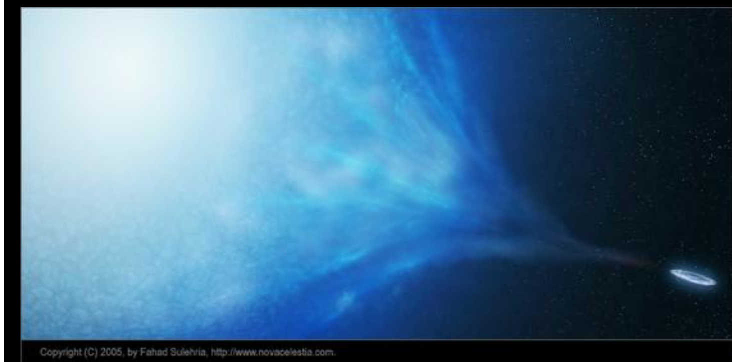
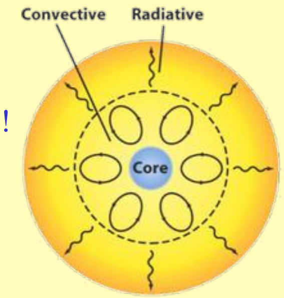
Stellar Evolution: High Mass Stars



High Mass Stars

- ***high mass stars***: > *8*$M_\odot$
- ***theoretical upper limit*** of ~ *200*$M_\odot$
- ***fusion*** ~ via ***CNO cycle***
- **very short *main sequence*** lifetime
(eg) *10*$M_\odot$ *:* ~30 million years!
- ***evolution*** proceeds as for ***intermediate mass stars*** until the **end** of ***He*** *fusion*



CLICKER: *Why do we think stars cannot form** with masses greater than ~200* $M_\odot$*?*

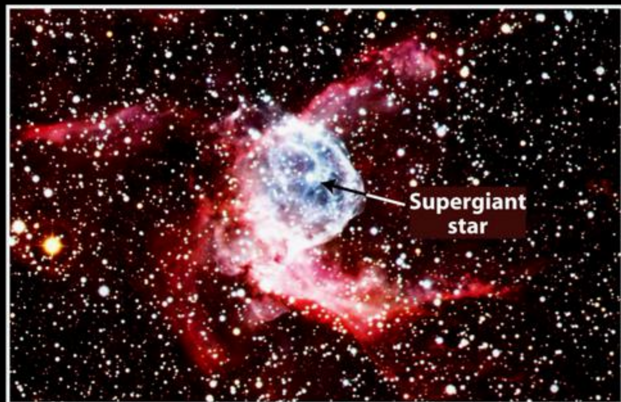
(a) fusion pressure exceeds gravity in outer layers
(b) rapid rotation at that mass rips the star apart
(c) >200 $M_\odot$ *stars immediately become black holes*
(d) molecular clouds never contain that much mass

- as core *contracts & heats up* > 100 million K, *star* moves beyond ***He*** *burning*
- ***envelope greatly*** expands: ***Supergiant***

(eg) Betelgeuse in Orion, Deneb in Cygnus

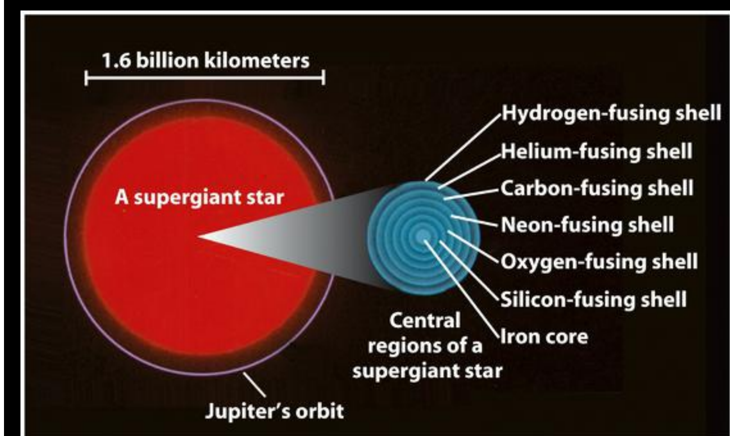
- undergo ***tremendous*** *mass loss* from ***envelope***
- *transient* periods of *pulsation* (***Cepheids***)

Mass Loss (*40 $M_\odot$, Canis Major)*



- ***core*** sequentially fuses *more massive nuclei*:
  H⇒ He⇒ C/O⇒ O/Ne/Mg⇒ Si/S⇒ Fe
- ***fusion reactions*** can proceed *in multiple ways*
  (eg) $^{16}O + {}^{4}He \Rightarrow {}^{20}Ne$ & $^{12}C + {}^{12}C \Rightarrow {}^{20}Ne + {}^{4}He$
- other ***fusion*** "byproducts" include ***Na, P, Ni***
- temperatures: *600 million K* (***C***), *3 billion K* (***Si***)
- ***fusion*** of ***Si*** creates iron (***Fe***) but ***Fe cannot*** fuse

Supergiant Core

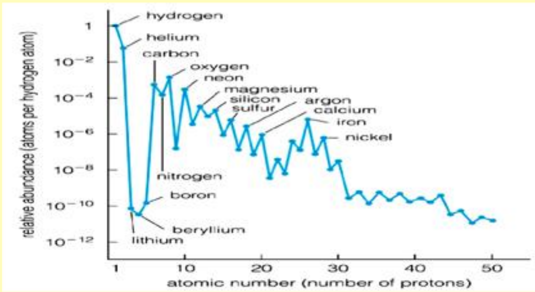


25$M_\odot$ Fusion Lifetimes

table 22-1 Evolutionary Stages of a 25-$M_\odot$ Star

Stage	Core temperature (K)	Core density (kg/m³)	Duration of stage
Hydrogen fusion	4×10^7	5×10^3	7×10^6 years
Helium fusion	2×10^8	7×10^5	7×10^5 years
Carbon fusion	6×10^8	2×10^8	600 years
Neon fusion	1.2×10^9	4×10^9	1 year
Oxygen fusion	1.5×10^9	10^{10}	6 months
Silicon fusion	2.7×10^9	3×10^{10}	1 day

• ***Fe*** is "*endpoint*" for both ***fusion*** & ***fission*** since it has *lowest mass-per-nuclear particle*
(eg) *cannot make Fe nuclei less "massive"*



(eg) *energy released in **H** fusion since $m_{He} < 4m_H$*

• ***peak*** in abundance at ***Fe*** in the ***periodic table***

• ***core*** is > *1.4 $M_\odot$* and ~ *size of Earth*

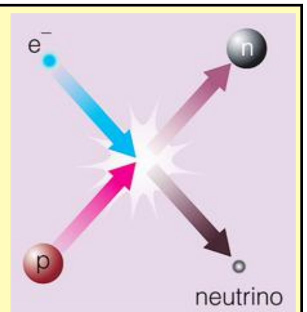
Q: *What happens when core is entirely made of **Fe**?*

• ***core collapses*** in a ***fraction of a second***

• electrons *already* crushed together
• ***electron degeneracy*** *ineffective (**Chandrasekhar**)*
• ***no*** *further **fusion** possible*

• *temperatures* rise to over *5 billion K*

• *protons & electrons fuse into neutrons*



• ***neutron degeneracy*** *opposes* collapse

• ***core*** is size of *city* (~ 20 km)

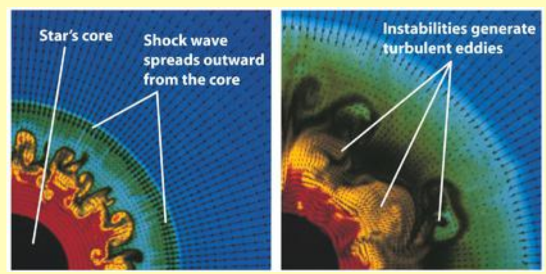
• *1 tsp* ~ mass of a *mountain*

(eg) *core density ~ 10^{17} kg/m^3 (like **atomic nuclei**)*

• *extremely* rigid ⇒ *in-falling* material "*bounces*"
• forms an outward moving ***shockwave*** (10^4 km/s!)

• rest of ***envelope*** *rapidly falls inward (~ 0.1c)*
• struck by outgoing *shockwave/neutrinos*

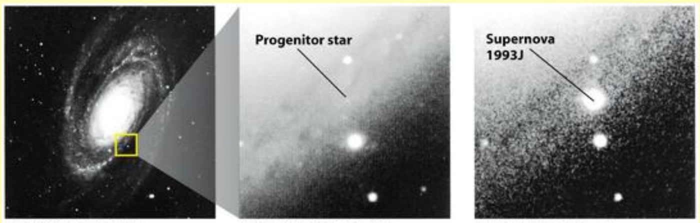
• ***envelope*** is torn apart, *compressing/heating* it & ***creating some heavy elements*** on ***periodic table***



"Not only are we a part of the Universe… but the universe is a part of us." Neil deGrasse Tyson

(Type II) Supernovae

- ***luminosity*** of explosion can reach $10^9 L_\odot$
- ***energy*** *released in a few seconds* is ***100x that produced by the Sun during its entire lifetime***



(a) Spiral galaxy M81 (b) Before the explosion (c) After the explosion

- for weeks, ***supernovae*** shine like *a small galaxy*

Historical Supernovae

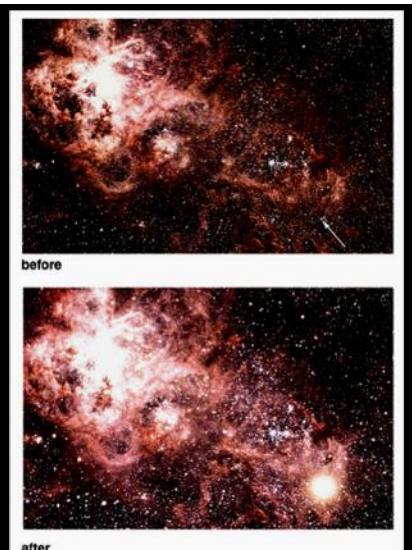
- only 5 *naked eye* ***supernovae*** in last 1000 years: *1006, 1054, 1181, 1572, 1604*
- ***all*** *of these took place* ***within*** *our galaxy*

- ***1006****: bright enough to cast shadows at night*
- ***1054****: bright enough to* ***read by*** *at night*
- ***1572****: Tycho Brahe's supernova*

- 1987 detection of energetic ***neutrinos***…

Supernova 1987a

(LMC, ~200,000 ly)

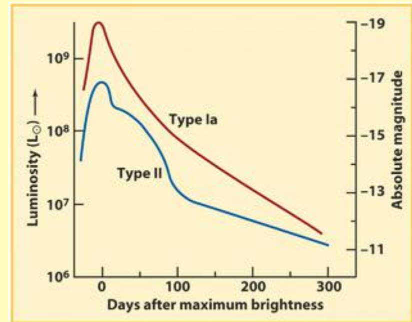


Supernova Remnants (*LMC*)

- filtered view with stars "subtracted"
- H (red), O (green), S (yellow)

Supernova Remnant
c. 1054 (Crab Nebula - Taurus)

Light Curves



• ***supernovae*** yield *distances*, since *peak luminosity* (how *bright* they *should* be) is *known* (variations?)

Neutron Stars

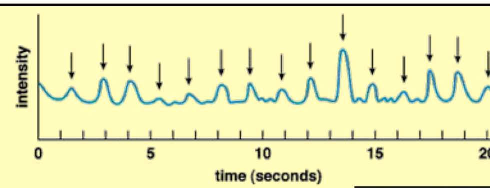
• ***neutron*** discovered in 1932

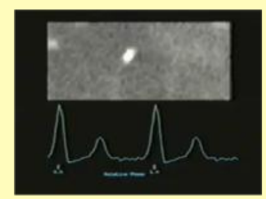
• ***Fritz Zwicky*** at *CalTech* proposed ***Neutron Star***

• ***neutron star***: remnant ***core*** of star *after supernova*
• ***electrons*** & ***protons*** combine to form ***neutrons***
• ***core*** supported by ***neutron degeneracy***

• ~ *3 $M_\odot$* ***neutron star*** *has* ***escape velocity*** of *0.5 c*

• seemed *too outrageous* to possibly be *true*





• 1967: *pulsating radio signals* detected in ***Cygnus*** by grad student Jocelyn Bell
• ***LGM's*** ("*Little Green Men*")

• too *common* & *regular*: renamed ***pulsars***

• ***pulsars*** found at centers of *Crab, Vela supernovae*

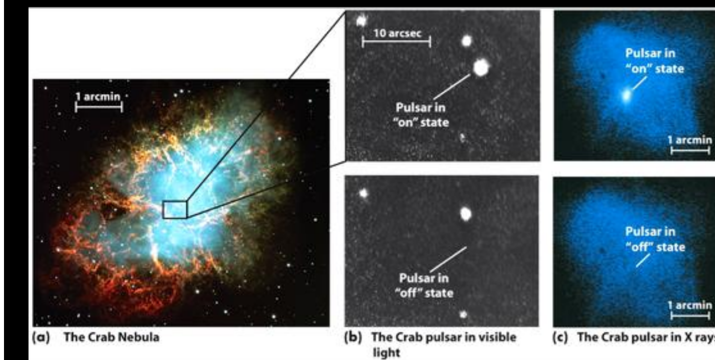
Q: *What could cause the pulsing signals?*

• ***pulsars*** *spin rapidly*
• up to 1000x per sec!

• must be *small, dense*

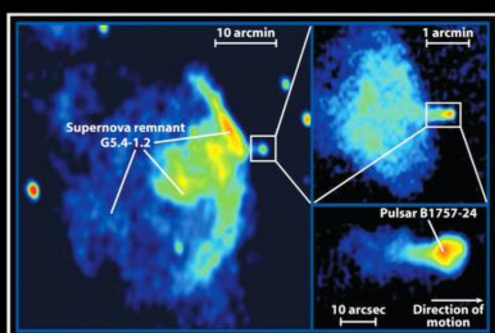
• *intense* ***magnetic field*** (10^{12} G) expels radiation in "*beams*" - like *lighthouse*

Crab Nebula Pulsar



Runaway Neutron Stars?

• ***supernova*** may explode ***asymmetrically, ejecting a neutron star at high speeds*** (>1000 km/s ?)



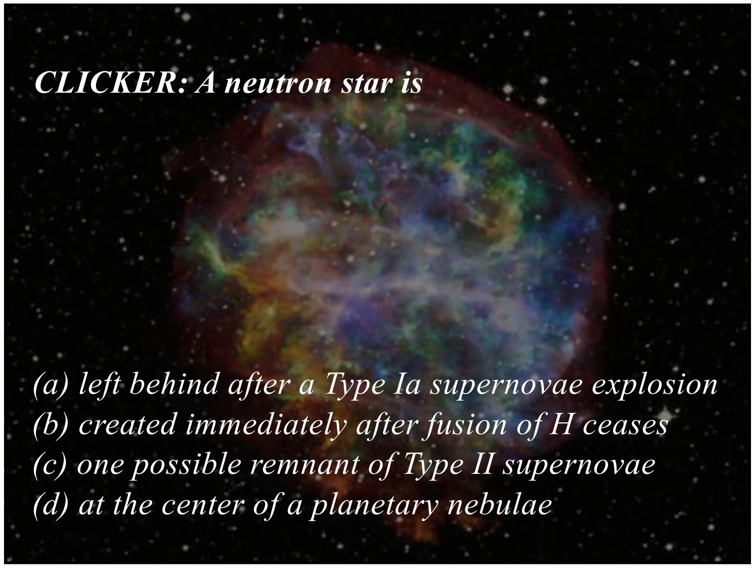
Neutron Star Limit

• ***gravity*** balanced by ***neutron degeneracy*** & ***strong nuclear force***

(eg) strong force *binds* ***neutrons*** *and* ***protons****; strongly resists compression - like billiard balls*

• ***Neutron Star Limit*** not as well known as ***Chandrasekhar Limit*** (***white dwarfs***), since ***strong force*** *is less well understood*

• if ***core >3M***$_\odot$, ***no force known can stabilize core***

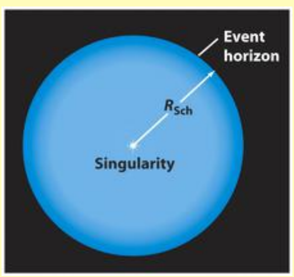


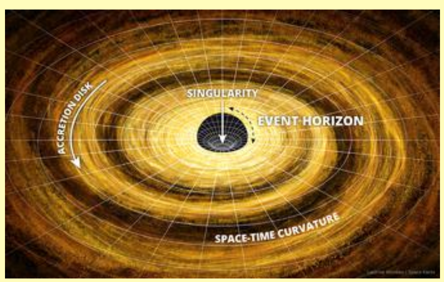
- ***core*** *collapses* to a *point* ("*singularity*")
- "*hole*" in the fabric of "***spacetime***"
- ***gravity*** so powerful that ***escape speed exceeds c***
- even ***light cannot*** escape!

"Black Holes"

- proposed in 1700s by ***Laplace*** using *Newton's escape speed*
- coined by ***John Wheeler*** (1967)

Features of Black Holes





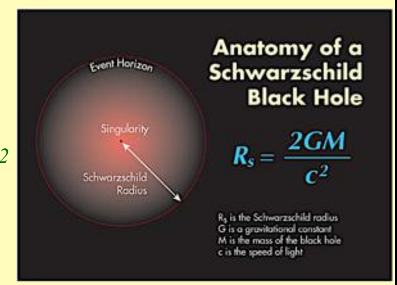
- ***event horizon****:* visible *boundary* of a ***black hole***
- at ***event horizon,*** the *escape velocity = **c***
- an ***accretion disk*** of *hot, rotating gas* may exist

Schwarzchild Radius

- R_{sch} is distance from ***singularity*** to ***event horizon***

$$R_{sch} = 2GM/c^2$$

- G = $6.67 \times 10^{-11}\ Nm^2/kg^2$
- c = $3.0 \times 10^{8}\ m/s$
- M in *kg,* R in *m*



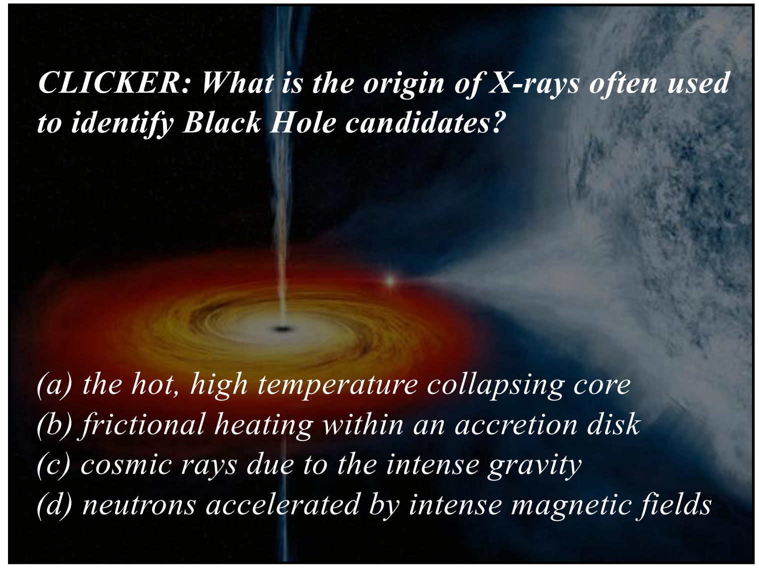
(eg) A *5 $M_\odot$ star forms a black hole of R_{sch}=15 km*

Finding Black Holes

Q: *How do you look for "nothing"?*

- ***accretion disk*** emissions
- ***gravitational interactions*** with other objects
- ***gravitational lensing*** by the black hole

- ***observational uncertainties*** **can** make it difficult to differentiate ***black holes*** from ***neutrons stars***



CLICKER: What is the origin of X-rays often used to identify Black Hole candidates?

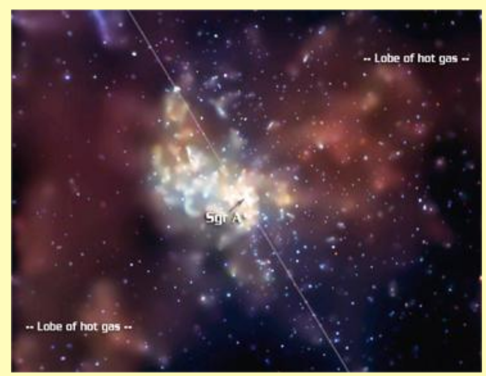
(a) the hot, high temperature collapsing core
(b) frictional heating within an accretion disk
(c) cosmic rays due to the intense gravity
(d) neutrons accelerated by intense magnetic fields

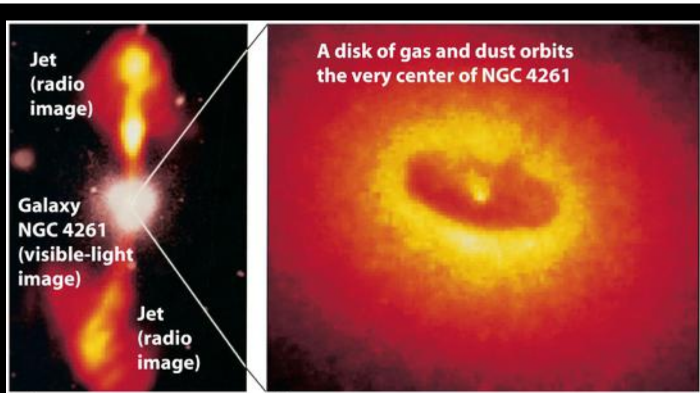
Black Hole candidate Cygnus X-1

- discovered in 1970 by ***Uhuru X-Ray satellite***
- ~30 $M_{\odot}$ B01 star & ~15 $M_{\odot}$ object co-orbiting

Supermassive Black Holes

- ***radio & X-ray measurements*** of the centers of galaxies show many have ***strong*** emission sources





• ***jets*** extend ~50,000 ly from 10^9 $M_\odot$ black hole
• HST image shows ***gas/dust disk*** 800 ly across, with material at speed 100's km/s (*Earth*: 30 km/s)

• ***M87, elliptical galaxy in Virgo (55 Mly away)***
• *6 billion solar mass supermassive black hole*

Black Hole FAQ

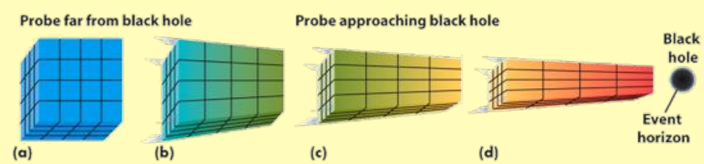
Q: *What would happen if* ***Sun*** *became a BH?*

Q: *Are BH's giant interstellar "vacuums"?*

Q: *Do BH's last forever?*

Falling into a stellar BH

• *time* & *space distort close to the* ***event horizon***



• wavelengths *lengthen (**gravitational redshift**)*

• ***cannot*** *(?)* survive journey to the ***singularity***