Plan of Lecture
Neutron Stars and Pulsars

Evaluation forms.

The discovery and nature of pulsars.

The structure of neutron stars.

Accreting neutron stars.

The Discovery of Pulsars

Cambridge, England, 1967.

Jocelyn Bell, graduate student.

Doing thesis on quasars.

Wired a scintillator array.

Looked at chart recorder traces.

After several miles of charts, she noticed some recurring "scruff".

Put on high-speed recorder.

Regular pulses, every $1\frac{1}{3}$ seconds!

Clearly from an extraterrestrial source.

Little Green Men?

The Nature of Pulsars

Several other pulsars were discovered afterwards.

Periods 0.03-4 seconds (known then).

Very regular.

Period always increased slightly.

What could cause a regular signal?

Rotation, pulsation, orbits.

For all of these, a fundamental minimum period is:

$P_{\rm min} \sim \sqrt{R^3/GM} \sim 1/\sqrt{G\rho}$.

For $P = 1/30$ s (Crab pulsar), this implies a minimum density of $\rho_{\rm min} > 10^{10}$ g cm^{-3}!

Denser than white dwarf...

Neutron Stars

We'll return to pulsars in a bit, but now we need to think of an object denser than white dwarfs. Black holes are, but they have no surface.

In 1932, Chadwick discovered the neutron.

Completes atoms: e^-, p, n.

Like electrons, neutrons are fermions.

White dwarfs are held up by electron degeneracy; could some stars be held up by neutron degeneracy?

1934: Baade and Zwicky suggest that supernovae may be the creation of neutron stars.

Little interest for 30 years, because how could you detect something so small?

Neutron Star Basics

"Standard" values for a neutron star are:

Mass about $1.4\,M_{\odot}$.

Radius about 10 km.

At this density (few$\times 10^{14}$ g cm^{-3}!!), all six billion people on Earth would fit in a teaspoon!

Surface gravity few$\times 10^{11}$ times Earth's!

Spin rate can be several hundred times per second.

Like white dwarfs, isolated neutron stars don't undergo fusion.

At birth in supernova, $\sim 10^{12}$ K; after a few thousand years, still a few million Kelvin!

Neutron Star Magnetic Fields

A typical young neutron star has a surface magnetic field $\sim 10^{11}$ G to maybe 10^{15} G.

Largest in universe.

Earth: 0.5 G at poles.

At these strengths, atoms are completely different.

Skinny cylinders.

Also shorter than zero-field atom.

Much smaller volume means that the energies are a lot larger.

At 10^{12} G, ground state energy is 12 times larger than in zero field!

Atoms may arrange in long linear chains.

Common Misconceptions

Question: why do neutron stars rotate rapidly and have strong magnetic fields?

Book's answer: if you took the Sun and squeezed it to a 10 km radius, it would rotate rapidly and have a strong magnetic field!

But the Sun won't become a neutron star.

Iron core of massive star.

Some fallback.

The core might not be rotating rapidly enough to produce the observed spin.

The magnetic field is probably generated during the collapse, not frozen in.

The origins of spin, magnetic field are open!

Neutron Star Structure

At the very surface, you have atoms, stretched by magnetic field.

Down lower (0.1-1 meter!), nuclei in sea of degenerate electrons.

At higher densities, energy of electrons gets larger.

Squeeze into protons, get neutrons.

Nuclei are richer in neutrons.

At a density of $\rho > 4 \times 10^{11}$ g cm^{-3}, free neutrons can exist outside nucleus.

Called "neutron drip"!

At higher densities, clumps, rods, or plates of nuclei in sea of neutrons.

Pasta-antipasta sequence!

Neutron Star Structure, Part 2

In the core of a neutron star, you have mainly neutrons (~90%), plus p and e^-.

Central density is few$\times 10^{14}$ g cm^{-3}.

Protons are superconducting.

Neutrons are superfluid.

At the very core, could have other weird forms of matter.

Quark matter?

"Condensates"?

Odd elementary particles?

Of great interest to nuclear physicists!

Return to Pulsars

What NS mechanism could work?

Pulsation, orbit, rotation.

Pulsation: period $\sim 1/\sqrt{G\rho}$.

<1 **ms for NS; too short!**

NS-NS orbit has reasonable periods.

However, orbit "stirs" spacetime, losing energy, so the orbit gets closer with time.

Period would *decrease*.

Rotation can occur with the right range of periods.

Spinning magnet loses energy.

Period would *increase*.

Best model: rotating neutron star.

The Lighthouse Model

But why do we see the pulsar behavior?

Although the basic idea was proposed *before* pulsars, many details still uncertain!

Key: radio waves etc. emitted *continuously*, in a beam.

Star rotates.

Beam sweeps past us.

We see "pulsations".

Radio emission is very strong; not thermal.

Why is emission produced in first place?

Probably e^-e^+ cascade.

Coherent emission.

Accreting Neutron Stars

Like WD, NS can accrete matter from a companion.

But NS is much more compact:

Gas hits surface at $\sim 0.6c$!!

Releases $\sim 0.2Mc^2$.

More efficient than nuclear fusion!

Heats surface to $\sim 10^{6-7}$ K.

Emission in X-rays.

At peak, accreting neutron stars can emit ~50,000 times Sun's luminosity.

What About Magnetic Fields?

Magnetic fields play an important role in NS accretion.

Consider the Earth: charged particles from Sun hit our field, are directed towards poles.

Result: aurorae!

For NS, this funneling creates bright spots. These rotate with the star.

Accretion-powered pulsars!

Normal: rotation-powered.

In addition, field "grabs" matter far away from the star.

There, gas rotates slowly.

Slows down spin of star!

Millisecond Pulsars

Not all NS have $\sim 10^{12}$ G fields...

In 1983, a 1.5 ms pulsar was discovered!

Magnetic field $\sim 10^9$ G.

What's going on? Think about matter accreting onto a low-field NS.

Field only grabs nearby matter.

Gas is orbiting fast there.

Star is spun up!

This is the "recycling" scenario.

We see them *after* accretion.

Low fields means not much spindown.

Best clocks in universe.

Lose 1 sec in 10^{12} yr!

X-ray Bursts

Just as with WD, a NS in a binary can pull over hydrogen and helium.

The H and He piles up on the surface.

When enough has accumulated, fusion can begin at the base.

Temperature increases.

Fusion rate increases.

As with WD, get a runaway. But this one is more violent...

Gravity stronger than fusion.

Most of layer stays on surface.

Everything consumed in seconds.

World's nuclear stockpile, per postage stamp, in ten seconds.

Summary

Neutron stars are arguably the coolest objects in the universe :).

Very dense, supported by degenerate n.

Pulsars are rotating NS.

Accreting NS are bright emitters of X-rays.

Challenge: what is the slowest pulsar known?