Chapter 22

Neutron Stars & Black Holes

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Learning Goals:

22.1 Neutron Stars

22.2 Pulsars

22.3 Neutron-Star Binaries

22.4 Gamma-Ray Bursts

22.5 Black Holes

22.6 Einstein’s Theories of Relativity

22.7 Space Travel Near Black Holes

22.8 Observation Evidence for Black Holes

22.1 Neutron Stars

Stellar Remnants

SN-I: The entire star shattered by the blast.

SN-II: The explosion destroys the parent star, Ultra compressed remnant at its center is left ➔ NEUTRON STAR.

Neutron-Star Properties:

- **Extremely small, 2R = 20 km, solid.**
- **Average Density = 10^{18} kg/m^3.**
- **100 million tons == cup of coffee**
- **Supported by neutron degeneracy pressure**
- **Enormous gravity: 70-kg man = 10 trillion-kg**
- **Rotate rapidly, conservation of angular momentum, few cycles / second**
- **Have very strong magnetic field, amplified by the collapse.**
- **Dies with time.**

22.2 Pulsars

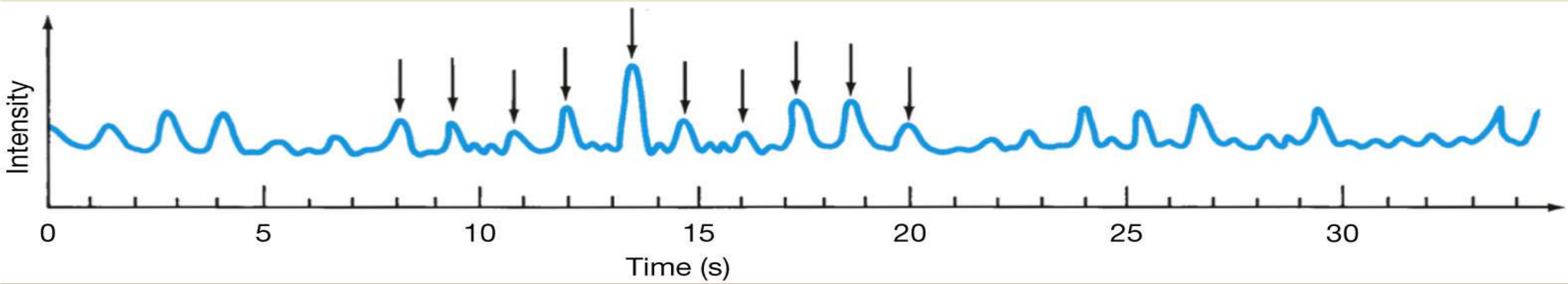
The first PULSAR was discovered in 1967. (Jocelyn Bell).

It emitted radio radiations in the form of regular pulses;

Each pulse stays for 0.01s, then disappear. Another pulse arrives after 1.34s.

The interval between pulses is a precise clock. Spinning stop after tens of million years.

It was realized that this was a neutron star, spinning very rapidly. (Hewish Nobel prize 1974)



22.2 Pulsars

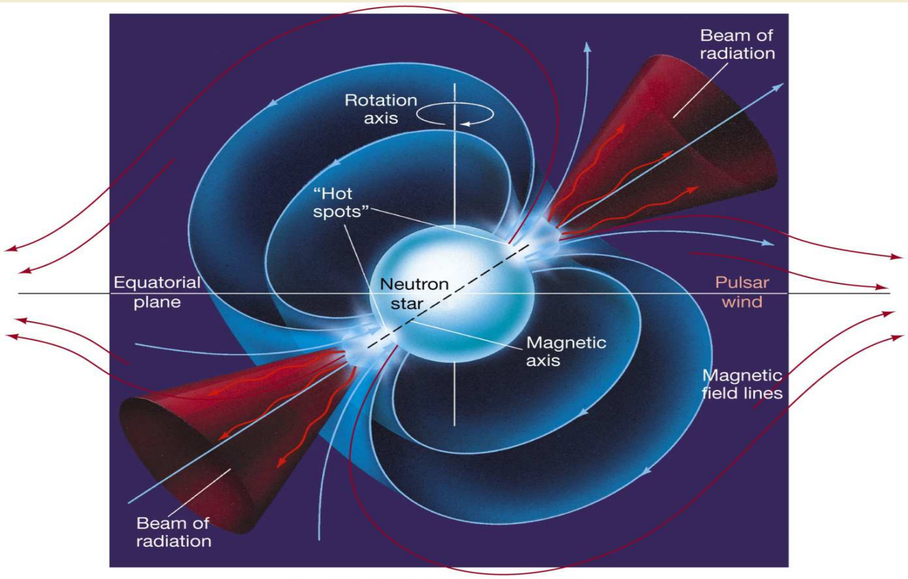
The mechanism of the rapid rotation of a pulsar:

Two hot spots on its surface continuously emit radiation in a narrow searchlight pattern.

The spots are localized near the star's magnetic poles.

The hot spots radiate steadily, and the resulting beams sweep through space like a revolving lighthouse beacon

This pulsar model is often known as the *lighthouse model*.



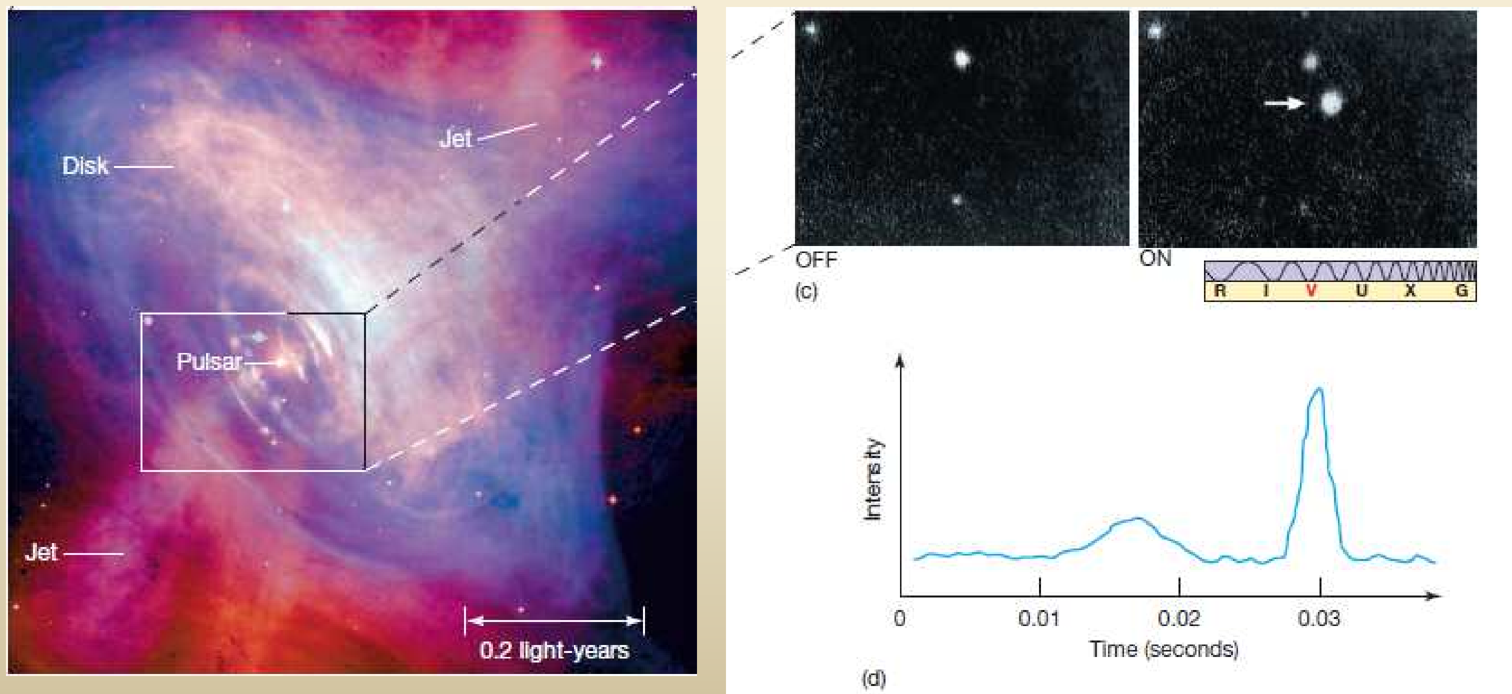
22.2 Pulsars

A few pulsars are associated with supernova remnants

There is a pulsar at the center of the Crab Nebula; the images below show it in the "off" and "on" positions. Pulse period 33 millisecond.

The Crab also pulses in the radio and X-ray parts of the spectrum.

The location of the pulsar is the center of the SN explosion.



22.2 Pulsars

Most pulsars emit radio radiation, few have been observed to pulse in the visible, X-ray, and gamma-ray parts of the spectrum.

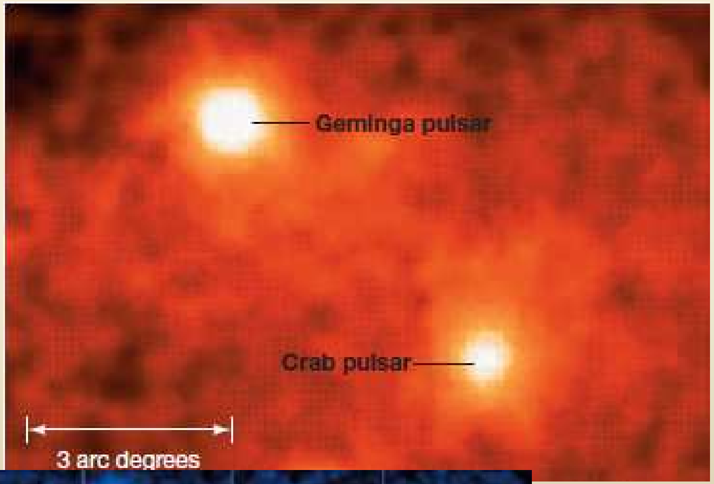
Figures show the Crab and the nearby Geminga pulsar in gamma rays.

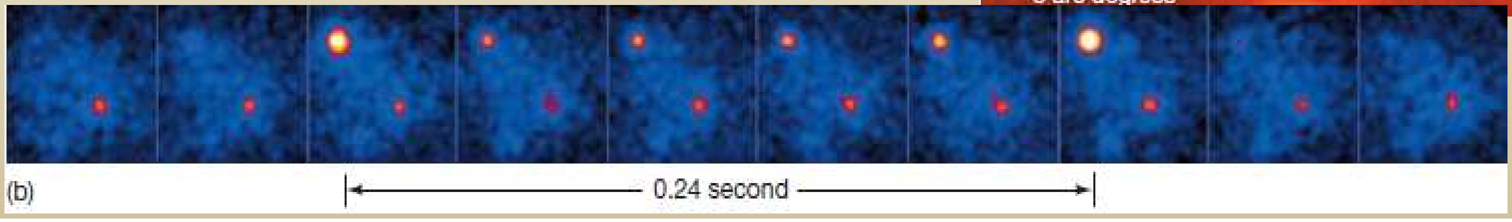
Pulses at different frequencies do not necessarily all occur at the same instant in the pulse cycle.

The period of pulses is flashing between 3 to 30 times per second.

Human eyes are insensitive to such fast pulsing rates.

Geminga pulsates strongly in gamma rays.

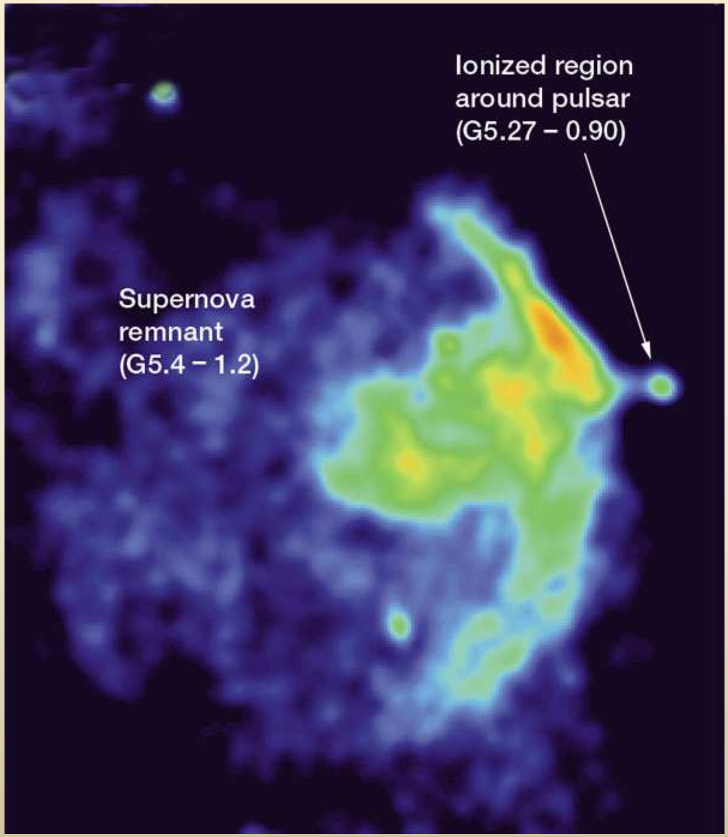




22.2 Pulsars

Most pulsars are observed (Doppler measurements) to have high speeds.

Neutron stars may receive substantial "kicks" due to asymmetries in the supernovae in which they formed.

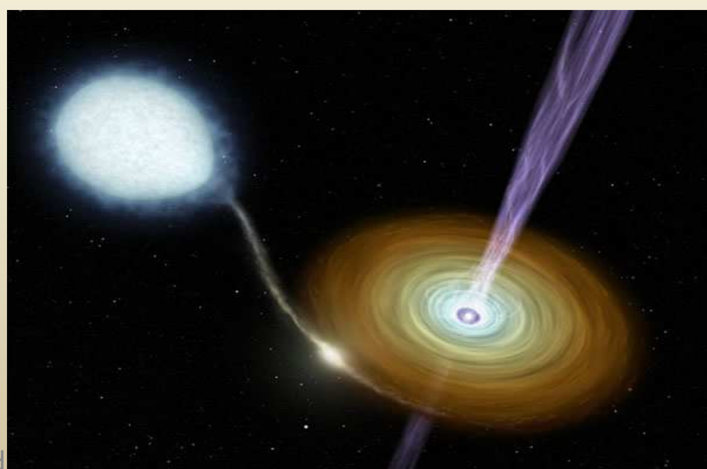


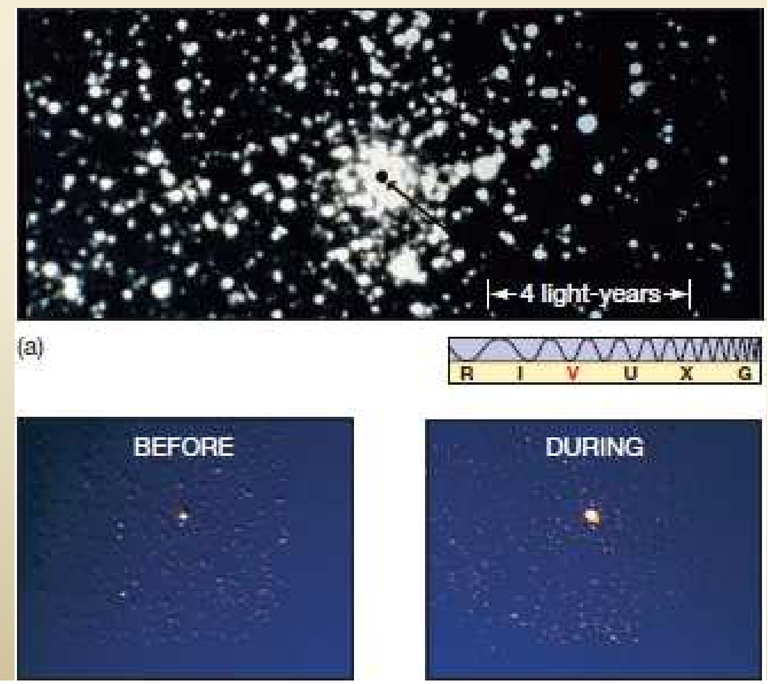
22.3 Neutron-Star Binaries

Most Stars are not single!

Many pulsars are isolated, but some do have companions.

- **Neutron star Mass = 1.4 M_{sun}, Chandrasekhar mass, M = 2 M_{sun} is reported.**
- **X-ray burster: rich source of X-rays near the centers of rich star clusters.**
- **Emit must of their energy in violent eruption, each thousands of times more luminous than our Sun. lasting for few seconds.**
- **Due to a neutron star close to another star.**





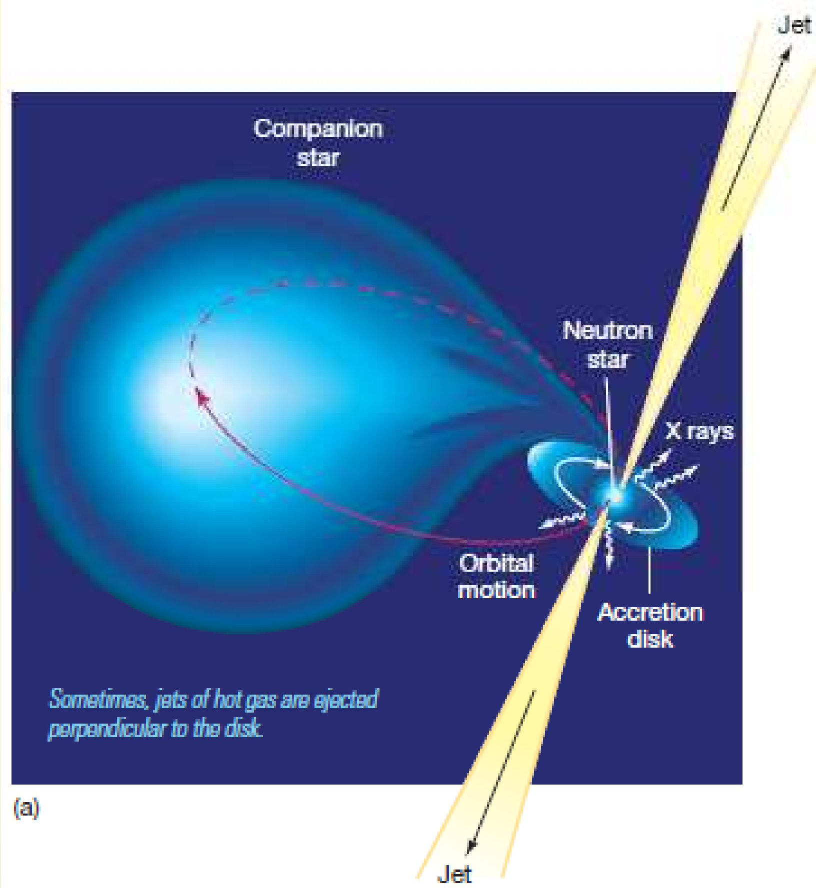
22.3 Neutron-Star Binaries

Similar to novae, MS star and neutron star.

- Material don't fall directly onto the surface
- Accretion disk, inner part is extremely hot ➔ steady stream of X-rays.
- If H fuses, sudden and rapid period of nuclear reactions ➔ huge energy released in a brief, intense flashes of X-rays ➔ X-ray burst

•Ex: SS433, 5000 pc, materials (M_{earth}) expels yearly in form of two opposite jets

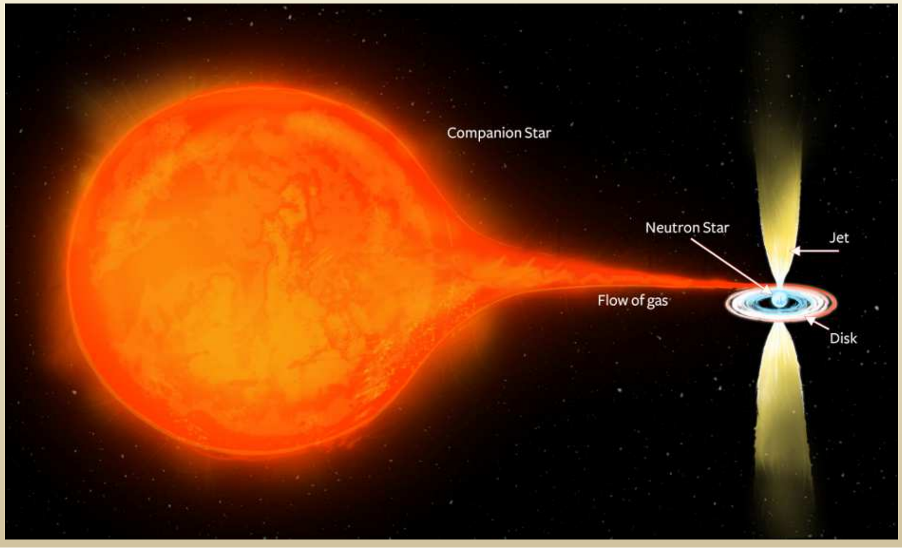
- Speed in jets = 80,000km/s

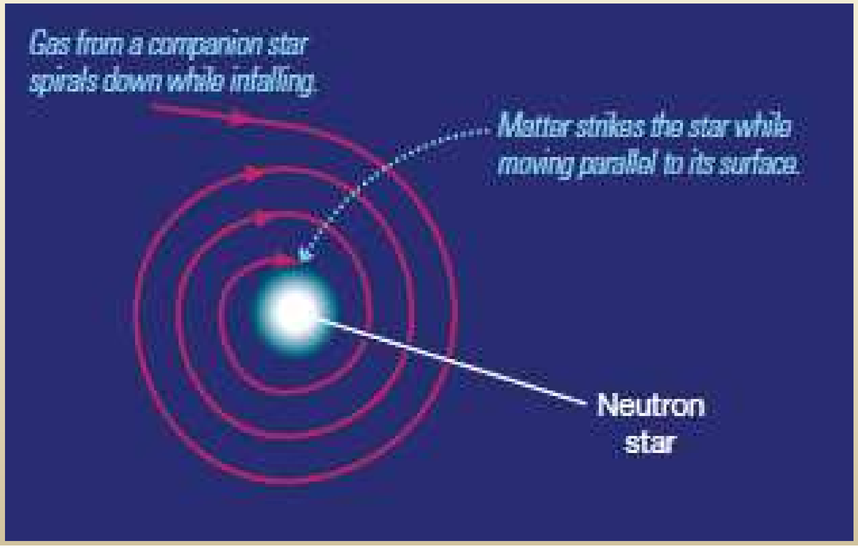


22.3 Neutron-Star Binaries

Millisecond Pulsars: rapidly rotating objects, 250 found in our Galaxy.

- Spin hundred of times per second, almost at breakup speed.
- *Found only in globular clusters, strange! Large stars need 10 Myr to SN.*
- Reasons for this fast spin, materials falling on it from its companion M.S.-star, this my take several 100s Myr. .
- It is two-stage process: Forming a neutron star, then achieved the rapid spin.
- X-ray bursts and millisecond pulsar are closely linked

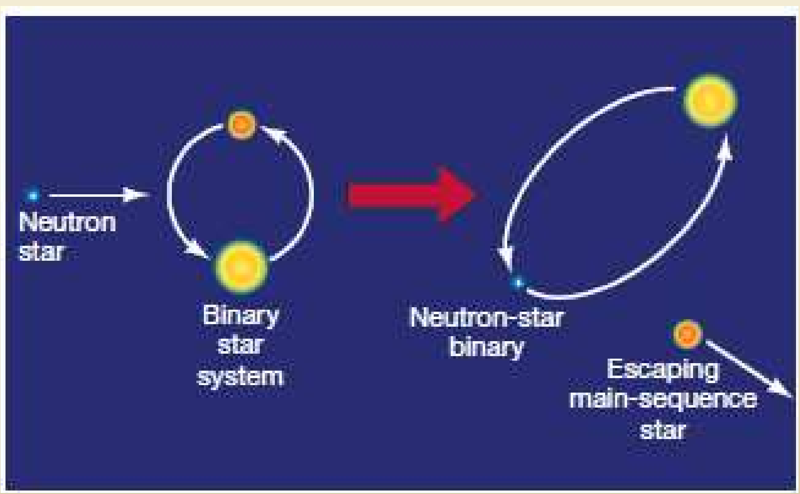


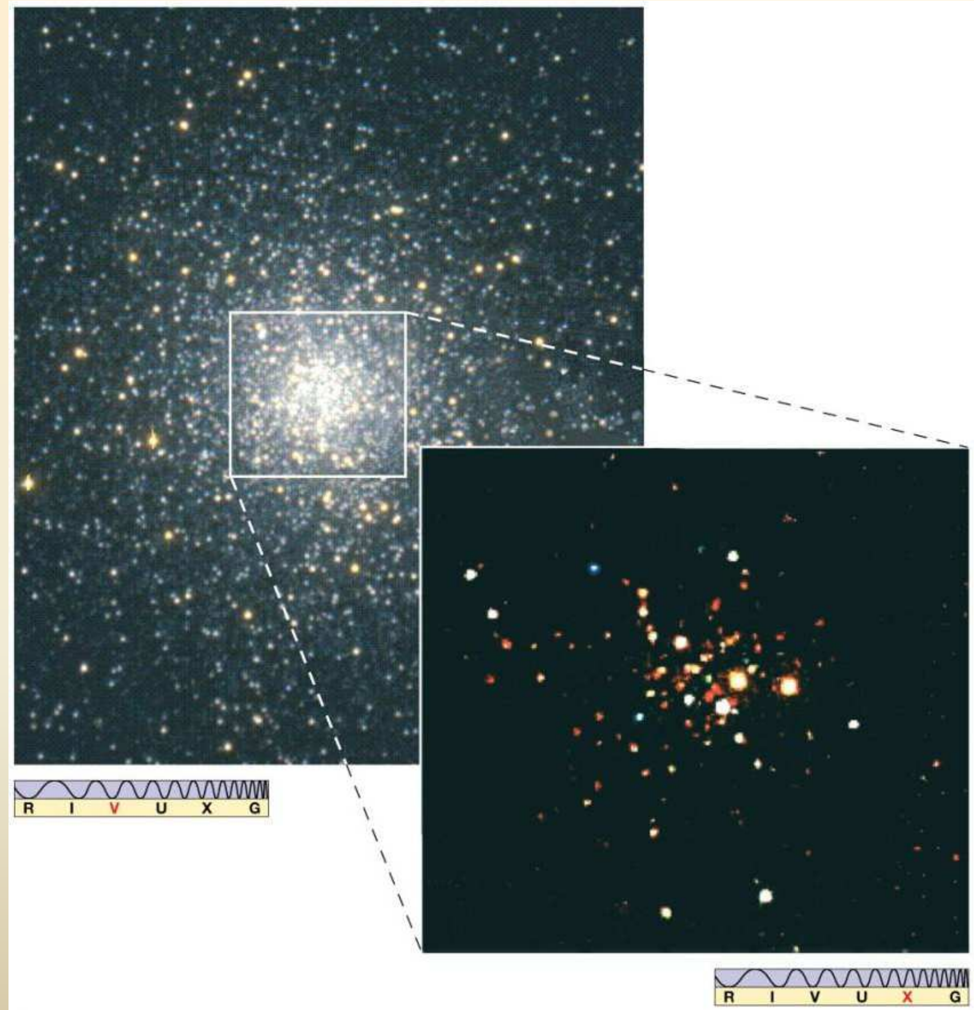


22.3 Neutron-Star Binaries

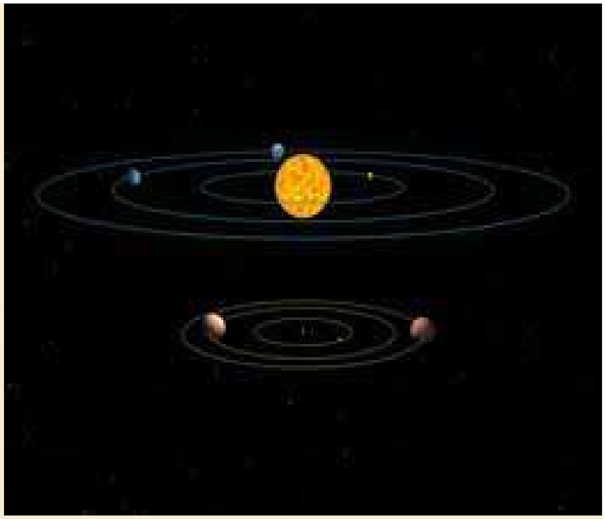
Globular cluster 47 Tucanea

- **108 X-ray sources at the center.**
- **54 are millisecond pulsars.**
- **Neutron star may become part of a binary system after it is formed**





22.3 Neutron-Star Binaries



Pulsar Planets

- The pulse period of a recently discovered pulsar lying some 500 pc from us varied in an unexpected way.

- The period fluctuates on two distinct time scale one of 67 days, the other of 98 days.

- These fluctuations are caused by the Doppler effect as the pulsar wobbles back and forth in space.

- two, planets, each about three times the mass of Earth! One orbits the pulsar at a distance of 0.4 AU and the other at a distance of 0.5 AU

- Their orbital periods are 67 and 98 days, respectively, matching the timing of the fluctuations.

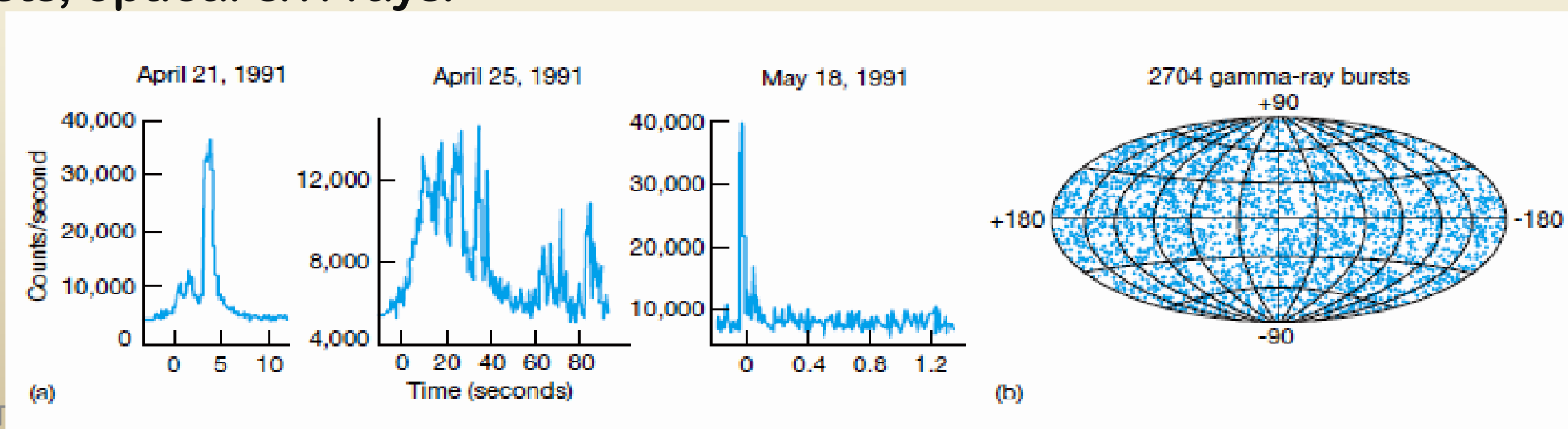
- Discovery of a third body, with mass comparable to Earth's Moon, orbiting only 0.2 AU from the pulsar.

- it is unlikely that any of these planets formed in the same way as our Earth!?!.

22.4 Gamma-Ray Bursts

Distances and Luminosities

- Bright, irregular flashes of Gamma-rays lasting only for few seconds.
- CGRO detected almost one/day for 9 years, 2704 have been observed
- Distributed uniformly across the sky, never repeat at the same location, no clustering, not similar to X-ray bursts.
- Cosmological distances, far outside our Galaxy. Poor resolution of gamma-telescopes ➔ positions is uncertain up to 1^{o}.
- To specify the distance, look at counterparts: objects associated with the bursts, optical & X-rays.



Successful searches for Gamma-Ray Bursts

NASA's *swift* mission, wide-angle Gamma-ray detector with one X-ray and one optical/ultraviolet telescopes.

• Gamma-ray detector observes the burst with an accuracy of 4', within a second other telescopes are directed to the event by computers. Telescopes are in ground and space.

• Swift detects the burst counterpart s at a rate of once/week.

• 1st detected in 1997; obtaining a visible spectrum afterglow of energetic burst.

• The Spectrum contained absorption lines from Fe and Mg, redshifted by a factor of two, 2 billion pc from the Earth.

➔ expansion of the universe

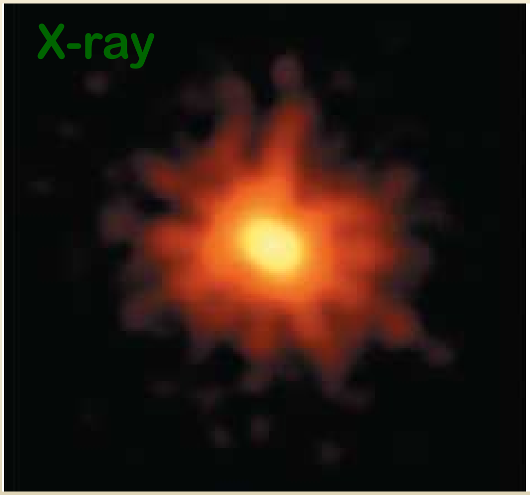
→Extremely energetic ~ 100 of times greater than a typical SN-scale

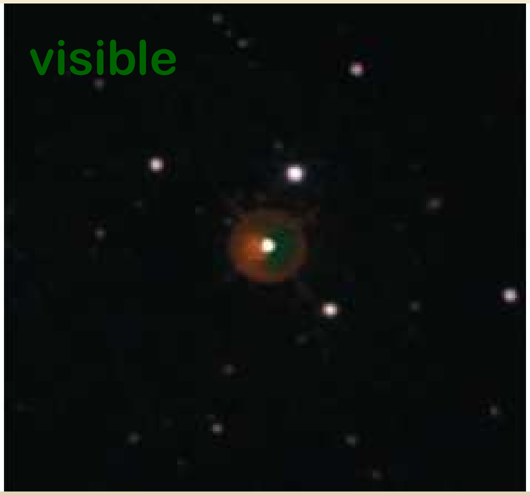
→ very large (seen by eye)

→ Gamma emitted: narrow jets similar to the light from laser.

Successful searches for Gamma-Ray Bursts

- Ex: GRB 080319B, extensively studied, brightest GRB to date?
- Its light reached Earth on 19/3/2008, was emitted 7.5 billion years ago.
- The flash was visible to unaided eye for few seconds.
- Moments after the detonation: it was observed by



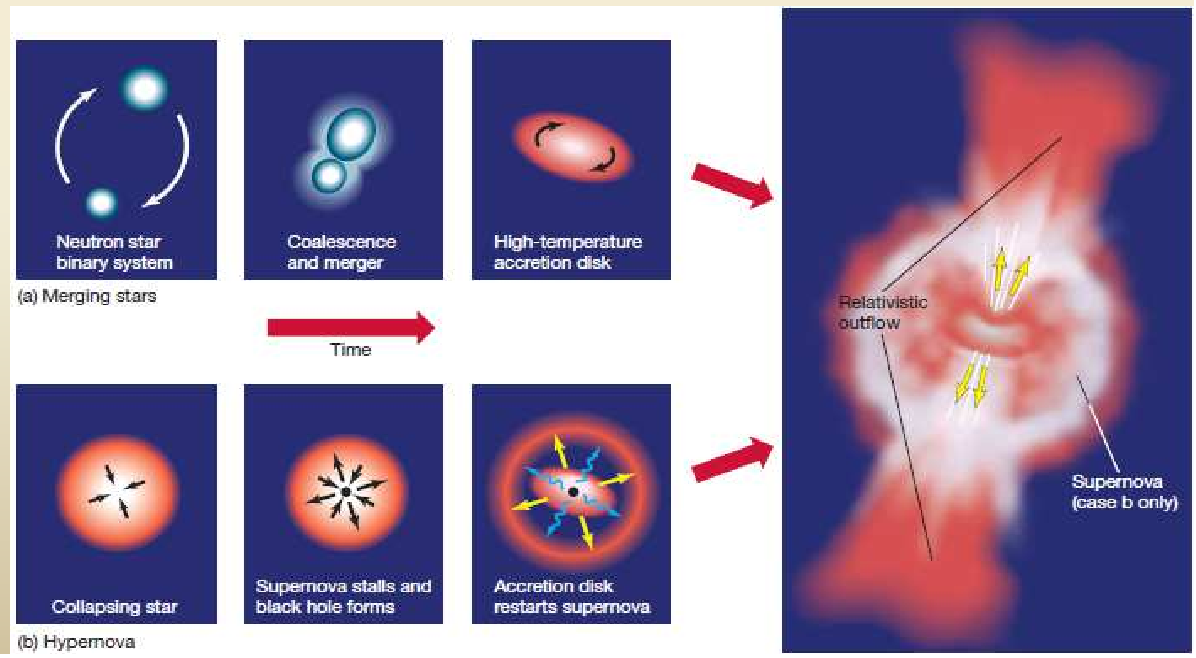


What Causes the Bursts?

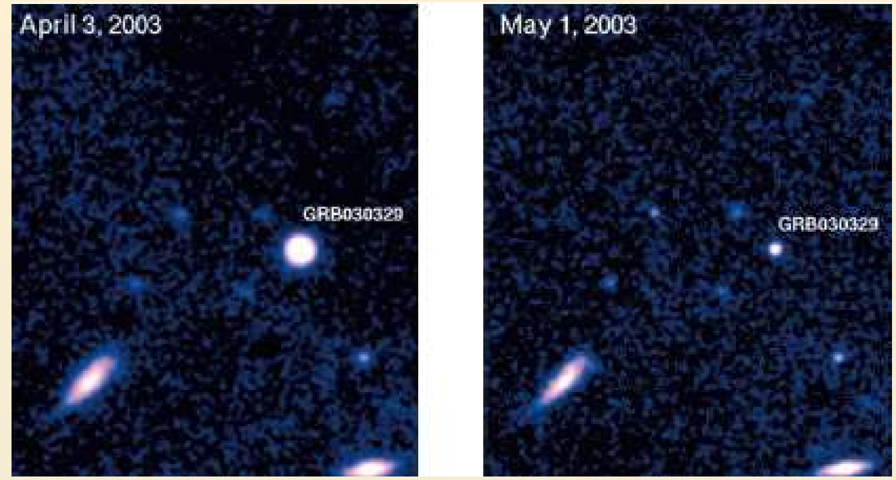
➔ Huge Energy from very small object.

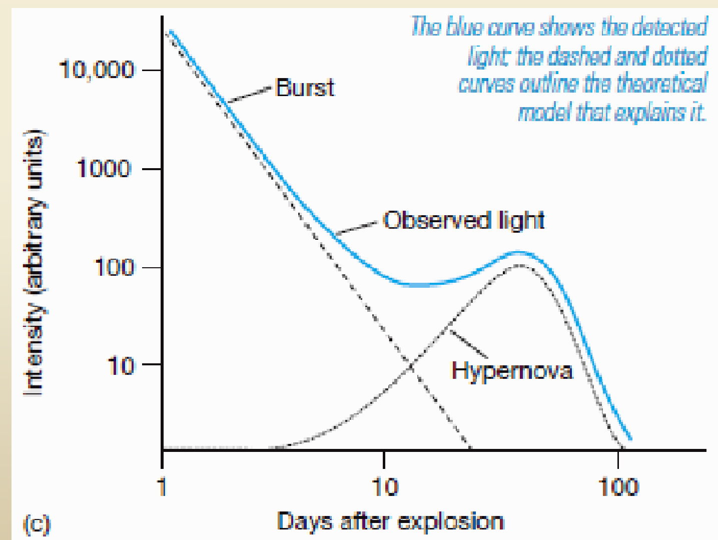
- **Originated from a volumes a few hundreds km across. HOW? 1 light-millisecond difference from its near and far sides == 300 km.**
- **Particles in the jet moves at nearly the speed of light ➔ Einstein's relativity**
- **Merging components of neutron stars or Hypernova (failed supernova).**
- **Hypernova Model:**

- **The blast wave racing outside the star stalls.**
- **Inner part begins to implode**
- **An accretion disk formed around the black hole.**
- **Relativistic jets created, and produced gamma ray as its slims the surrounding shell of gas.**
- **The accretion disk restarts the SN, blasting what remains.**



Ex: GRB 030329, $25M_{sun}$





Theory & observation agrees:

i. Neutron -star-merger model accounts for short GRBs.

ii. Hypernova-model predicts GRBs of relatively long duration.

22.5 Black Holes

Properties of some of the dense stellar remnants we have encountered in stellar evolutions.

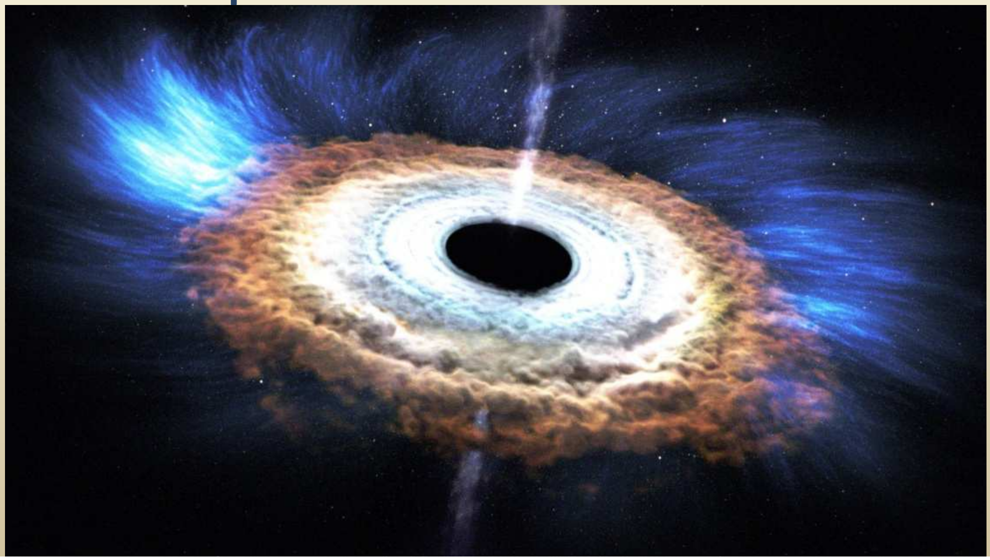
TABLE 22.1 Properties of Stellar Remnants

Remnant	Typical Mass (solar masses)	Typical Radius (km)	Typical Density (kg/m^3)	Support	Context (Section)
brown dwarf	less than 0.08	70,000	10^5	electron degeneracy	H fusion never started (19.3)
white dwarf	less than 1.4	10,000	10^9	electron degeneracy	stellar core after fusion stops at C/O (20.3)
black dwarf	less than 1.4	10,000	10^9	electron degeneracy	"cold" white dwarf (20.3)
neutron star	1.4–3 (approx.)	10	10^{18}	neutron degeneracy	remnant of a core collapse supernova (22.1)
black hole	more than 3	10	infinite at the center	none	remnant of a core collapse supernova with massive progenitor (22.5)

22.5 Black Holes

The final stage of stellar evolution

- **Mass of the core exceeds 3 solar masses, original star > 25 solar mass.**
- **The gravity pull overwhelmed the neutron degeneracy pressure.**
- **Even magnetism and rotation are useless!!**
- ***Gravity is huge, light is unable to escape!!***
- **No information is coming out of it.**
- **Massive core remnant collapses on itself and vanishes forever: BLACK HOLE.**



22.5 Black Holes

Escape Speed

- Escaped velocity from Earth = 11 km/s ➔ Newton Laws
- A body escape speed $v_{\text{escape}} = \sqrt{2GM/r}$
- If the Earth radius decreases to 1 cm ➔ escape speed = speed of light
- Einstein theory of relativity: Nothing can move faster than the speed of light, all things, *including light*, are attracted by gravity.
- *nothing—absolutely nothing—could escape from the surface of such a compressed body.*

Black Hole Properties

- Three Physical properties can be measured from the outside:

   I. Hole's mass

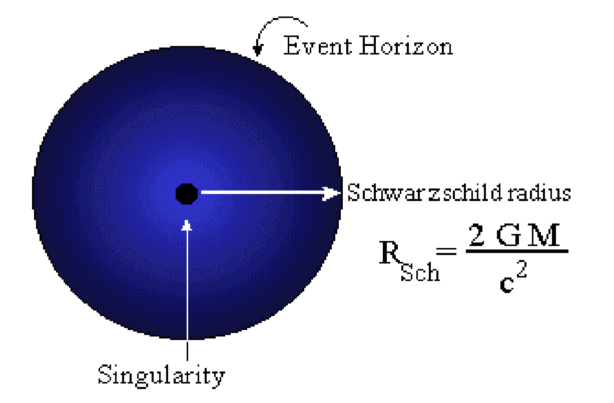
   II. Hole's charge

   III. Angular momentum

22.5 Black Holes

- Critical radius for an object where escaping speed equals the speed of light
- Schwarzschild radius $R_{Sch} = 2GM / c^2$

Earth	1 cm
Jupiter (300 Earth)	3 m
The Sun (300,000 Earth)	3 km
3 M_{sun}	9 km

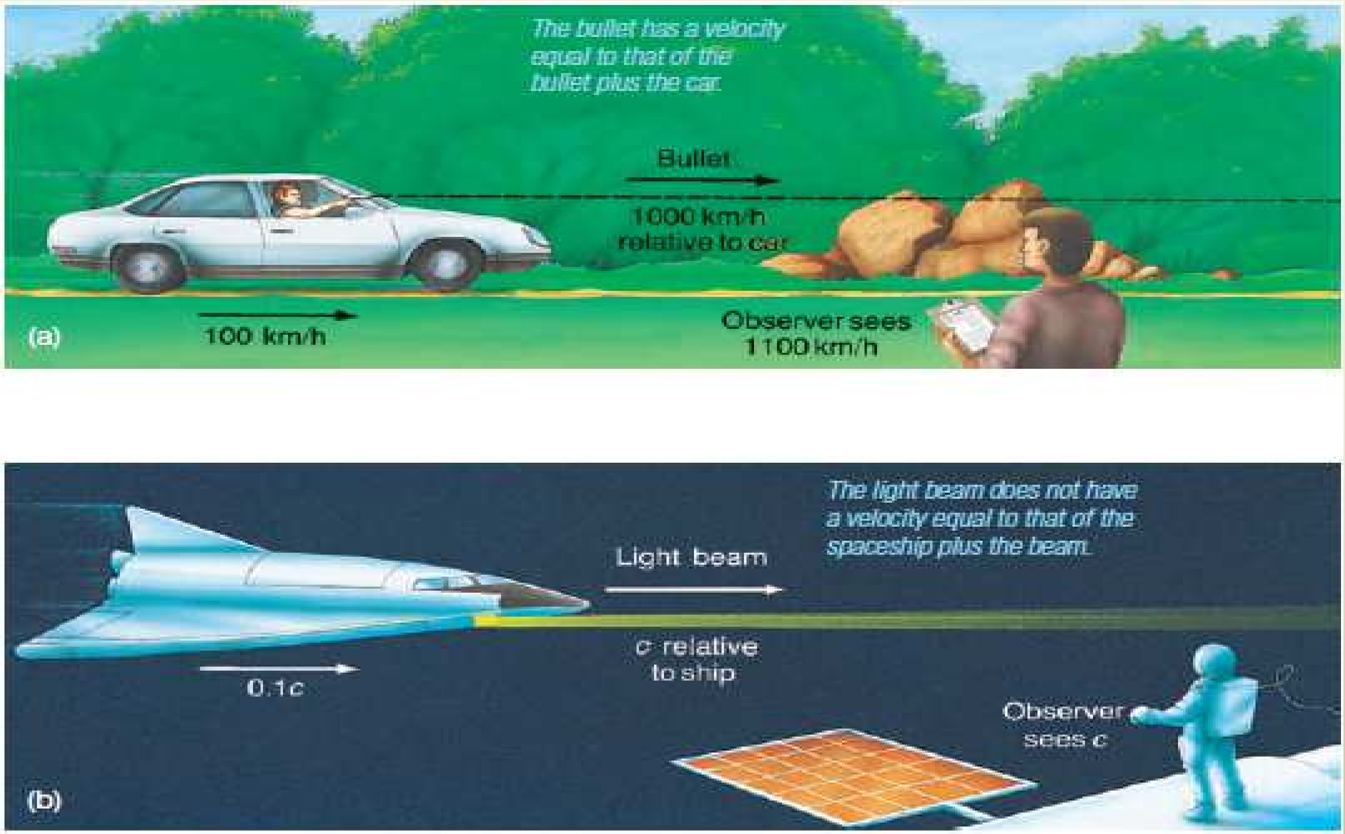


- A black hole is an object that happens to lie within its own Schwarzschild radius.
- **Event horizon**: *The surface of an imaginary sphere with radius equal to the Schwarzschild radius and centered on a collapsing star.*
- A region where nothing can be seen. Physical (boundary radius).
- 1.4M_{sun} neutron star has a radius of 10 km ➔ Schwarzschild radius = 4.2 km
- Neutron star's radius decreases with increasing mass, When m = 3M_{sun} ➔ star lies within its event horizon ➔ M.S. star should be 20 – 25 M_{sun}

22.6 Einstein’s Theory of Relativity

Special Theory of Relativity

1- The speed of light, c, is the maximum possible speed in the universe, and all observers measure the same value for c, regardless of their motion. The basic laws of physics are the same to all unaccelerated observers.



22.6 Einstein's Theory of Relativity

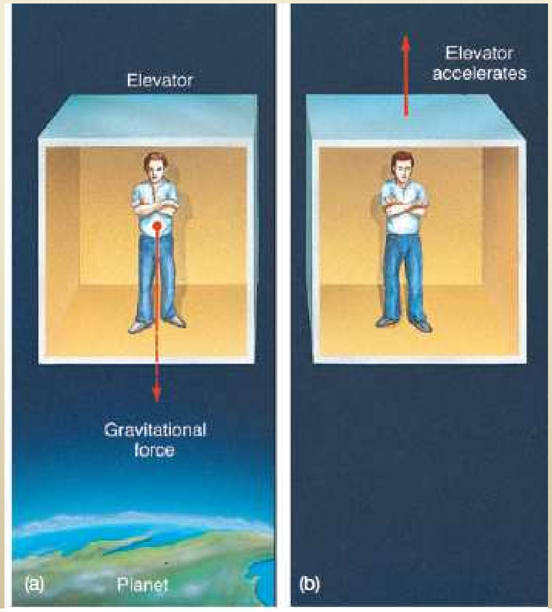
Special Theory of Relativity

2- There is no absolute frame of reference in the universe; there is no way to tell who is moving and who is not. Instead, only relative velocities between observers matter (hence the term "relativity").

3- Neither space nor time can be considered independently of one another. Rather, they are each components of a single entity: spacetime. There is no absolute, universal time—observers' clocks tick at different rates, depending on the observers' motions relative to one another.

General Theory of Relativity

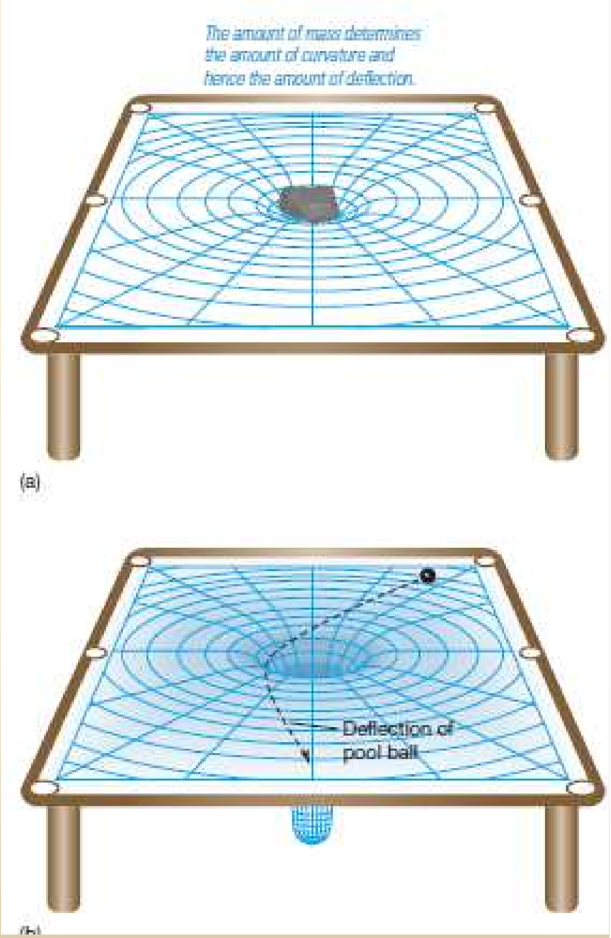
No difference between gravitational field and accelerating frame of reference: Equivalence Principle



22.6 Einstein's Theory of Relativity

General Theory of Relativity

- The main concept: all matter tends to curve space in its vicinity
- Planets & stars react by changing their paths.
- Newton: planets move in curved trajectories because of the gravitational force.
- Einstein: Planets move in curved paths because they are falling through space.
- The more the mass, the greater is the wrapping.
- Matter or radiation is deflected by the curvature of spacetime near a star.
- When gravity is weak, Einstein and Newton predict the same orbit.
- As the gravitating mass increases, the two theories diverge.



22.6 Einstein's Theory of Relativity

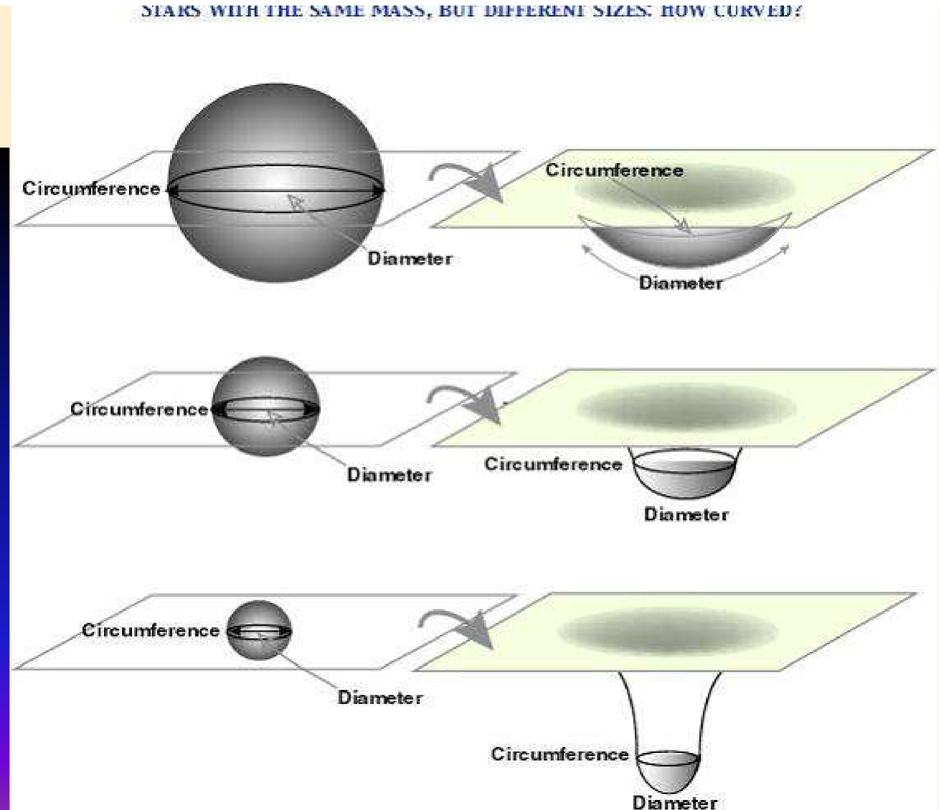
Curved Space and Black Holes

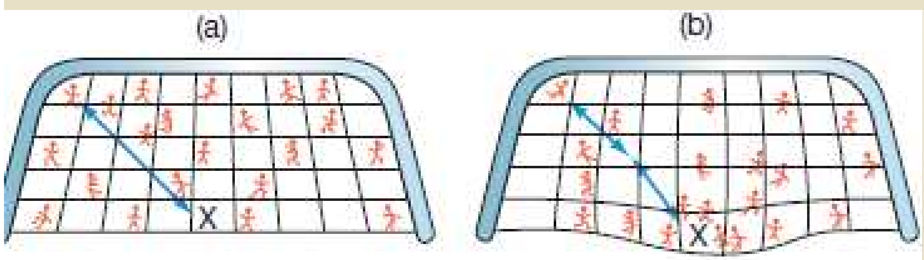
• Newton theory is adequate to describe white dwarfs and neutron stars.

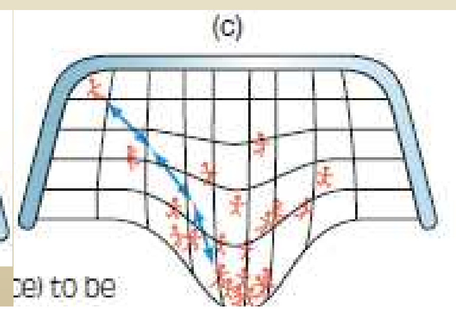
• Einstein theory ➔ Black holes.

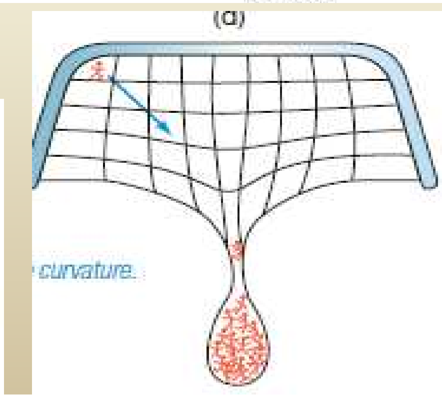
• At the event horizon itself, the curvature is so great that space "folds over" on itself, causing objects within to become trapped and disappear.

• This analogy depicts how a black hole wraps space completely around on itself.



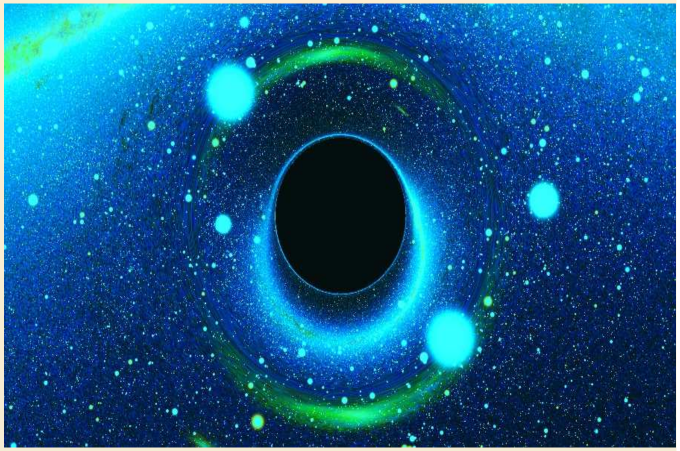


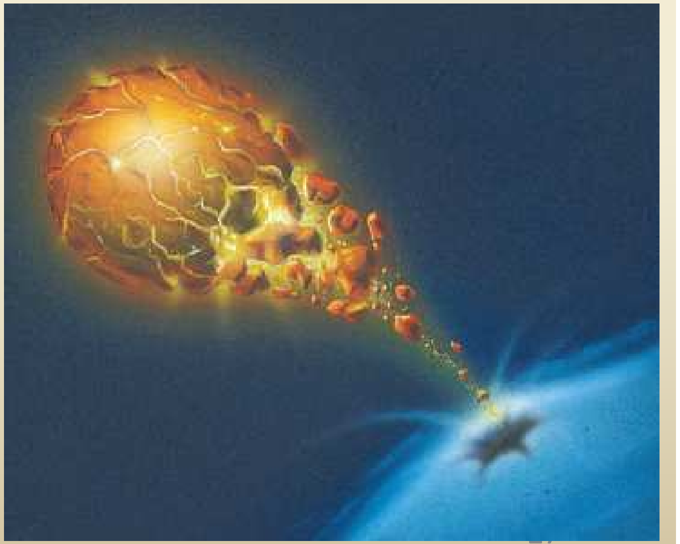




22.7 Space Travel Near Black Holes

- The orbit of an object near a black hole is basically the same as its orbit near a star of the same mass.
- Black holes are not cosmic vacuum cleaners.
- If an object's orbit happens to take it too close to the event horizon—it will be unable to get out.
- A black hole will accrete a little material from its surroundings ➔ its M & R of its event horizon increase slowly over time.
- ***Tidal forces***: Falling matter is vertically stretched, horizontally squeezed, accelerated to high speed.
- This causes a great frictional heating. Before reaching the event horizon, the matter emits radiation up to X-ray ➔ ***Source of energy.***

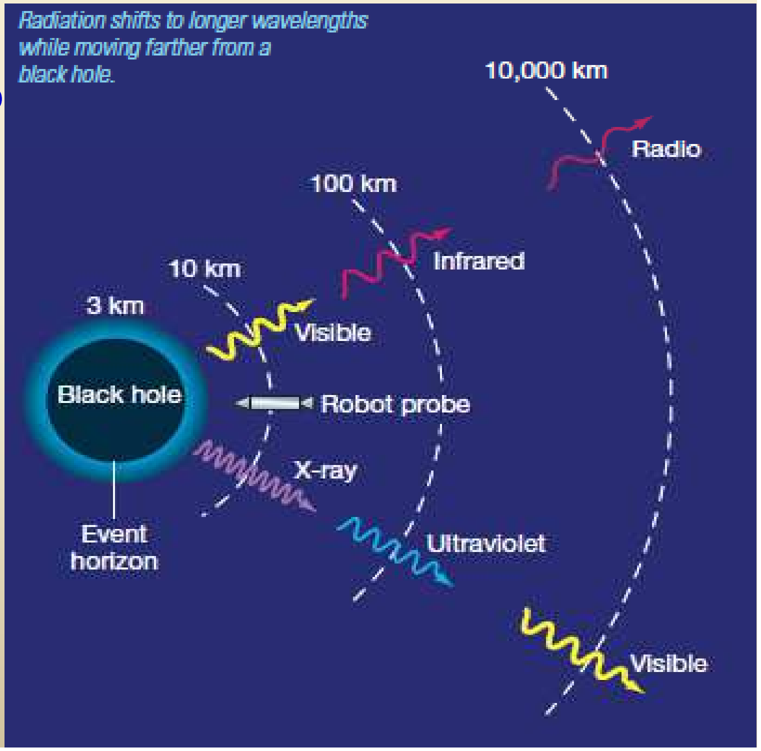




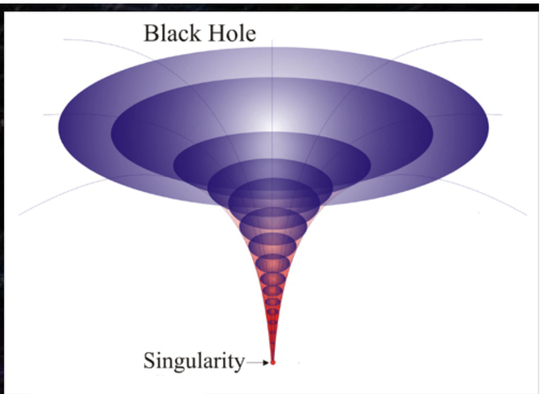
22.7 Space Travel Near Black Holes

Approaching the Event Horizon

- A robot with a light source of known frequency travelling toward a black hole.
- Its emitted light will be *redshifted*, not because of Doppler effect!!!!
- *Gravitational redshifted*: As predicted by Einstein's General Relativity.
- Photon are attracted by gravity.
- Escaped photons will use a lot of energy to do so
- Photons escape from the event horizon ➔ redshifted to infinite wavelength.
- What about the robot's clock????
- Close to the hole clock is slower than a clock on the board ➔ Time Dilation
- On reaching the event horizon ➔ frozen time!!
- External observer can not witness falling material below the event horizon.



22.7 Space Travel Near Black Holes



Deep Down Inside

- No one really knows!?!?
- Can an entire star simply shrink to a point and vanish?
- *Singularity* : General relativity predicts ➔ the core remnant of a high-mass star will collapse to a point at which density & gravitational field become infinite.
- Singularities are not physical ➔ the present laws of physics are simply inadequate to describe the final moments of a star's collapse.
- The theory of gravity is incomplete ➔ Q.M. is not able to describe matter on very small scales ➔ *Quantum Gravity*
- The merger of general relativity with quantum mechanics..

22.8 Observational Evidence for Black Holes

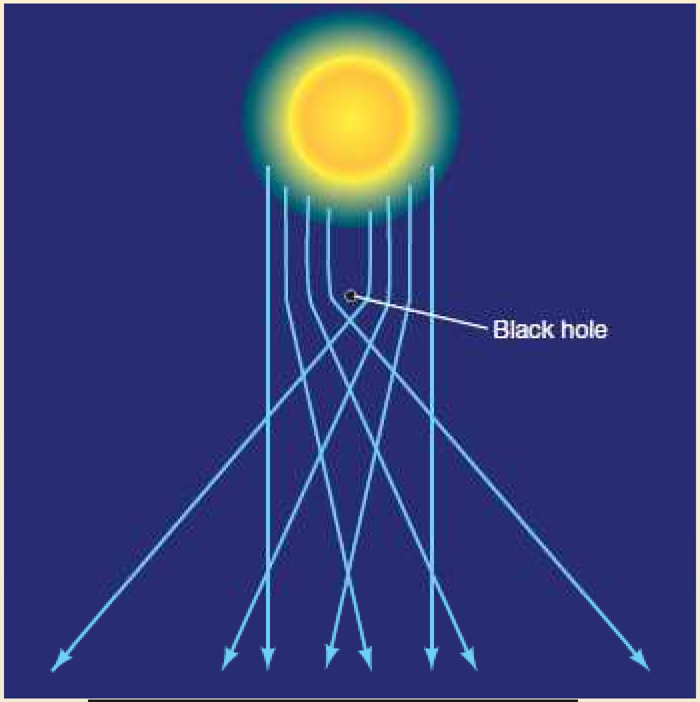
Stellar Transits?

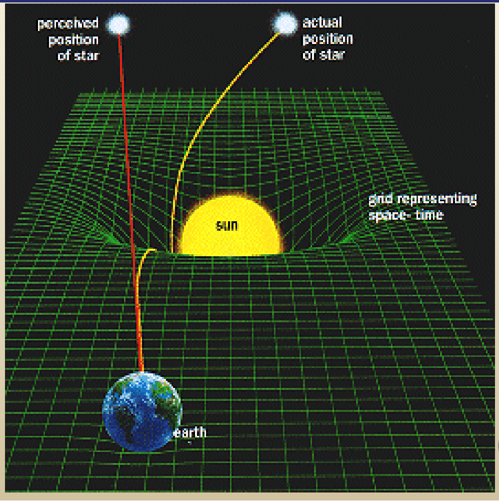
- One way to detect a black hole is if we observed it transiting a star.
- Such an event would be extremely hard to see.

→ 12,000-km-diameter Venus is barely noticeable when it transits the Sun.

➔ 10-km-wide object moving across the image of a faraway star would be completely invisible.

- the background starlight would be deflected as it passed the black hole on its way to Earth,
- A phenomenon that has been measured during solar eclipses.





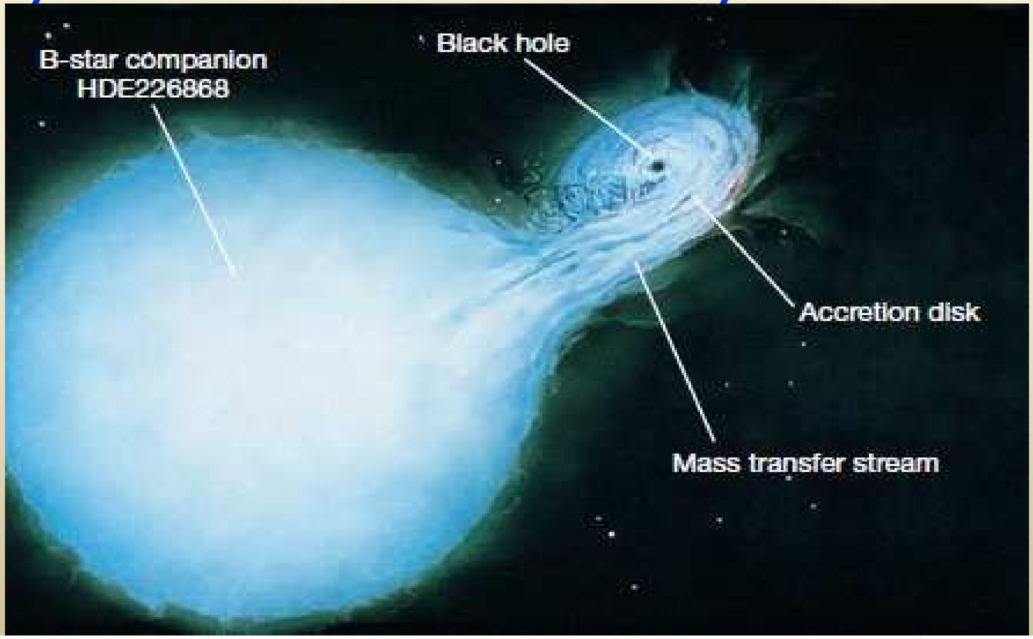
22.8 Observational Evidence for Black Holes

Black Holes in Binary Systems

- **A much better way to find black holes is to look for their effects on other objects**

- **A few close binary systems suggest that one of their members may be a black hole.**

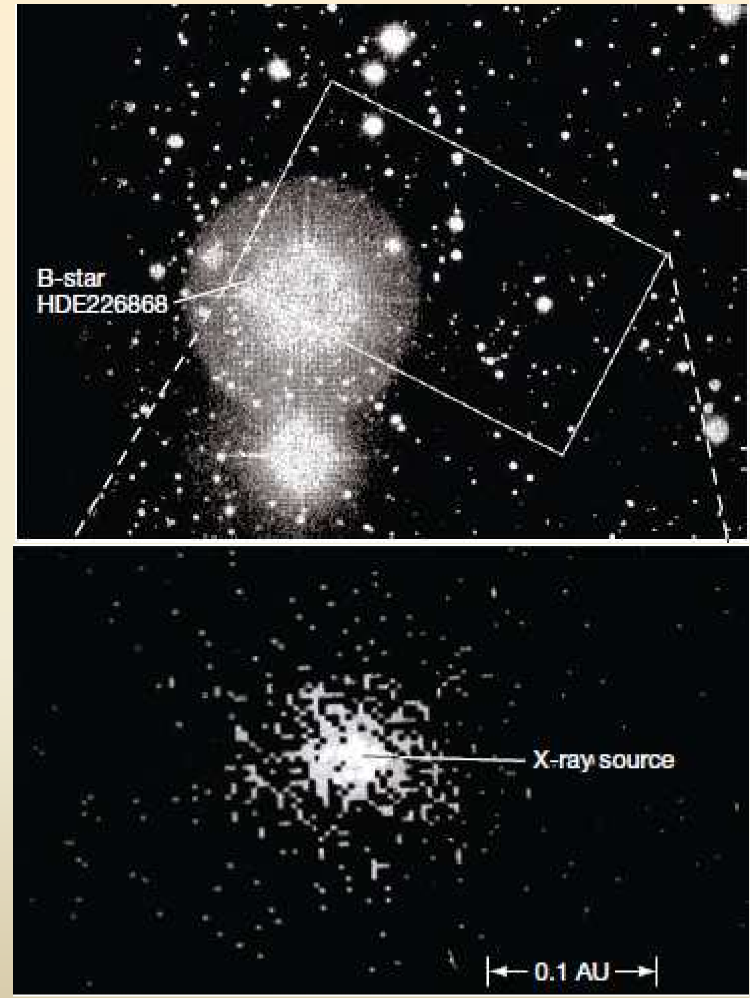
- **The black-hole candidate is an X-ray source called Cygnus X-1, 6200 ly, studied in detail by the *Uhuru* satellite in the early 1970s.**



22.8 Observational Evidence for Black Holes

Cygnus X-1 is a very strong black-hole candidate:

- Its visible partner is about **25** solar masses.
- The system's total mass is about **35** solar masses, so the X-ray source must be about **10** solar masses.
- **Hot gas** appears to be flowing from the visible star to an unseen companion.
- Short **time-scale variations** indicate that the source must be very **small ➔ black hole**



22.8 Observational Evidence for Black Holes

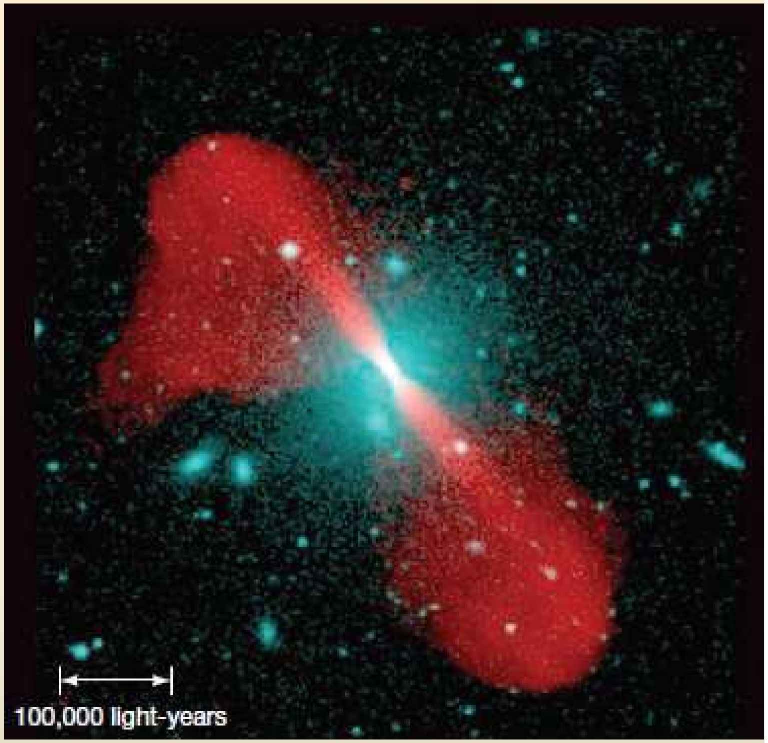
Black Holes in Galaxies

• The strongest evidence for black holes comes from the centers of many galaxies, including our own.

• Stars and gas near the centers of many galaxies are moving extremely rapidly, orbiting some very massive, unseen object.

• Masses inferred from Newton's laws range from millions to billions of times the mass of the Sun.

• The centers of many galaxies contain supermassive black holes – about 1 million solar masses.



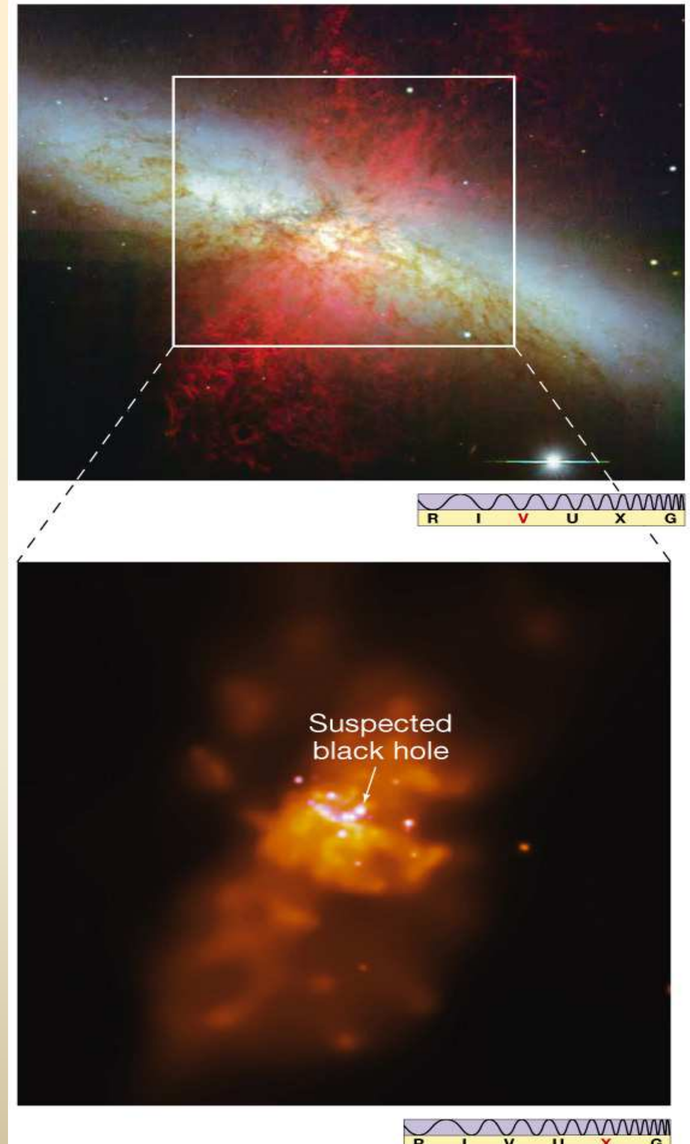
22.8 Observational Evidence for Black Holes

Do Black Holes exist?

- X-ray observations of the center of the starburst galaxy M82 (100,000 light-years across and 12 million light-years away) reveal a collection of bright sources thought to be the result of matter accreting onto intermediate-mass black holes.

- The black holes are probably young, have masses between 100 and 1000 times the mass of the Sun, and lie relatively far (about 600 light-years) from the center of M82.

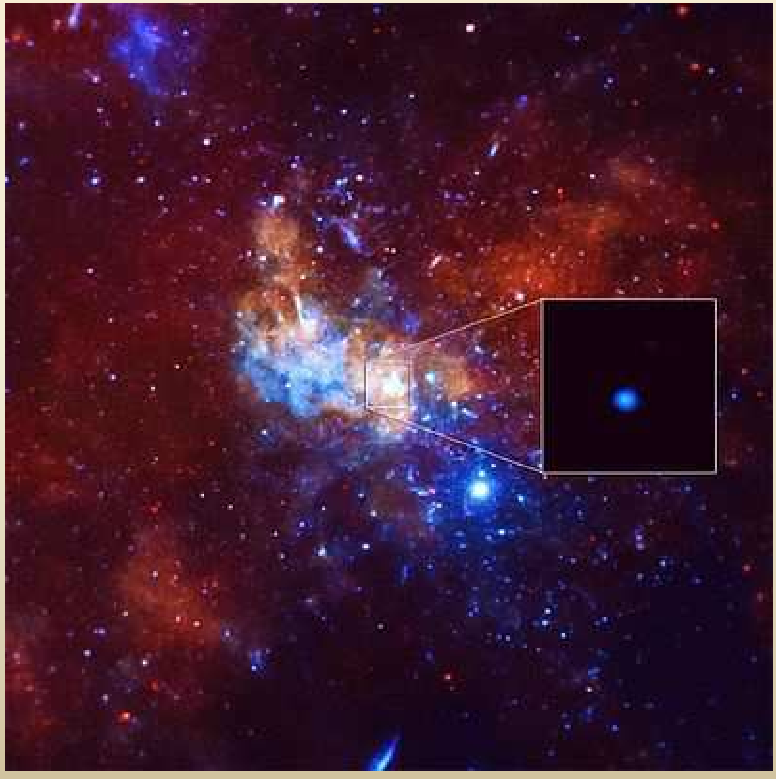
- The brightest (and possibly most massive) black hole candidate is marked by an arrow.

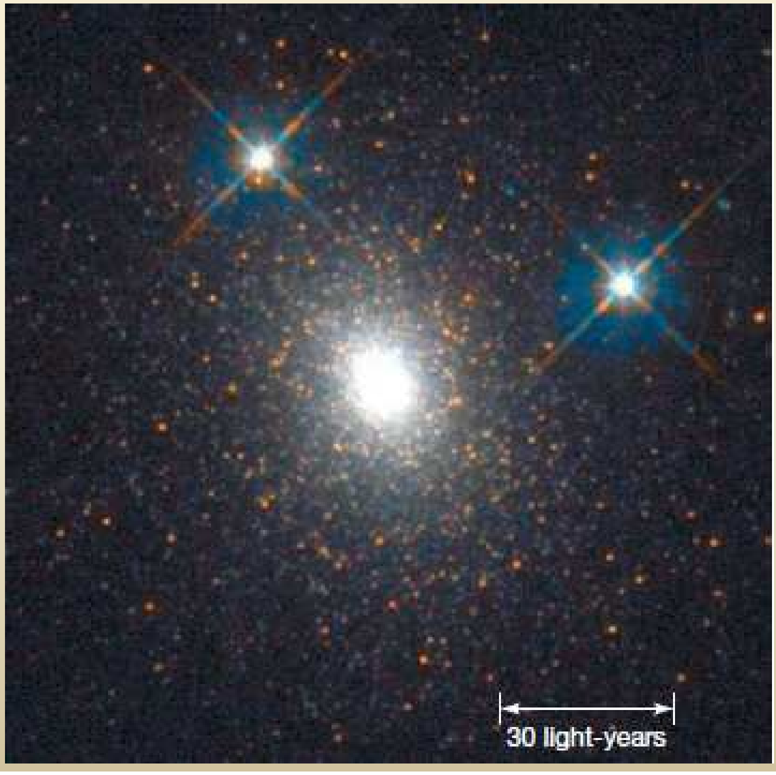


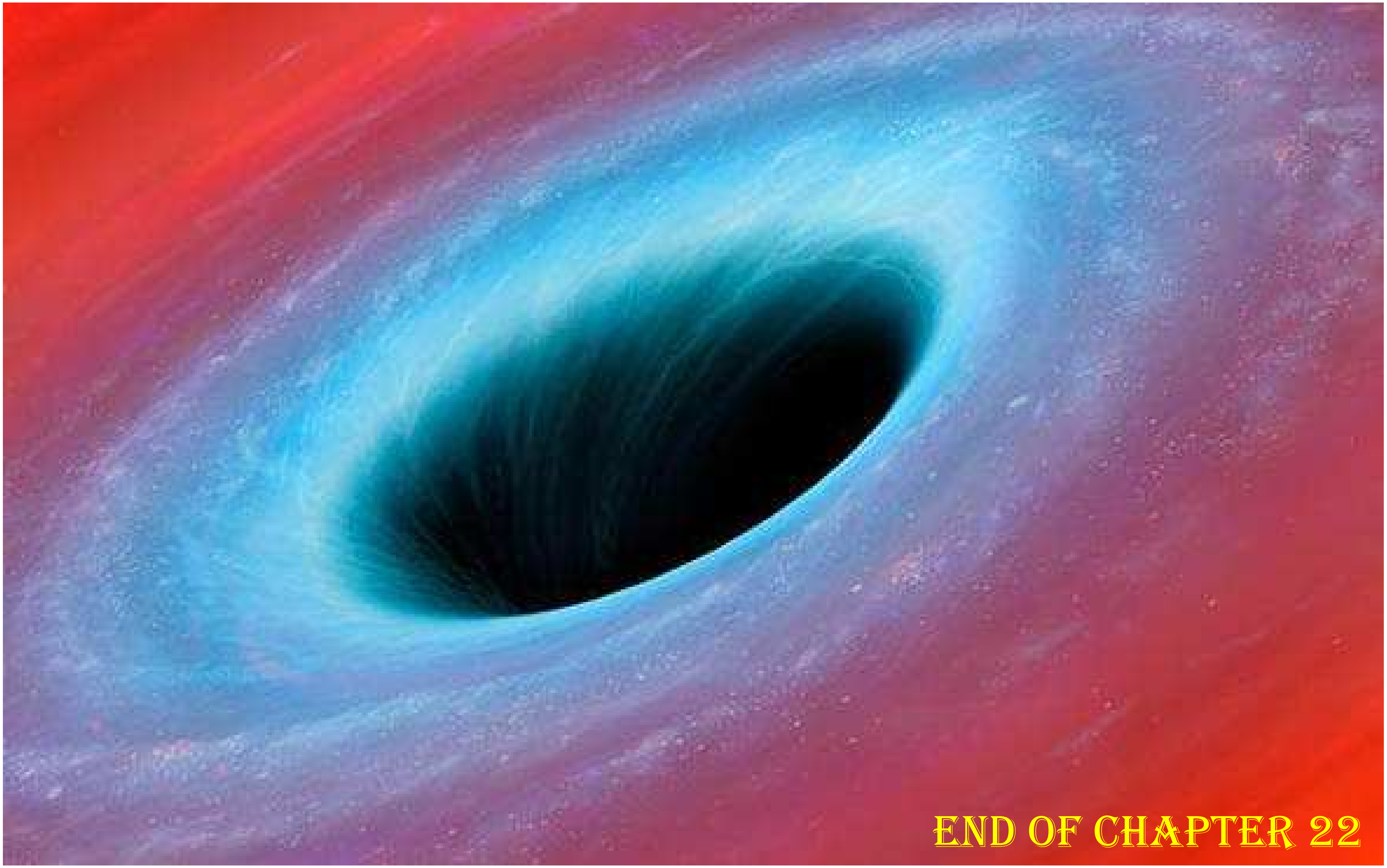
22.8 Observational Evidence for Black Holes

Do Black Holes exist?

• Stars near the center of the massive globular cluster G1 do not move as expected if the cluster's mass is as smoothly distributed as its light. Instead, the observations suggest that an intermediate-mass black hole resides at the cluster's center






END OF CHAPTER 22