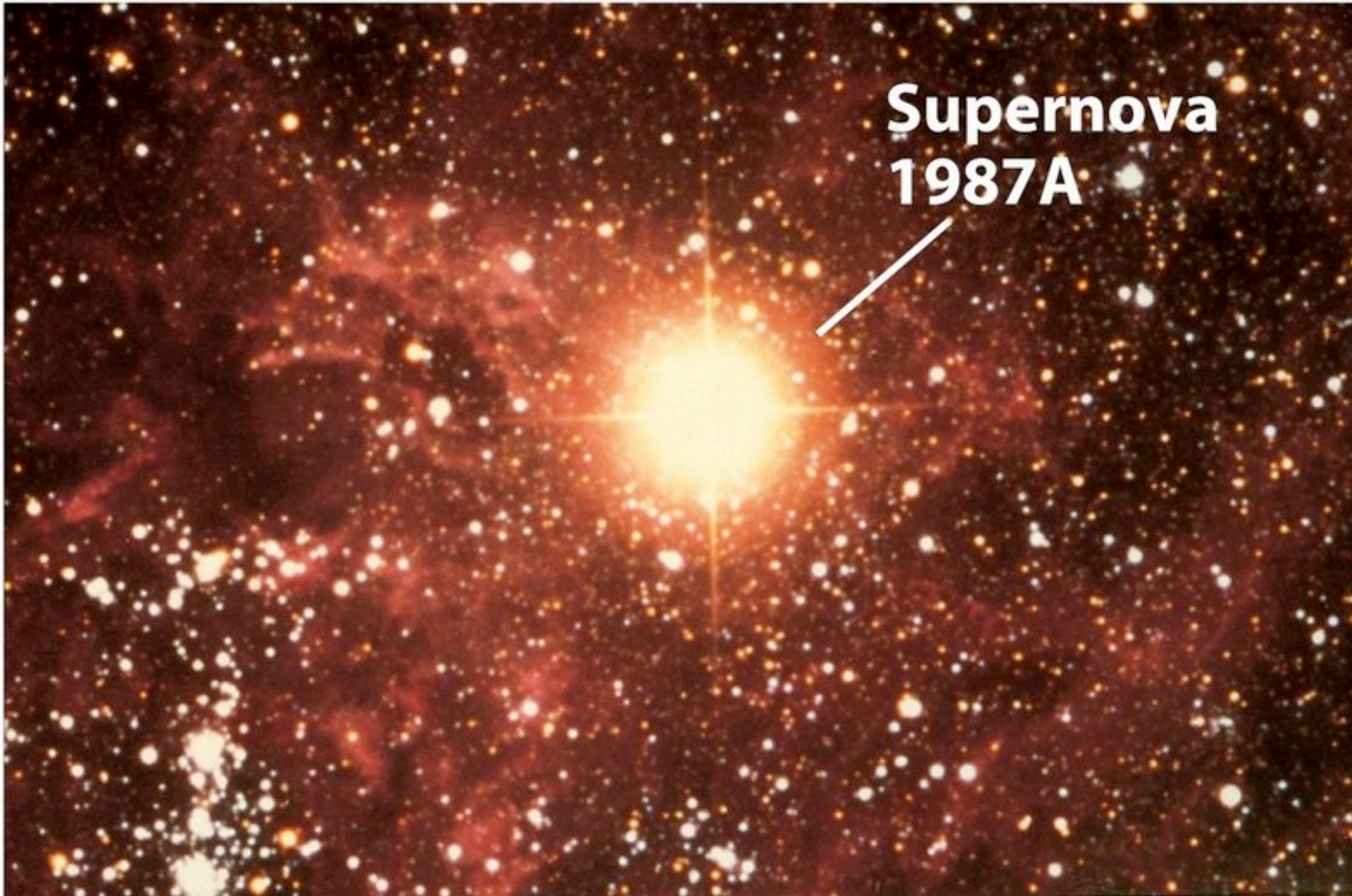
- All of the elements present outside the compact remnant are ejected, contributing to Galactic nucleosynthesis. Additonal elements are created in the explosion itself. One important species, ^{56}Ni, is created in the deepest layers to be ejected. This will later be important to the light curve as it decays to iron.

- The first optical indication that a supernova has happened is when the shock wave erupts from the surface.



Before the star exploded

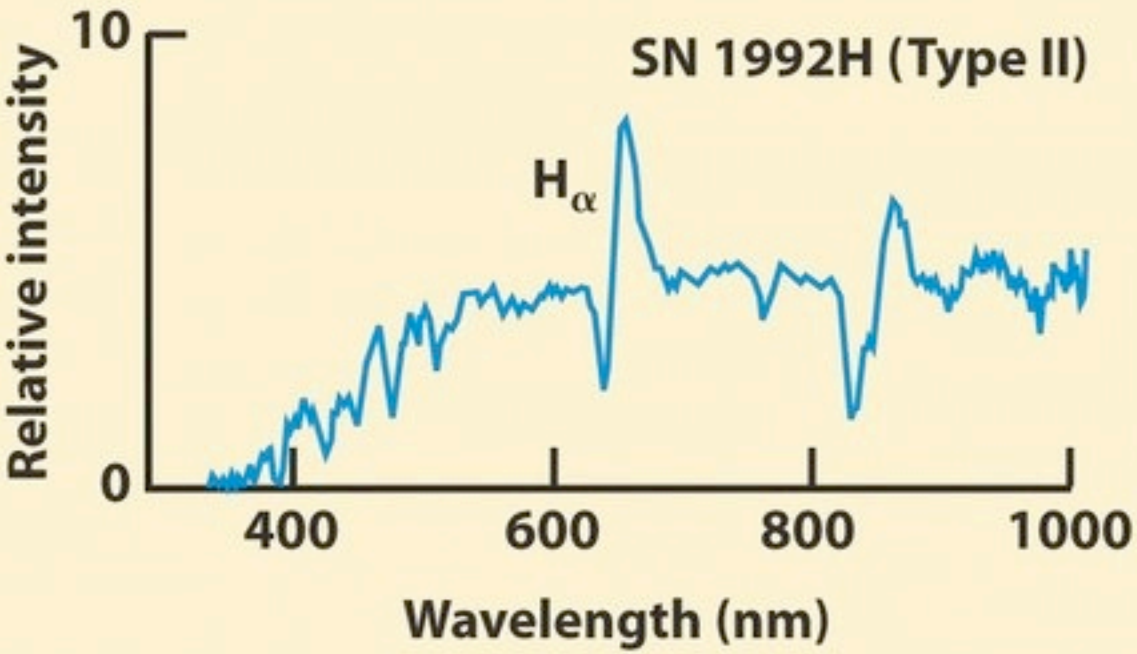
After the star exploded

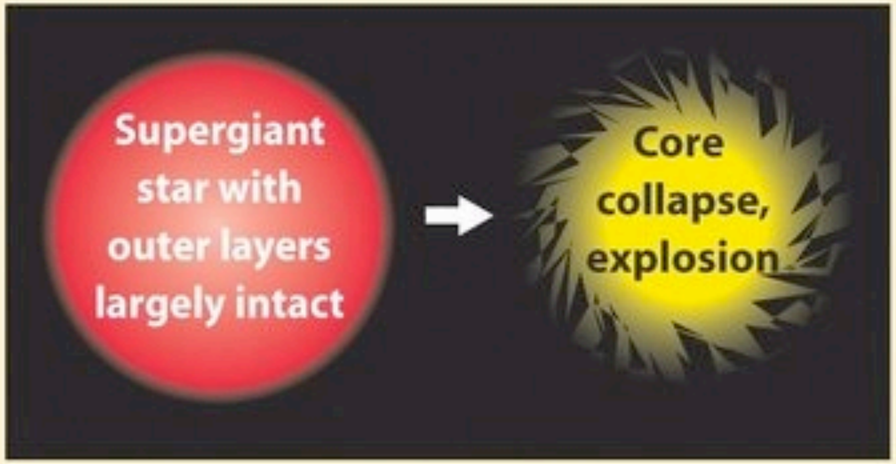


After the star exploded

(d) Type II supernova

- The spectrum has prominent hydrogen lines such as H_α.
- Produced by core collapse in a massive star whose outer layers were largely intact.





Supernovae (type II)

What causes the enormous light output ?

Radioactive decay of ^{56}Ni formed in explosion

$$^{56}_{28}Ni \rightarrow {}^{56}_{27}Co + e^{+} + \nu_e + \gamma$$

$$\downarrow$$

$$^{56}_{26}Fe + e^{+} + \nu_e + \gamma$$

$\boxed{Q}$ What is a test you could make | in on the sky & the lab of this statement ?

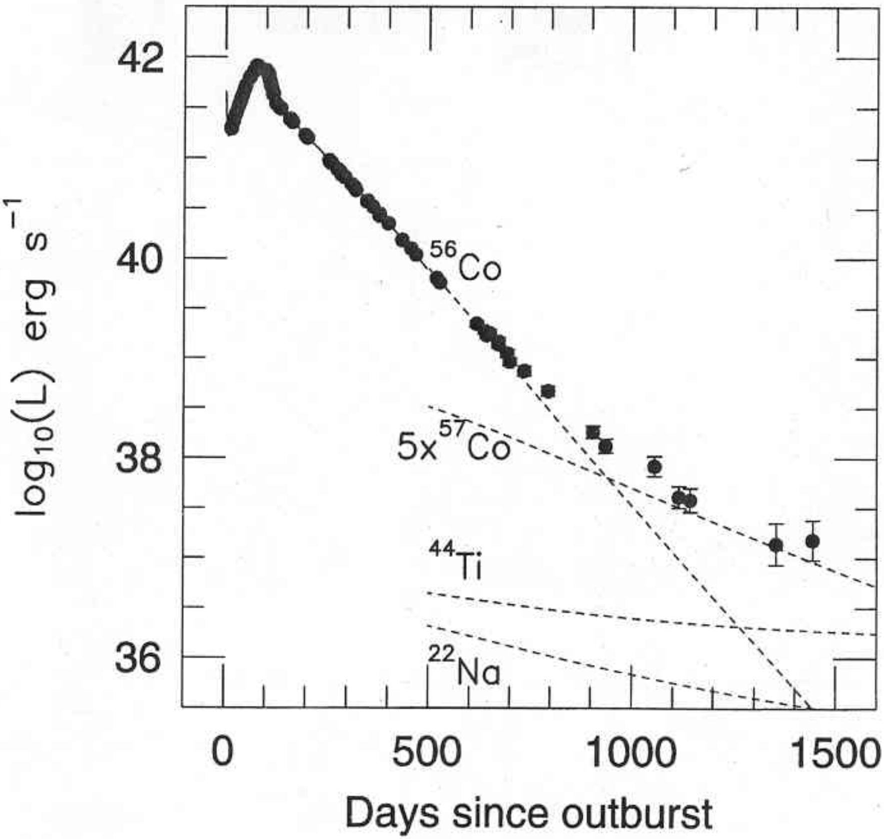


Figure 13.20 The bolometric light curve of SN 1987A through the first 1444 days after the explosion. The dashed lines show the contributions expected from the radioactive isotopes produced by the shock wave. The initial masses are estimated to be $^{56}_{28}$Ni (and later $^{56}_{27}$Co), 0.075 $M_\odot$; $^{57}_{27}$Co, 0.009 $M_\odot$ (five times the solar abundance); $^{44}_{22}$Ti, 1×10^{-4} $M_\odot$; and $^{22}_{11}$Na, 2×10^{-6} $M_\odot$. (Figure from Suntzeff et al., *Ap. J. Lett.*, *384*, L33, 1992.)

Take some ^{56}Ni and some ^{56}Co and watch it decay : measure its half life $t_{1/2}$

if no of nuclei of isotope reduce as

$$N(t) = N_0 e^{-\lambda t}$$

$t_{1/2}$ = amount of time for N_0 to reduce by 2

$$= \frac{\ln 2}{\lambda}$$

half life of ^{56}Ni = 6 days

^{56}Co = 77.7 days

SN 1987a light curve agrees

Nucleosynthesis in supernovae

The disintegration of Fe nuclei during core collapse produces many neutrons

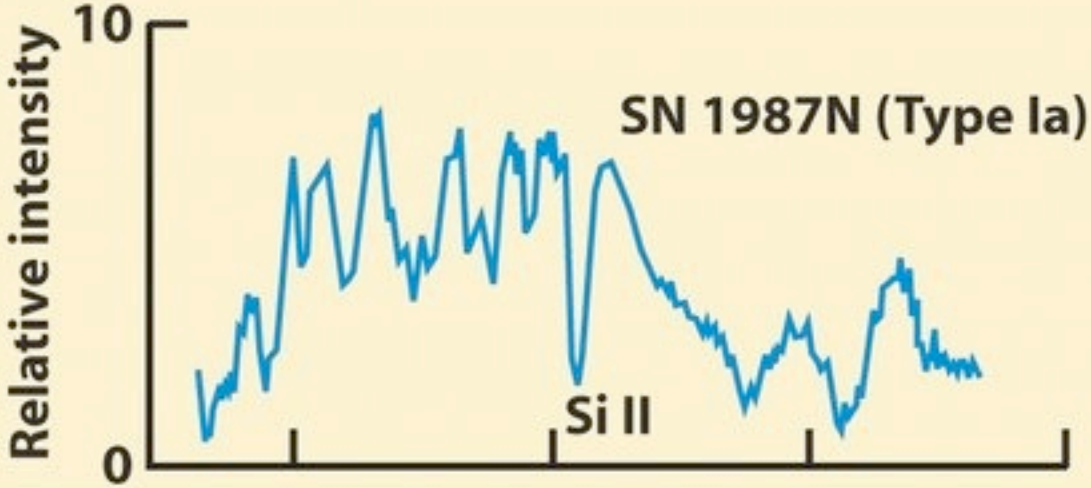
Many more are produced in reverse β decay

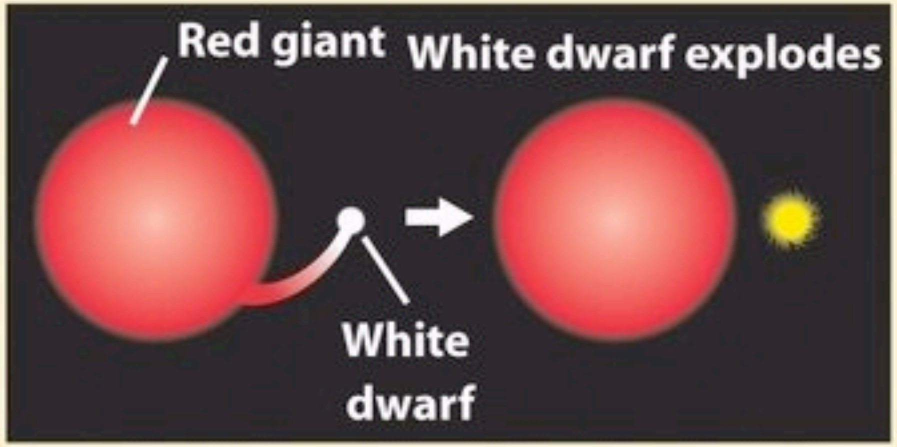
This large flux of neutrons is exactly what is needed to form elements heavier than Fe

(why?)

(a) Type Ia supernova

- The spectrum has no hydrogen or helium lines, but does have a strong absorption line of ionized silicon (Si II).
- Produced by runaway carbon fusion in a white dwarf in a close binary system (the ionized silicon is a by-product of carbon fusion).





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.

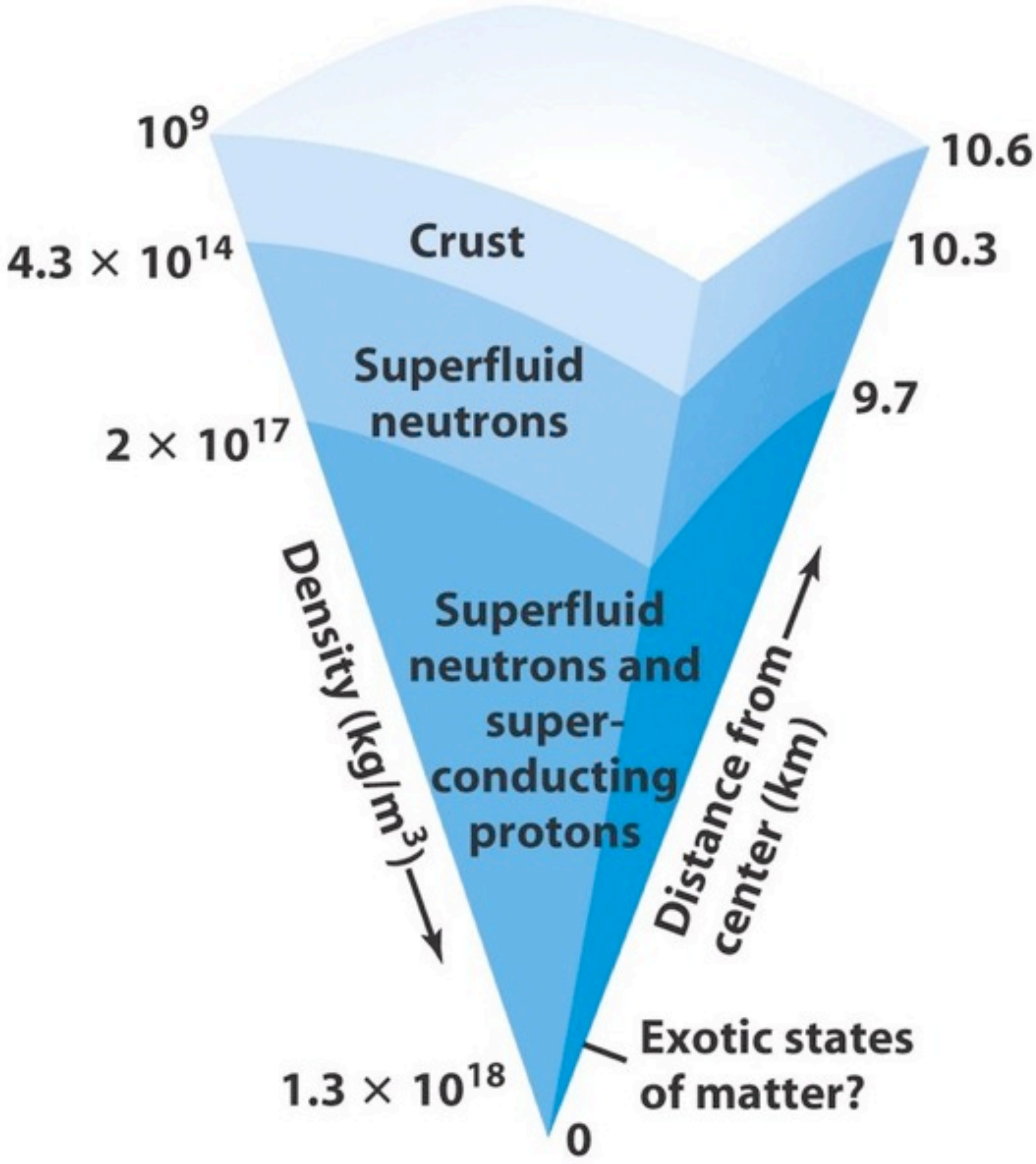
Mass depends on mass loss both before SN and during explosion

Neutron star

Supported by neutron degeneracy pressure

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

Manhattan, meet neutron star



10^9
4.3×10^{14}
2×10^{17}
1.3×10^{18}
Crust
Superfluid neutrons
Superfluid neutrons and super-conducting protons
Density (kg/m^3)
10.6
10.3
9.7
0
Distance from center (km)
Exotic states of matter?

see Carroll & Ostlie p603,4

Structure of neutron star

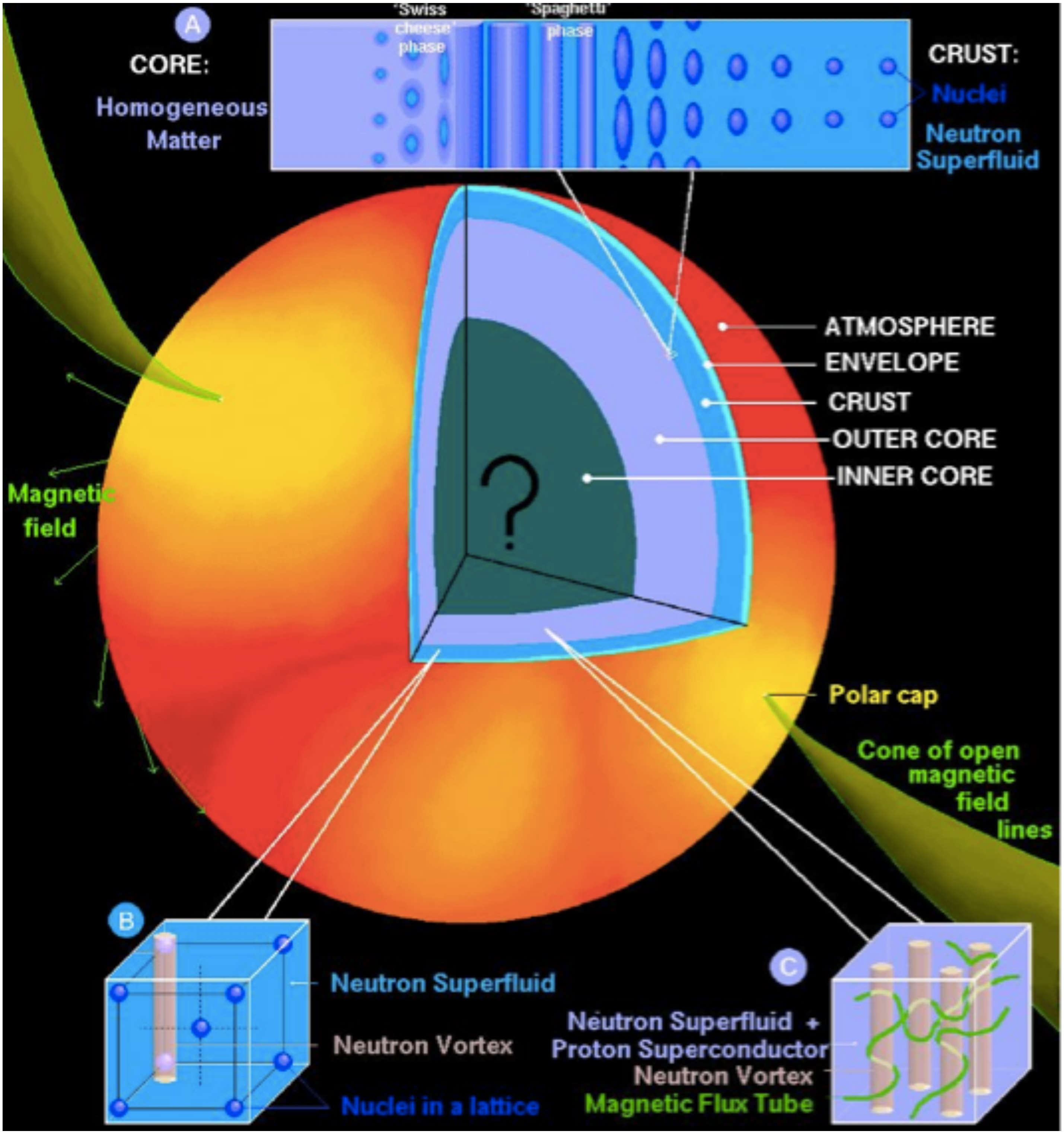
(poorly understood)
(weird .....)

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 star radius ~ 10 km



Cole Miller UMD

NEUTRON STAR ALMOST A BLACK HOLE

The Schwarzschild radius for a 1.4 solar mass black hole is

$$R_S = \frac{2GM}{c^2}$$

or 4 km. Neutron stars are close to being black holes. Their escape speed is about 1/3 c and their binding energy is about 20% mc^2

The average density of a neutron star, $3M/4pR^3$, is ~ 10^{15} g cm^{-3}, greater than the density of an atomic nucleus

Stan Woosley notes

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 ?

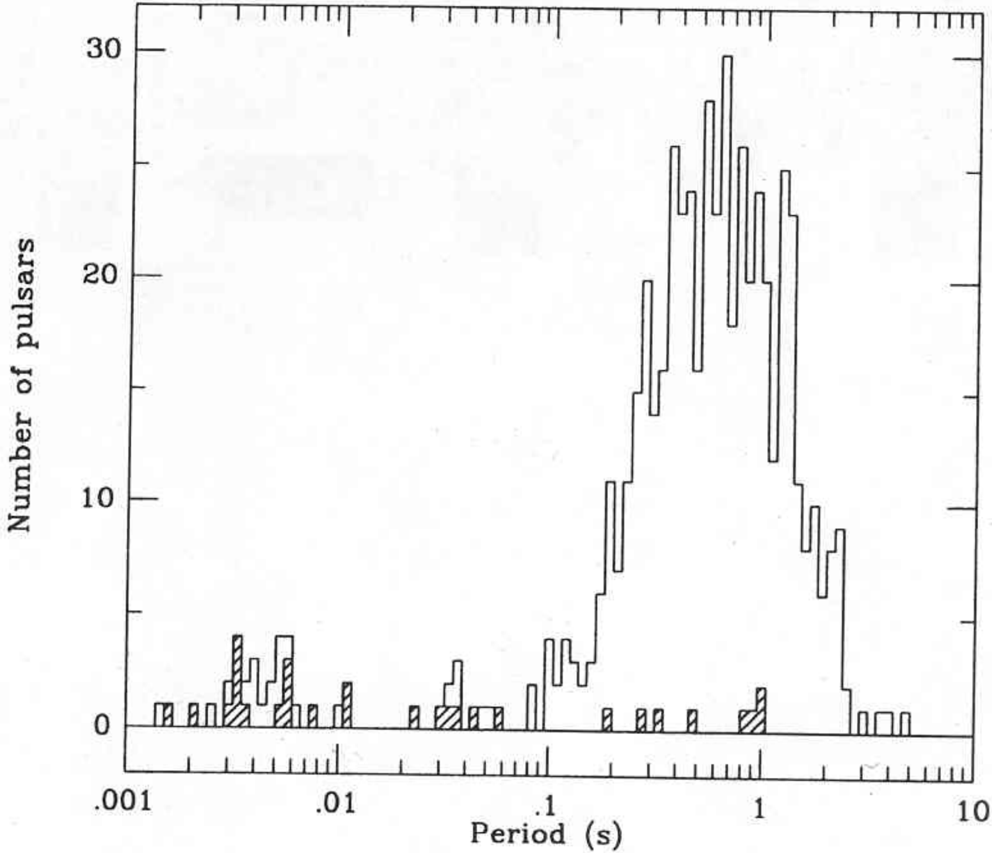


Figure 15.14 The distribution of periods for 558 pulsars. Binary pulsars are indicated by the shaded area, and the millisecond pulsars are on the left. The average period is about 0.8 s. (Figure from Taylor, Manchester, and Lyne, *Ap. J. Suppl.*, *88*, 529, 1993.)

Neutron stars

- Exceedingly collapsed : 1 solar mass inside
  10
  a radius of ~ 15 km

Almost
- 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 :

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

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

$$\omega = \frac{2\pi}{T} \Rightarrow \frac{T_{ns}}{T_\odot} = \frac{R_{ns}^2}{R_\odot^2} = \cancel{30 \times} \frac{1}{2 \times 10^9}$$

$$T_{ns} = \frac{30 \times 24 \times 3600}{2 \times 10^9} = 1.3 \times 10^{-3}\ \text{s}$$

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 = 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 :

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

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

for typical star

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

Pulsar emission mechanism

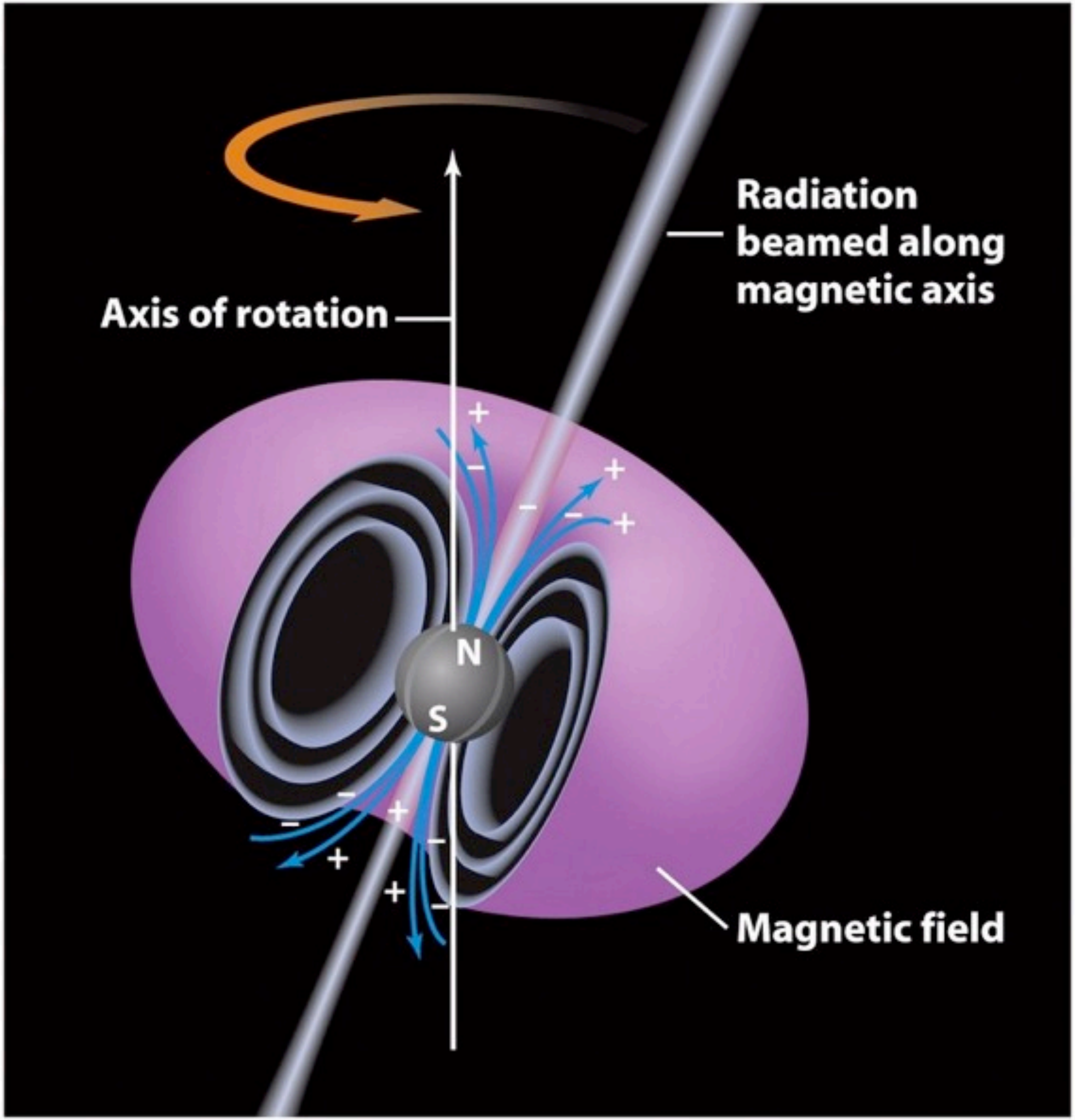
Like the Earth, a pulsar's magnetic field is not aligned exactly with its rotation axis.

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

Charged particles spiral around magnetic field lines

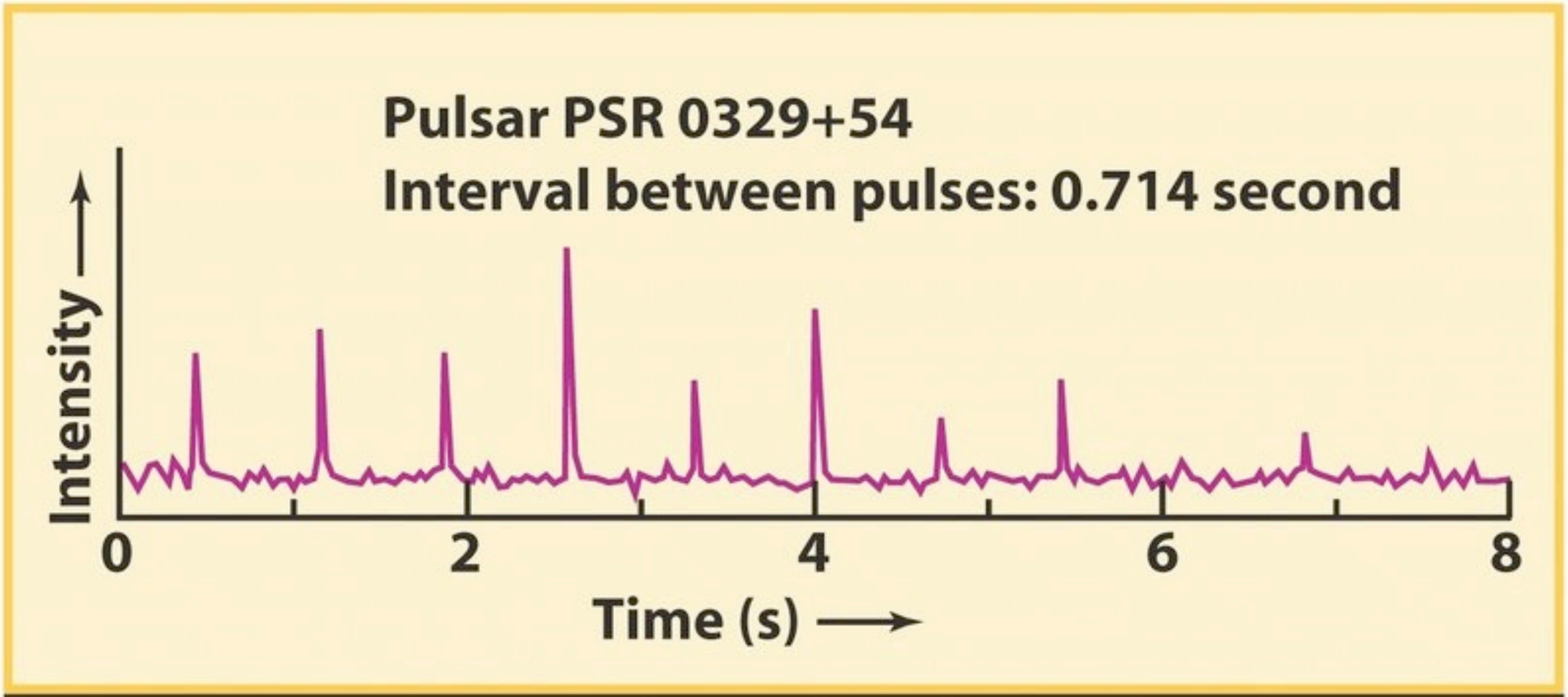
→ synchrotron radiation

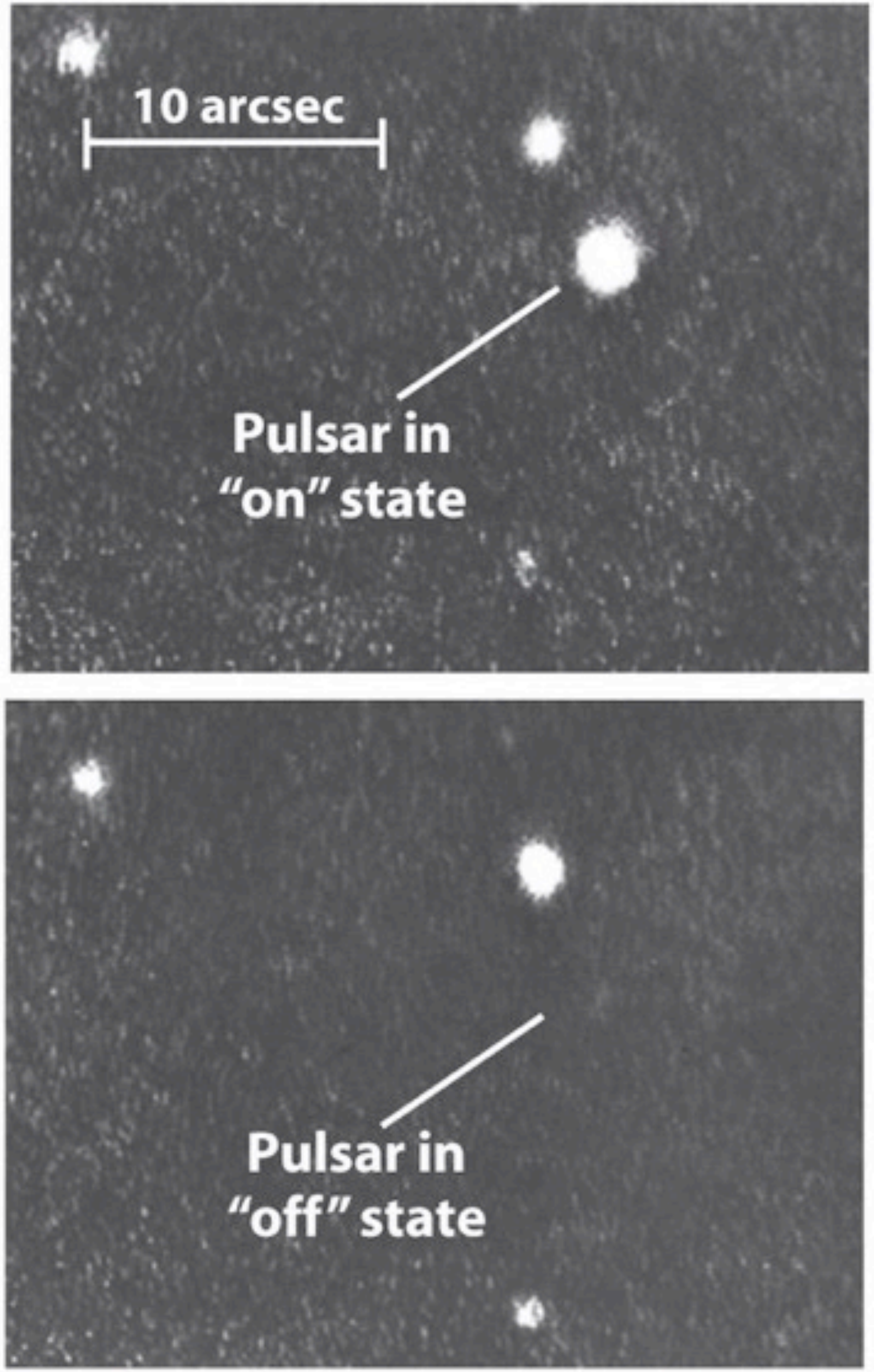
Pulsar works like a lighthouse: we only get a pulse when the beam sweeps past us.



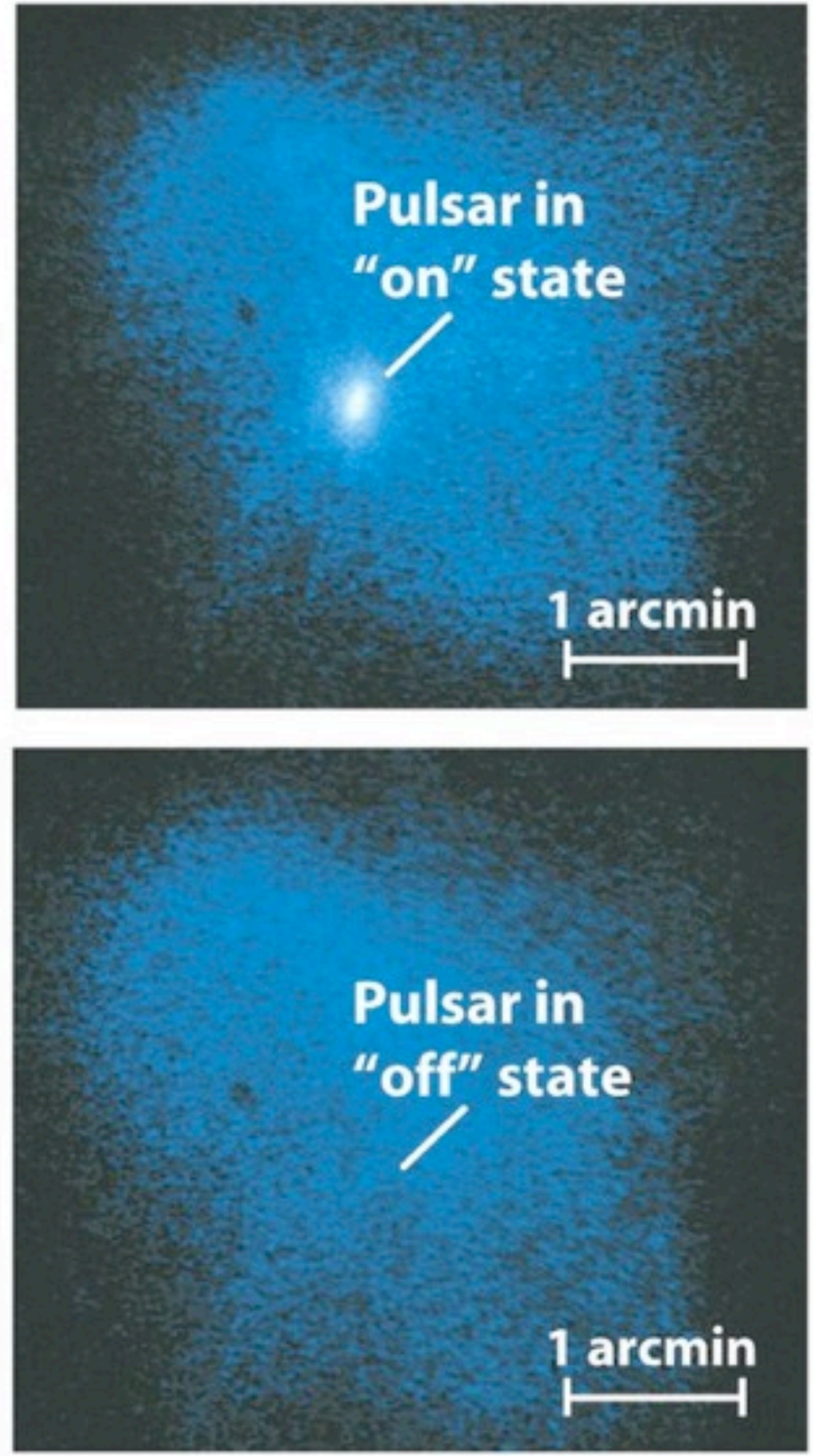
Radiation beamed along magnetic axis
Axis of rotation
N
S
Magnetic field

http://www.jb.man.ac.uk/~pulsar/Education/Sounds/sounds.html





The Crab pulsar in visible light



The Crab pulsar in X rays

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)

$\boxed{A}$ 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]

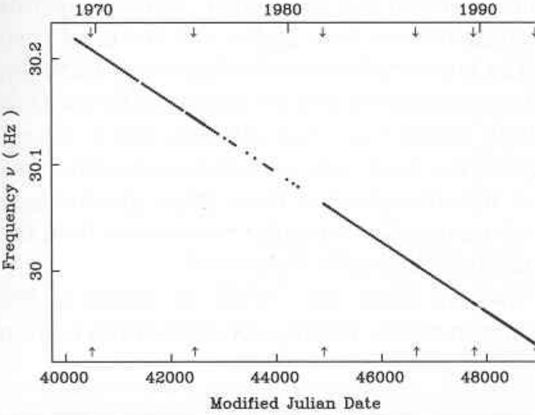


Fig 11.12. Period changes for the Crab pulsar. The general slowdown is clear. Glitches, brief period increases, are indicate by the locations of the arrows. [Michael Kramer/Lyne & Smith Pulsar Astronomy, 2nd edn, CUP]