Neutron Stars and Black Holes
Formation of Neutron Stars

A supernova explosion of a $M > 8 \, M_{\text{Sun}}$ star blows away its outer layers.

The central core will collapse into a compact object of ~ a few $M_{\text{Sun}}$.

Compact objects more massive than the Chandrasekhar Limit (1.4 $M_{\text{Sun}}$) collapse beyond the formation of a white dwarf.

$\Rightarrow$ Pressure becomes so high that electrons and protons combine to form stable neutrons throughout the object:

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

$\Rightarrow$ Neutron Star
Properties of Neutron Stars

Typical size: $R \sim 10 \text{ km}$
Mass: $M \sim 1.4 - 3 \, M_{\text{sun}}$
Density: $r \sim 10^{14} \text{ g/cm}^3$

⇒ a piece of neutron star matter of the size of a sugar cube has a mass of ~ 100 million tonnes

A neutron star (more than the mass of the Sun) would comfortably fit within, e.g., Washington, D.C.
Discovery of Pulsars

Angular momentum conservation

- Collapsing stellar core spins up to periods of ~ a few milliseconds

Magnetic fields are amplified up to $B \sim 10^9 - 10^{15}$ Gauss
(up to $10^{12}$ times the average magnetic field of the sun)

- Rapidly pulsed (optical and radio) emission from some objects interpreted as spin period of neutron stars
Pulsars / Neutron Stars

Neutron star surface has a temperature of ~ 1 million °K

Wien’s displacement law,

$$\lambda_{\text{max}} = \frac{3,000,000 \text{ nm}}{T[\text{K}]}$$

gives a maximum wavelength of $$\lambda_{\text{max}} = 3 \text{ nm}$$, which corresponds to X-rays
Pulsar Winds

Pulsars are emitting winds and jets of highly energetic particles.

These winds carry away about 99.9% of the energy released from the slowing-down of the pulsar’s rotation.
Lighthouse Model of Pulsars

A Pulsar’s magnetic field has a dipole structure, just like Earth’s.

Radiation is emitted mostly along the magnetic poles.

As in the case of Earth, the magnetic axis of a neutron star could be inclined to its rotational axis.

The rotation of the neutron star will sweep its beams around like beams from a lighthouse.

While a beam points roughly toward Earth, we detect a pulse.

While neither beam is pointed toward us, we detect no energy.

Beams may not be as exactly symmetric as in this model.
Images of Pulsars and Other Neutron Stars

The Vela Pulsar moving through interstellar space

The Crab nebula and pulsar
The Crab Pulsar

Remnant of a supernova observed in A.D. 1054

Pulsar wind + jets
The Crab Pulsar (2)

Visual image

X-ray image
Light Curves of the Crab Pulsar

Pulsar pulse shapes can be quite different in different wavelength ranges (e.g., optical vs. X-rays)
Proper Motion of Neutron Stars

Some neutron stars are moving rapidly through interstellar space.

This might be a result of anisotropies/asymmetries during the supernova explosion which formed the neutron star.
Binary Pulsars

Some pulsars form binaries with other neutron stars (or black holes)

*Radial velocities* resulting from the orbital motion lengthen the pulsar period when the pulsar is moving away from Earth...

...and shorten the pulsar period when it is approaching Earth...
Neutron Stars in Binary Systems: X-ray Binaries

Example: Her X-1

- $2 \, M_{\text{sun}}$ (F-type) star

Star eclipses neutron star and accretion disk periodically

Orbital period: 1.7 days

Accretion disk material heats to several million °K → X-ray emission
Neutron Stars in Binary Systems: X-ray Binaries (2)

Neutron-star X-ray binaries are often found in star clusters where stars are crowded close together.
Some pulsars have planets orbiting around them. Just like in binary pulsars, this can be discovered through variations of the pulsar period. As the planets orbit around the pulsar, they cause it to wobble around, resulting in slight changes of the observed pulsar period.
Animation: Neutron Star
Just like white dwarfs (Chandrasekhar limit: $1.4 \, M_{\text{Sun}}$), there is a mass limit for neutron stars:

Neutron stars cannot exist with masses $> 3 \, M_{\text{Sun}}$

We know of no mechanism to halt the collapse of a compact object with $> 3 \, M_{\text{Sun}}$

It will collapse into a single point – a singularity:

⇒ a Black Hole
Escape Velocity

Velocity needed to escape Earth’s gravity from the surface: \( v_{\text{esc}} \approx 11.6 \text{ km/s} \)

Now, gravitational force decreases with distance (~ \( 1/d^2 \)) ➔
Starting out high above the surface ➔ lower escape velocity

If you could compress Earth to a smaller radius ➔ higher escape velocity from the surface
The Schwarzschild Radius

- There is a limiting radius where the escape velocity reaches the speed of light, \( c \):

\[
R_s = \frac{2GM}{c^2}
\]

\( G = \) Universal constant of gravity
\( M = \) Mass

\( R_s \) is called the Schwarzschild Radius
Schwarzschild Radius and Event Horizon

No object can travel faster than the speed of light

- Nothing (not even light) can escape from inside the Schwarzschild radius

- We have no way of finding out what’s happening inside the Schwarzschild radius

Event horizon
# Schwarzschild Radii

Table 14-1 | The Schwarzschild Radius

<table>
<thead>
<tr>
<th>Object</th>
<th>Mass ((M_\odot))</th>
<th>Radius</th>
</tr>
</thead>
<tbody>
<tr>
<td>Star</td>
<td>10</td>
<td>30 km</td>
</tr>
<tr>
<td>Star</td>
<td>3</td>
<td>9 km</td>
</tr>
<tr>
<td>Star</td>
<td>2</td>
<td>6 km</td>
</tr>
<tr>
<td>Sun</td>
<td>1</td>
<td>3 km</td>
</tr>
<tr>
<td>Earth</td>
<td>0.000003</td>
<td>0.9 cm</td>
</tr>
</tbody>
</table>
Animation: Schwarzschild Radius
General Relativity Effects Near Black Holes (1)

At a distance, the gravitational fields of a black hole and a star of the same mass are virtually identical.

At small distances, the much deeper gravitational potential will become noticeable.
General Relativity Effects Near Black Holes (2)

An astronaut descending down towards the event horizon of the BH will be stretched vertically (tidal effects) and squeezed laterally.

This effect is called "spaghettification"
General Relativity Effects Near Black Holes (3)

Time dilation

Clocks starting at 12:00 at each point

After 3 hours (for an observer far away from the BH):

Clocks closer to the BH run more slowly

Time dilation becomes infinite at the event horizon

Event Horizon
General Relativity Effects Near Black Holes (4)

Gravitational Red Shift

All wavelengths of emissions from near the event horizon are stretched (red shifted)

→ Frequencies are lowered (photons lose energy)

Event Horizon
Observing Black Holes

No light can escape a black hole

⇒ Black holes cannot be observed directly

If an invisible compact object is part of a binary, we can estimate its mass from the orbital period and radial velocity

Mass > 3 $M_{\text{Sun}}$

⇒ Black Hole
Black Hole Candidates

<table>
<thead>
<tr>
<th>Object</th>
<th>Location</th>
<th>Companion Star</th>
<th>Orbital Period</th>
<th>Mass of Compact Object</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cygnus X-1</td>
<td>Cygnus</td>
<td>B0 supergiant</td>
<td>5.6 days</td>
<td>&gt;3.8 $M_{\odot}$</td>
</tr>
<tr>
<td>LMC X-3</td>
<td>Dorado</td>
<td>B3 main-sequence</td>
<td>1.7 days</td>
<td>~10 $M_{\odot}$</td>
</tr>
<tr>
<td>AO620-00</td>
<td>Monocerotis</td>
<td>K main-sequence</td>
<td>7.75 hours</td>
<td>10 ± 5 $M_{\odot}$</td>
</tr>
<tr>
<td>V404 Cygni</td>
<td>Cygnus</td>
<td>K main-sequence</td>
<td>6.47 days</td>
<td>12 ± 2 $M_{\odot}$</td>
</tr>
<tr>
<td>J1655-40</td>
<td>Scorpius</td>
<td>F main-sequence</td>
<td>2.61 days</td>
<td>6.9 ± 1 $M_{\odot}$</td>
</tr>
<tr>
<td>QZ Vul</td>
<td>Vulpecula</td>
<td>K main-sequence</td>
<td>8 hours</td>
<td>10 ± 4 $M_{\odot}$</td>
</tr>
<tr>
<td>4U 1543-47</td>
<td>Lupus</td>
<td>A main-sequence</td>
<td>1.123 days</td>
<td>2.7–7.5 $M_{\odot}$</td>
</tr>
<tr>
<td>V4641 Sgr</td>
<td>Sagittarius</td>
<td>B supergiant</td>
<td>2.81678 days</td>
<td>8.7–11.7 $M_{\odot}$</td>
</tr>
<tr>
<td>XTE J1118+480</td>
<td>Ursa Major</td>
<td>K main-sequence</td>
<td>0.170113 days</td>
<td>&gt;6 $M_{\odot}$</td>
</tr>
</tbody>
</table>

Compact object with $> 3$ $M_{\odot}$ must be a black hole.
Black-Hole vs. Neutron-Star Binaries

Black Holes: Accreted matter disappears beyond the event horizon without a trace.

Neutron Stars: Accreted matter produces an X-ray flash as it impacts on the neutron star surface.
Black Hole X-Ray Binaries

Accretion disks around black holes

Strong X-ray sources

Rapidly, erratically variable (with flickering on time scales of less than a second)

Sometimes: Quasi-periodic oscillations (QPOs)

Sometimes: Radio-emitting jets
Gamma-Ray Bursts (GRBs)

Short (~ a few s), bright bursts of gamma-rays

Later discovered with X-ray and optical afterglows lasting several hours – a few days

Many have now been associated with host galaxies at large (cosmological) distances
A model for Gamma-Ray Bursts

At least some GRBs are probably related to the deaths of very massive (> 25 $M_{\text{sun}}$) stars. In a supernova-like explosion of stars this massive, the core might collapse not to a neutron star, but directly to a black hole. Such stellar explosions are termed *hypernovae*.
Magnetars

Some neutron stars have magnetic fields ~ 1000 times stronger even than normal neutron stars: Magnetars

Earthquake-like ruptures in the surface crust of Magnetars cause bursts of “soft” (lower energy) gamma-rays
Class Announcements

• Lecture PDFs and other materials available from: web.science.mq.edu.au/~zucker/Astronomy_170.html
• Assignment #4 is due Friday, May 7th
• If you did not attend one of the three observing practicals, please e-mail me ASAP
• Call for nominations to Physics Student Liaison Committee – please e-mail me if you’re interested
Physics Student Liaison Committee
Meeting Sem1, 2010

Thursday 20 May, 12noon - Lunch will be provided

Purpose of the meeting
• is to seek student feedback on the current semester’s units and programs. Each undergraduate unit is invited to nominate two students as class representatives.

Student observers
• are welcome and should email Helen (helen@science.mq.edu.au) at least ten days prior to the meeting to advise her of your wish to attend.

Confirmation of invitation to attend
• will be emailed to your MQ student address.

Outcomes from the meeting
• will be incorporated into next year’s teaching and reported at next year’s SLC.

We look forward to seeing you there.
Associate Professor David Coutts, Head, Department of Physics and Engineering