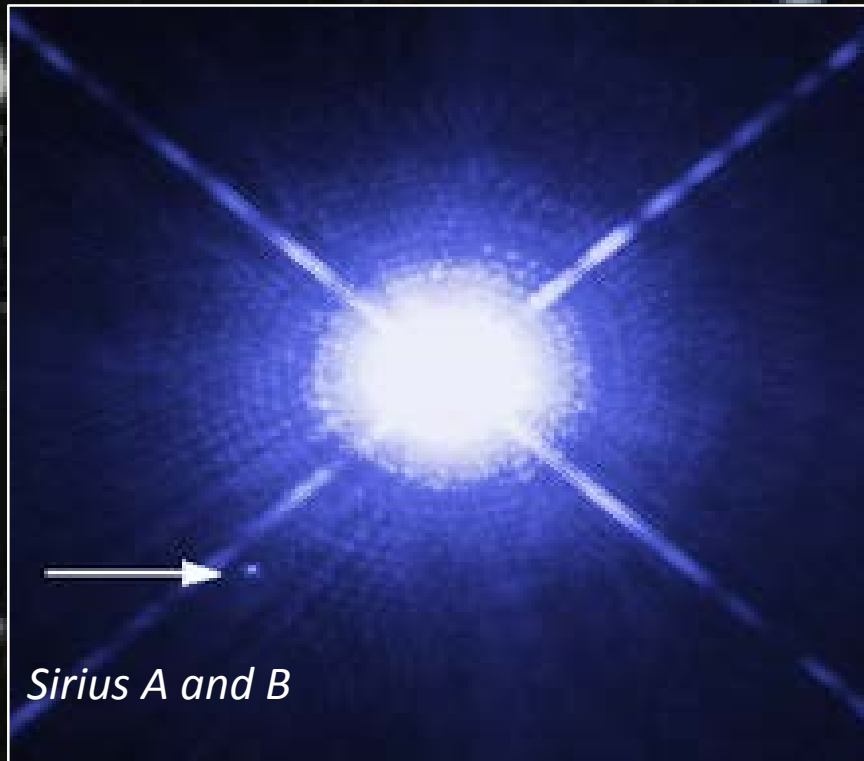


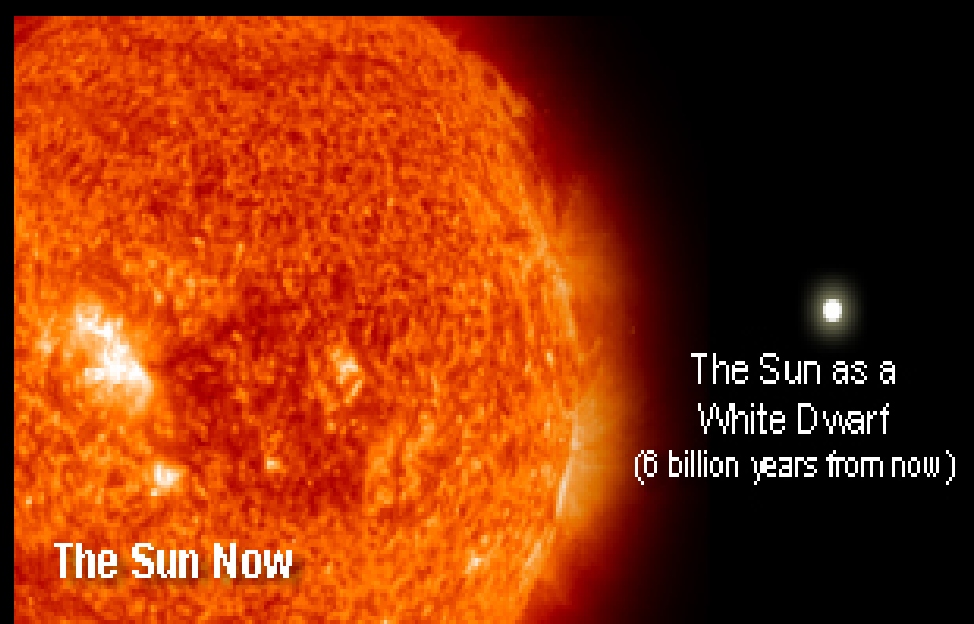
White Dwarfs and Electron Degeneracy

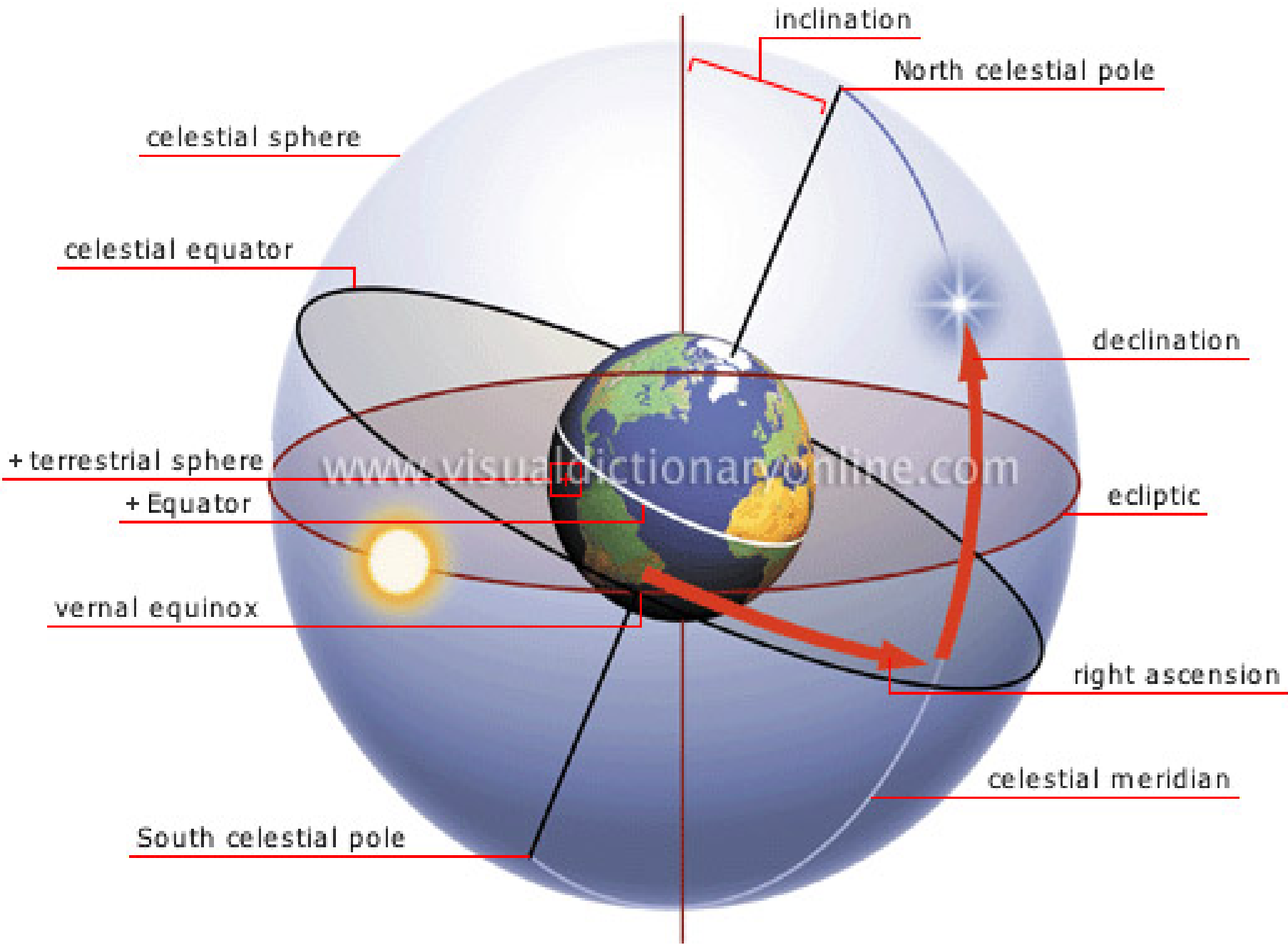


*Farley V. Ferrante
Southern Methodist University*

Outline

- Stellar astrophysics
- White dwarfs
 - Dwarf novae
 - Classical novae
 - Supernovae
- Neutron stars



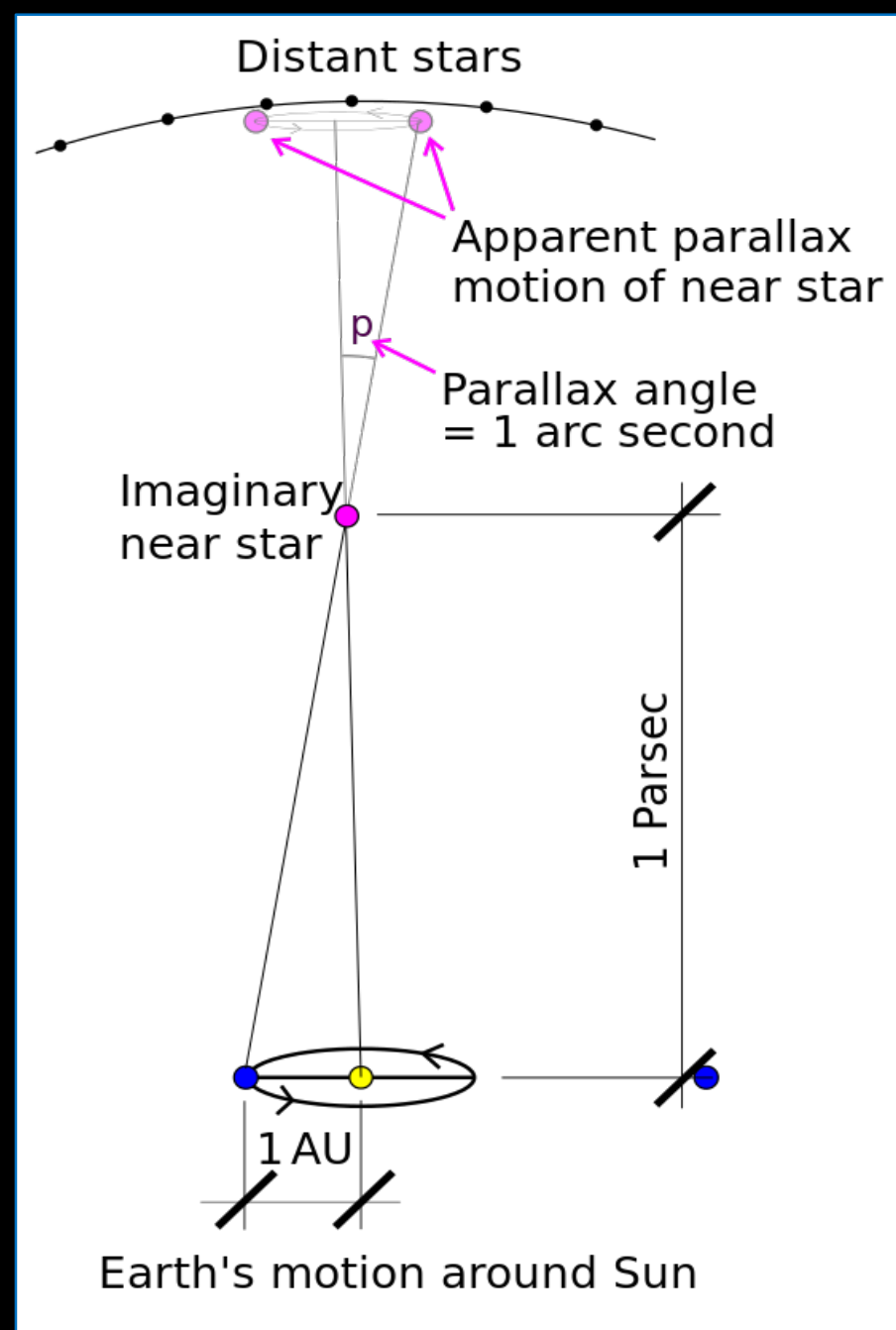
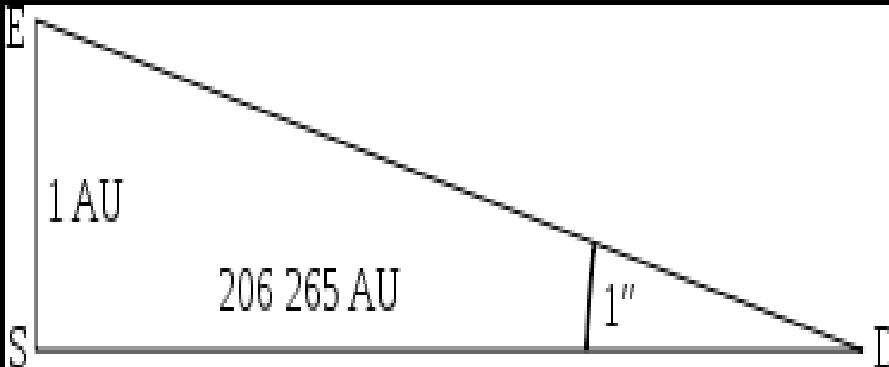


Apparent magnitude	Brightness relative to magnitude 0	Example	Apparent magnitude	Brightness relative to magnitude 0	Example	Apparent magnitude	Brightness relative to magnitude 0	Pogson's ratio: $\sqrt[5]{100} \approx 2.512$ Example
-27	6.31×10^{10}	Sun	-7	631	SN 1006 supernova	13	6.31×10^{-6}	3C 273 quasar / limit of 4.5–6" (11–15 cm) telescopes
-26	2.51×10^{10}		-6	251	ISS (max)	14	2.51×10^{-6}	Pluto (max) / limit of 8–10" (20–25 cm) telescopes
-25	1×10^{10}		-5	100	Venus (max)	15	1×10^{-6}	
-24	3.98×10^9		-4	39.8		16	3.98×10^{-7}	Charon (max)
-23	1.58×10^9		-3	15.8	Jupiter (max) , Mars (max)	17	1.58×10^{-7}	
-22	6.31×10^8		-2	6.31	Mercury (max)	18	6.31×10^{-8}	
-21	2.51×10^8		-1	2.51	Sirius	19	2.51×10^{-8}	
-20	1×10^8		0	1	Vega , Saturn (max)	20	1×10^{-8}	
-19	3.98×10^7		1	0.398	Antares	21	3.98×10^{-9}	Callirrhoe (satellite of Jupiter)
-18	1.58×10^7		2	0.158	Polaris	22	1.58×10^{-9}	
-17	6.31×10^6		3	0.0631	Cor Caroli	23	6.31×10^{-10}	
-16	2.51×10^6		4	0.0251	Acubens	24	2.51×10^{-10}	
-15	1×10^6		5	0.01	Vesta (max) , Uranus (max)	25	1×10^{-10}	Fenrir (satellite of Saturn)
-14	3.98×10^5		6	3.98×10^{-3}	typical limit of naked eye ^[note 2]	26	3.98×10^{-11}	
-13	1.58×10^5	Full moon	7	1.58×10^{-3}	Ceres (max)	27	1.58×10^{-11}	visible light limit of 8m telescopes
-12	6.31×10^4		8	6.31×10^{-4}	Neptune (max)	28	6.31×10^{-12}	
-11	2.51×10^4		9	2.51×10^{-4}		29	2.51×10^{-12}	
-10	1×10^4		10	1×10^{-4}	typical limit of 7x50 binoculars	30	1×10^{-12}	
-9	3.98×10^3	Iridium flare	11	3.98×10^{-5}		31	3.98×10^{-13}	
-8	1.58×10^3		12	1.58×10^{-5}		32	1.58×10^{-13}	visible light limit of HST

Distance Modulus

$$m - M = 5 \left[\log_{10} (d) - 1 \right]$$

- Absolute magnitude (M)
 - Apparent magnitude of an object at a standard luminosity distance of exactly 10.0 parsecs (~ 32.6 ly) from the observer on Earth
 - Allows true luminosity of astronomical objects to be compared without regard to their distances
- Unit: parsec (pc)
 - Distance at which 1 AU subtends an angle of $1''$
 - 1 AU = 149 597 870 700 m ($\approx 1.50 \times 10^8$ km)
 - 1 pc ≈ 3.26 ly
 - 1 pc $\approx 206\,265$ AU



Stellar Astrophysics

- Stefan-Boltzmann Law:

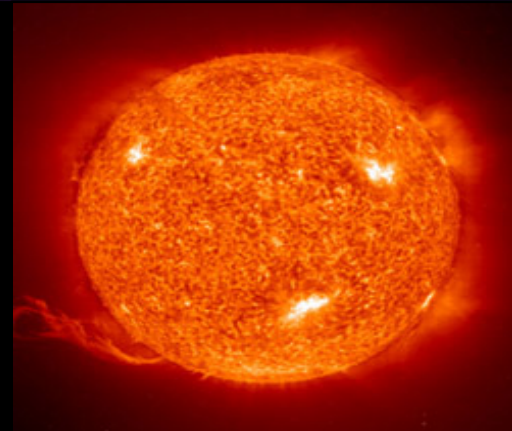
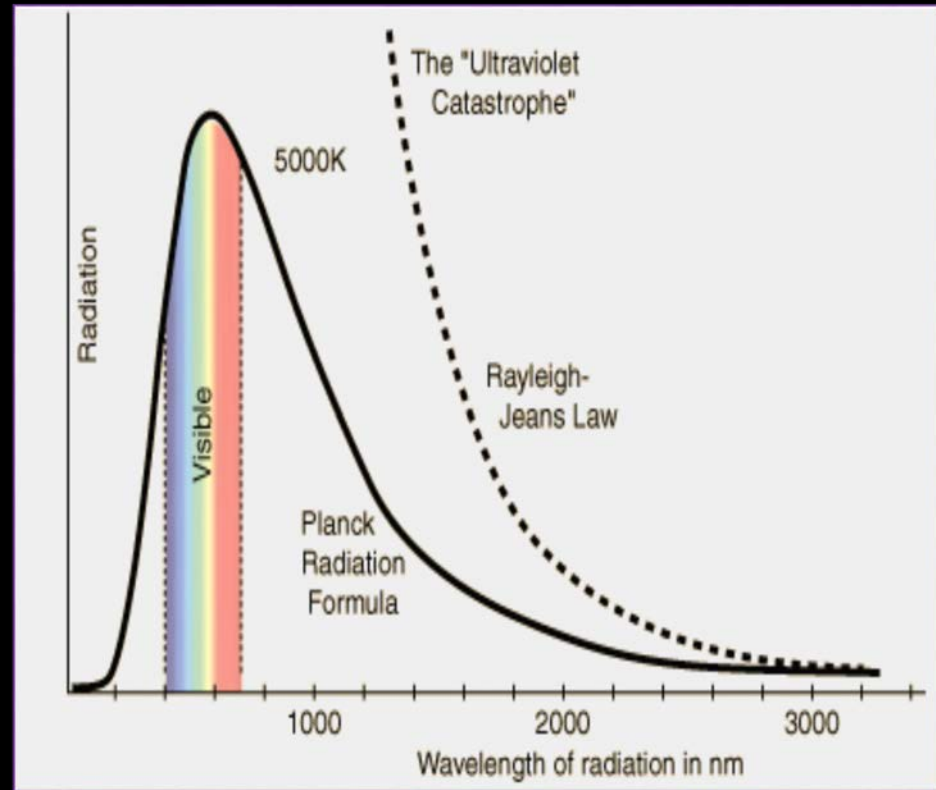
$$F_{bol} = \sigma T^4; \sigma = \frac{2\pi^5 k^4}{15c^2 h^3} = 5.67 \times 10^{-5} \text{ ergs}^{-1} \text{ cm}^{-2} \text{ K}^{-4}$$

- Effective temperature of a star: Temp. of a black body with the same luminosity per surface area
- Stars can be treated as black body radiators to a good approximation
- Effective surface temperature can be obtained from the B-V color index with the Ballesteros equation:

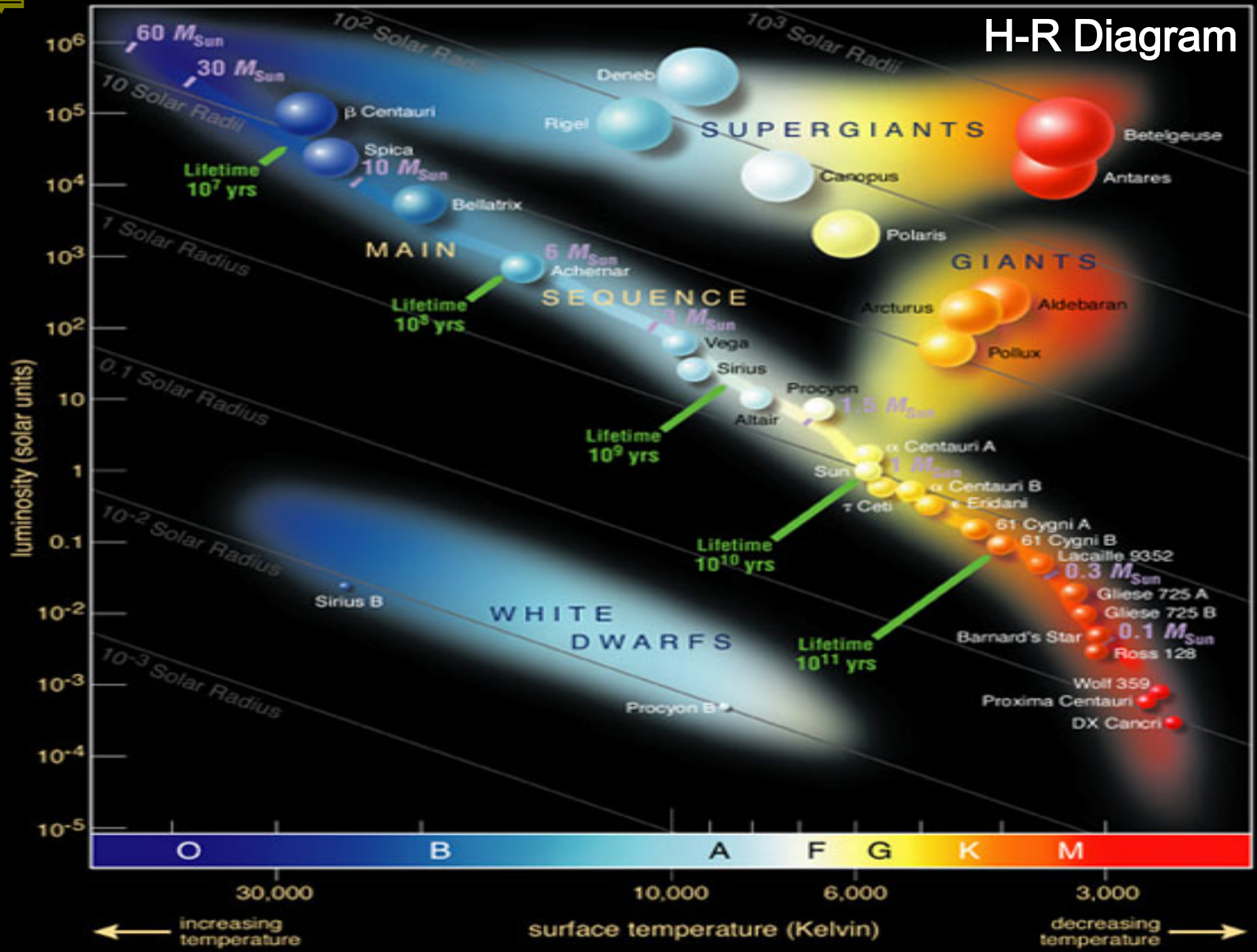
$$T = 4600 \left(\frac{1}{0.92(B-V) + 1.70} + \frac{1}{0.92(B-V) + 0.62} \right)$$

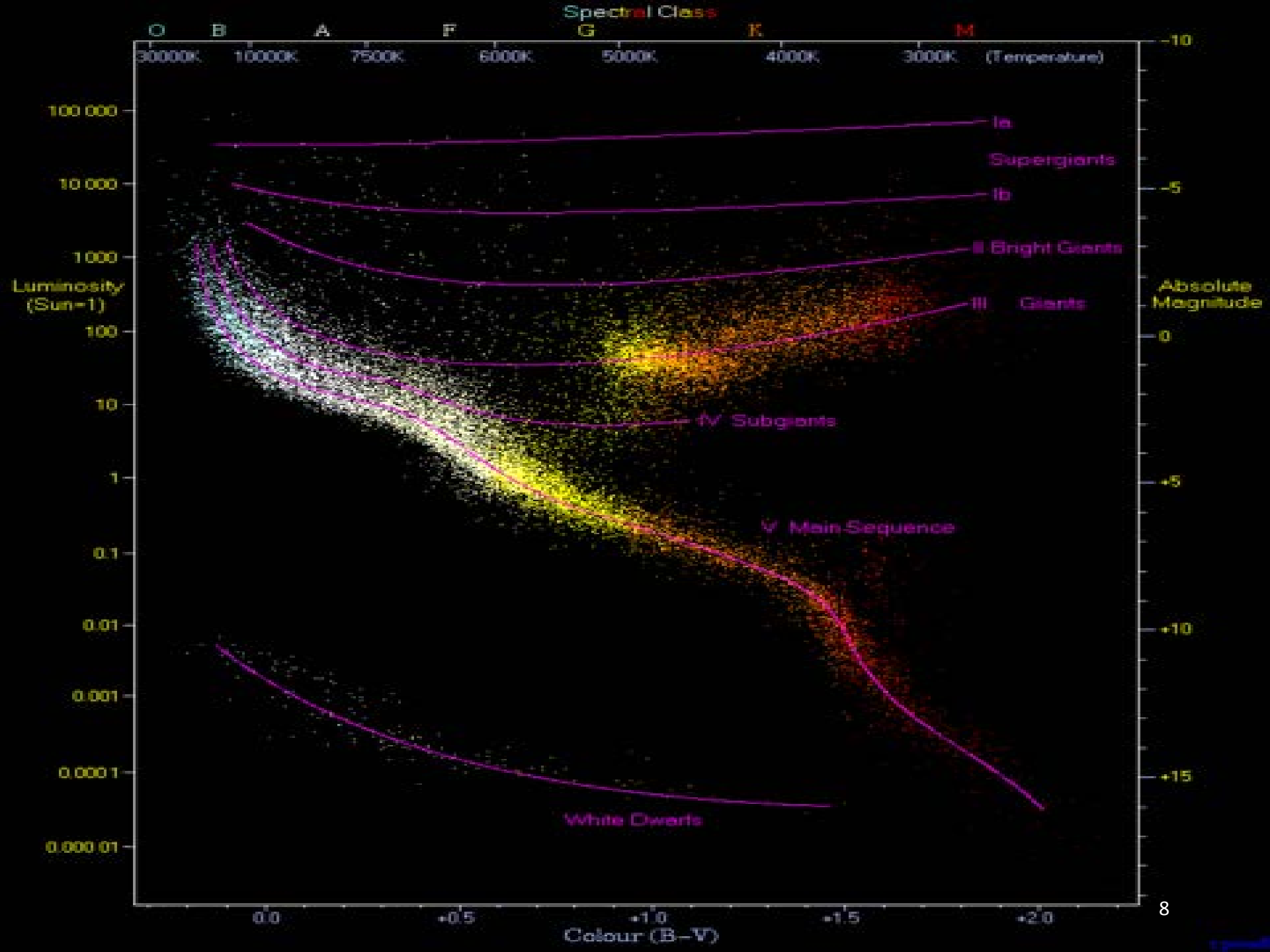
- Luminosity:

$$L = 4\pi r_*^2 \sigma T_E^4$$



H-R Diagram





Life History of Stars

Mass	Core Details	Comments
$> 0.08M_{\text{sun}}$	Low mass ball of gas, not hot enough for hydrogen fusion	Stars in this mass range are not stars, but brown dwarfs of spectral type L and T.
$0.08M_{\text{sun}} < M < 0.5M_{\text{sun}}$	Fusion of H \rightarrow ^4He . Star is never hot enough to fuse ^4He to ^{12}C or ^{16}O .	Stars in this mass range are M on the main sequence. End up white dwarfs made of helium.
$0.5M_{\text{sun}} < M < 5M_{\text{sun}}$	Fusion of H \rightarrow ^4He \rightarrow ^{12}C and ^{16}O . Center is not hot enough to fuse ^{12}C and ^{16}O .	Stars in this mass range are A, F, G and K on the main sequence. End up white dwarfs made of ^{12}C and ^{16}O .
$5M_{\text{sun}} < M < 7M_{\text{sun}}$	Fusion of H \rightarrow ^4He \rightarrow ^{12}C and ^{16}O \rightarrow ^{20}Ne and ^{24}Mg .	Stars in this mass range are B on main sequence. End up as white dwarfs made of ^{20}Ne and ^{24}Mg .
$M > 7M_{\text{sun}}$	Fusion of H \rightarrow ^4He \rightarrow ^{12}C and ^{16}O \rightarrow ^{20}Ne and ^{24}Mg \rightarrow heavier elements.	Stars in this mass range are O on the main sequence. End up as neutron stars or black holes.

White dwarf

- Core of solar mass star
- Pauli exclusion principle:
Electron degeneracy
- Degenerate Fermi gas of oxygen
and carbon
- 1 teaspoon would weigh 5 tons
- No energy produced from fusion
or gravitational contraction

Hot white dwarf NGC 2440. The white dwarf is surrounded by a "cocoons" of the gas ejected in the collapse toward the white dwarf stage of stellar evolution.

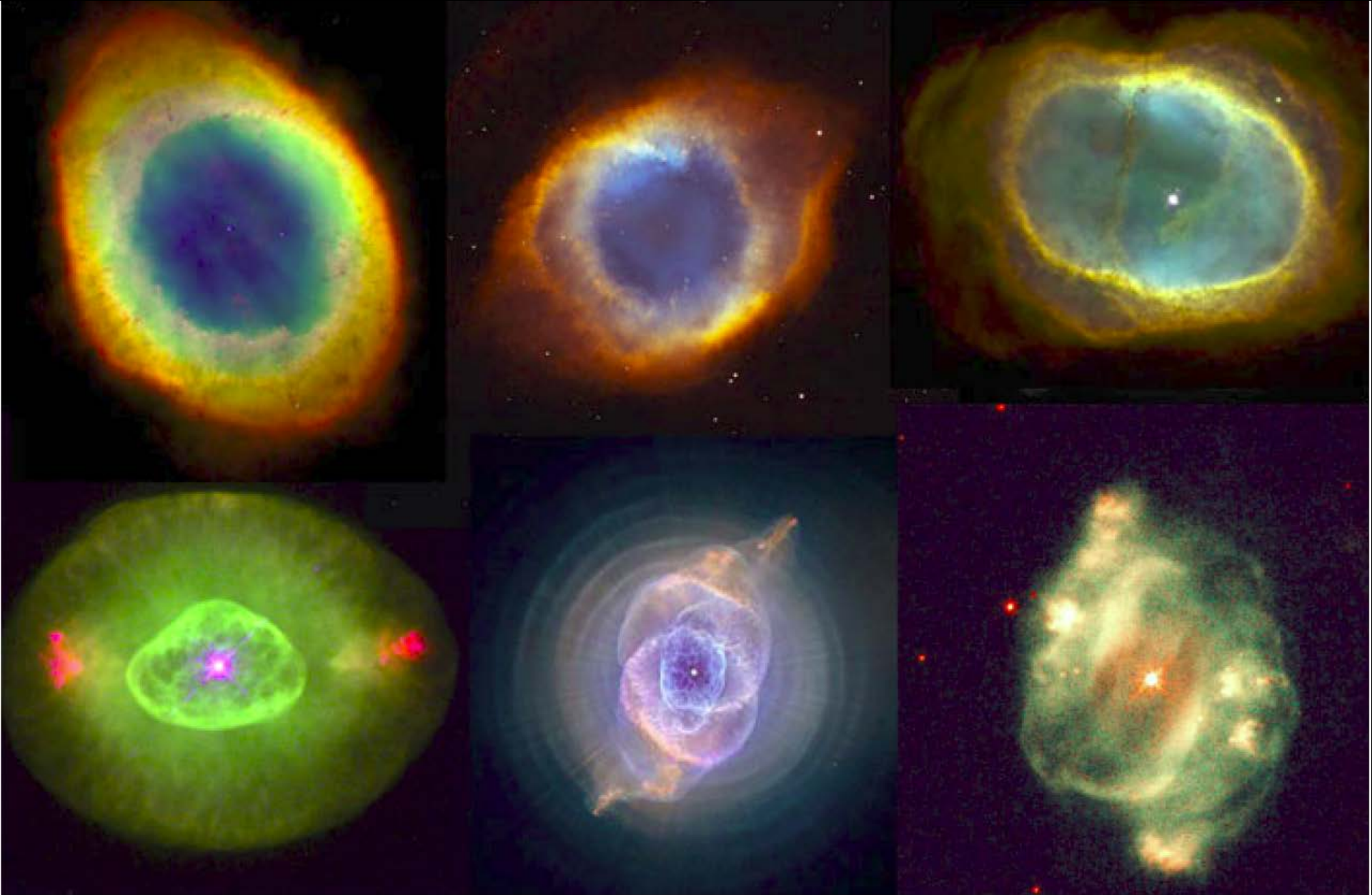


Figure 4.2 Several examples of planetary nebulae, newly formed white dwarfs that irradiate the shells of gas that were previously shed in the final stages of stellar evolution. The shells have diameters of $\approx 0.2 - 1$ pc. Photo credits: M. Meixner, T.A. Rector, B. Balick et al., H. Bond, R. Ciardullo, NASA, NOAO, ESA, and the Hubble Heritage Team

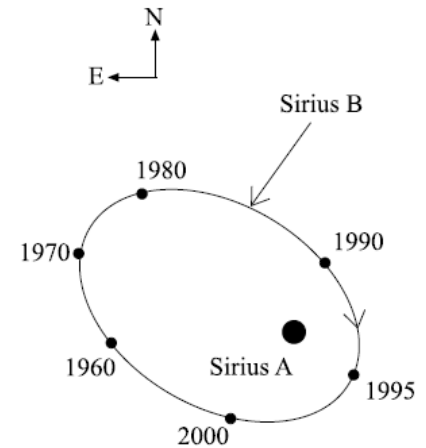
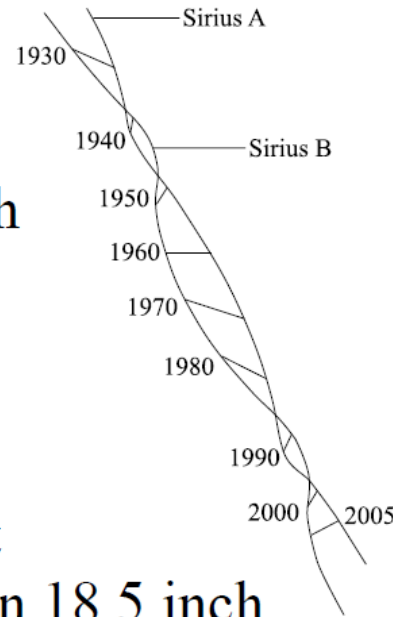
White Dwarfs

Sirius B is a white dwarf companion to Sirius A.

In 1844 German astronomer Friedrich Bessel deduced the existence of a companion star from changes in the proper motion of Sirius.

In 1862, astronomer Alvan Clark first observed the faint companion using an 18.5 inch refractor telescope at the Dearborn Observatory.

In 1915 Walter Adams observed the spectrum of the star, determining it was a faint whitish star. This led astronomers to conclude it was a white dwarf.



Matter at Quantum Densities

As stars evolve, their cores contract and the core density increases. At some point the distance between the atoms is smaller than their de Broglie wavelengths and classical assumptions can no longer be used.

Recall: **de Broglie Wavelength**

$$\lambda = \frac{h}{p} = \frac{h}{(2mE)^{1/2}} \approx \frac{h}{(3mkT)^{1/2}}$$

Since,

$$p = mv$$

$$p = \sqrt{2mE}$$

$$E_K = \frac{1}{2}mv^2$$

$$v = \sqrt{\frac{2E}{m}}$$

$$E \sim \frac{3kT}{2}$$

↑
*mean energy
of a particle*

Question: Which will reach the quantum domain first, electrons or protons?

Although both electrons and protons share the same energy, electrons have smaller mass and longer wavelengths. The electron density will reach the quantum domain first.

When the inter particle spacing is of order 1/2 a de Broglie wavelength, quantum effects will become important.

$$\rho_q \approx \frac{m_p}{(\lambda/2)^3} = \frac{8m_p(3m_e kT)^{3/2}}{h^3}$$

Calculate the quantum density at the center of the sun ($T = 15 \times 10^6 \text{ K}$).

$$\rho_q \approx \frac{8 \times 1.7 \times 10^{-24} \text{ g} (3 \times 9 \times 10^{-28} \text{ g} \times 1.4 \times 10^{-16} \text{ erg K}^{-1} \times 15 \times 10^6 \text{ K})^{3/2}}{(6.6 \times 10^{-27} \text{ erg s})^3}$$

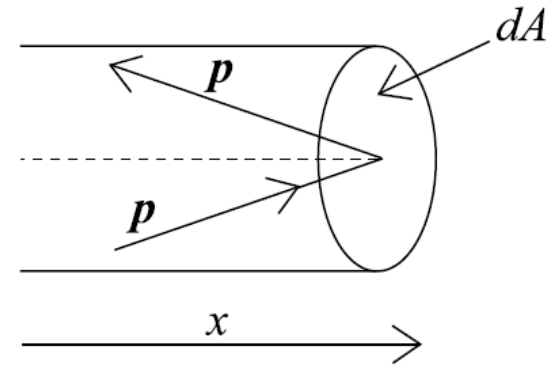
$$\rho_q = 640 \text{ g cm}^{-3}$$

The core density of the sun is 150 g cm^{-3} .
Much below the quantum regime.

Pressure Exerted by Ideal Gas

Consider ideal gas particles hitting the sides of a container.

Recall, that particles with momentum p_x impart $2p_x$ to the surface with each reflection.



The force per unit area imparted is then

$$\frac{dF_x}{dA} = \frac{2p_x}{dAdt} = \frac{2p_x v_x}{dAdx} = \frac{2p_x v_x}{dV}$$

where we used:

$$v_x = \frac{dx}{dt}$$

To get the pressure, we sum forces due to particles of all momenta.

$$P = \int_0^{\infty} dN(p) \frac{p_x v_x}{dV} dp$$

Note: half the particles are not moving towards walls.

Simplify:

$$p_x v_x = m v_x^2 = \frac{1}{3} m v^2 = \frac{1}{3} p v$$

$$P = \int_0^\infty dN(p) \frac{p_x v_x}{dV} dp$$

If we assume the velocities are isotropic: $v_x^2 = v_y^2 = v_z^2$

Substitute:

$$P = \frac{1}{3} \int_0^\infty n(p) p v dp$$

where we used: $dN/dV \equiv n$

For a non-relativistic degenerate gas:

$$n_e(p) dp = \begin{cases} 8\pi p^2 \frac{dp}{h^3} & \text{if } |\mathbf{p}| \leq p_f \\ 0 & \text{if } |\mathbf{p}| > p_f \end{cases}$$

$$\begin{aligned} P_e &= \frac{1}{3} \int_0^{p_f} \frac{8\pi}{h^3} \frac{p^4}{m_e} dp = \frac{8\pi}{3h^3 m_e} \frac{p_f^5}{5} \\ &= \left(\frac{3}{8\pi} \right)^{2/3} \frac{h^2}{5m_e} n_e^{5/3} \end{aligned}$$

$$v = p/m_e$$

$$n_e = \frac{8\pi}{3h^3} p_f^3$$

Finally, noting $n_e = Z n_+ = Z \rho / A m_p$

$$P_e = \left(\frac{3}{\pi} \right)^{2/3} \frac{h^2}{20 m_e m_p^{5/3}} \left(\frac{Z}{A} \right)^{5/3} \rho^{5/3}$$

Re-derive scaling relations between mass and radius with an index $(4 + \epsilon)/3$.

$$P \sim b\rho^{5/3} \longrightarrow P \sim \rho^{(4+\epsilon)/3} = \frac{M^{(4+\epsilon)/3}}{r^{(4+\epsilon)}}$$

Equating with pressure from our stellar equations.

$$P \sim \frac{GM\rho}{r} \sim \frac{M^2}{r^4}$$

$$\frac{M^{4/3} M^{\epsilon/3}}{r^4 r^\epsilon} = \frac{M^{(4+\epsilon)/3}}{r^{4+\epsilon}} \sim \frac{M^2}{r^4}$$

$$r^\epsilon \sim M^{(\epsilon-2)/3}$$

$$r \sim M^{(\epsilon-2)/3\epsilon}$$

When $\epsilon \rightarrow 0$

$$r \rightarrow M^{-\infty} = 0$$

$$P_e = \left(\frac{3}{\pi}\right)^{2/3} \frac{h^2}{20m_e m_p^{5/3}} \left(\frac{Z}{A}\right)^{5/3} \rho^{5/3}$$

Comments:

The electron pressure does not depend on temperature.

For a typical white dwarf, $\rho \sim 10^6 \text{ g cm}^{-3}$ and $T \sim 10^7 \text{ K}$.

Their $Z/A \sim 0.5$.

$$P_e \sim \frac{(6.6 \times 10^{-27} \text{ erg s})^2}{20 \times 9 \times 10^{-28} \text{ g} (1.7 \times 10^{-24} \text{ g})^{5/3}} 0.5^{5/3} (10^6 \text{ g cm}^{-3})^{5/3} = 3 \times 10^{22} \text{ dyne cm}^{-2}$$

Compare to the thermal pressure of nuclei at this temperature.

$$P = n kT = 2 \times 10^{20} \text{ dyne cm}^{-2}$$

Thus, degenerate electron pressure completely dominates the pressure in these stars.

Properties of White Dwarfs

Mass-Radius Relationship:

Recall the EOS for a degenerate non-relativistic electron gas:

$$P_e = \left(\frac{3}{\pi}\right)^{2/3} \frac{h^2}{20m_e m_p^{5/3}} \left(\frac{Z}{A}\right)^{5/3} \rho^{5/3}.$$

The scaling relation for this equation is

$$P \sim b\rho^{5/3} \sim b\frac{M^{5/3}}{r^5} \quad \text{where } b \text{ is a constant}$$

Recall our scaling relations from the equations of stellar structure:

$$P \sim \frac{GM\rho}{r} \sim \frac{GM^2}{r^4}$$

Equating these pressures yields:

$$r \sim \frac{b}{G} M^{-1/3}$$



What?

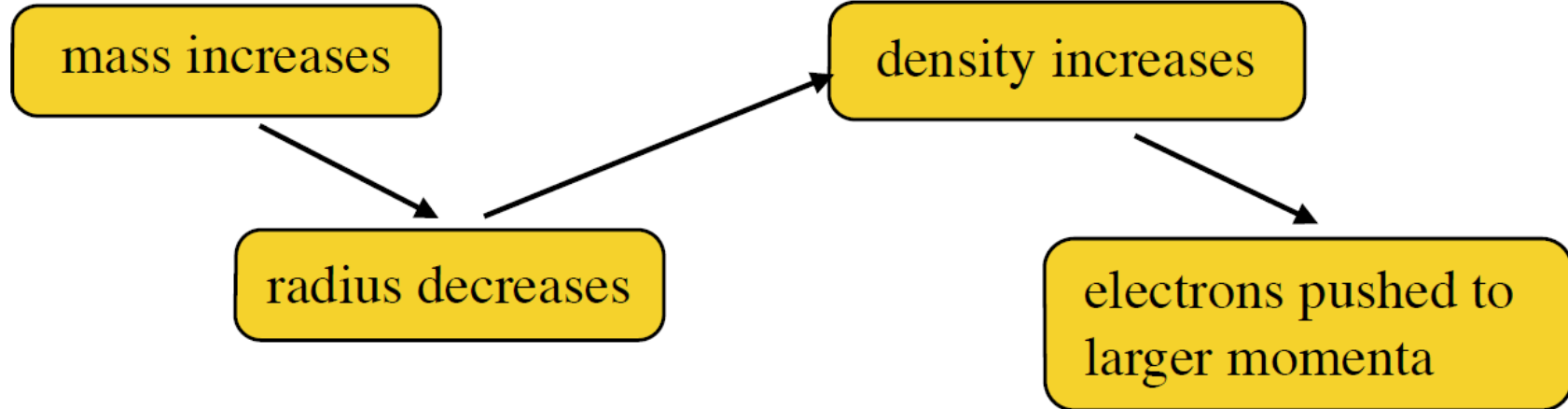
Notice: The radius decreases with increasing mass!

A white dwarf with $Z/A = 0.5$ and $M = 1M_{\text{sun}}$ has a radius of ~ 4000 km.

$$r \sim \frac{b}{G} M^{-1/3}$$

Fully working out the equations of stellar structure gives an equation for radius of

$$r_{\text{wd}} = 2.3 \times 10^9 \text{cm} \left(\frac{Z}{A} \right)^{5/3} \left(\frac{M}{M_{\odot}} \right)^{-1/3}$$



Mass/radius relation for degenerate star

- Stellar mass = M ; radius = R

- Gravitational potential energy:

$$E_{gr} = -\frac{3GM^2}{5R}$$

- Heisenberg uncertainty:

$$\Delta x \Delta p \geq \hbar$$

- Electron density:

$$n = \frac{3N}{4\pi R^3} \approx \frac{M}{m_p R^3}$$

$$\Delta x \approx n^{-1/3} \quad \Delta p \approx \frac{\hbar}{\Delta x} \approx \hbar n^{1/3}$$

- Kinetic energy:

$$\varepsilon = \frac{p^2}{2m_e} \quad K = N\varepsilon = \frac{M}{m_p} \varepsilon \approx \frac{\hbar^2 M^{5/3}}{m_e m_p^{5/3} R^2}$$

Mass/radius relation for degenerate star

- Total energy:
$$E = K + U \approx \frac{\hbar^2 M^{5/3}}{m_e m_p^{5/3} R^2} - \frac{GM^2}{R}$$

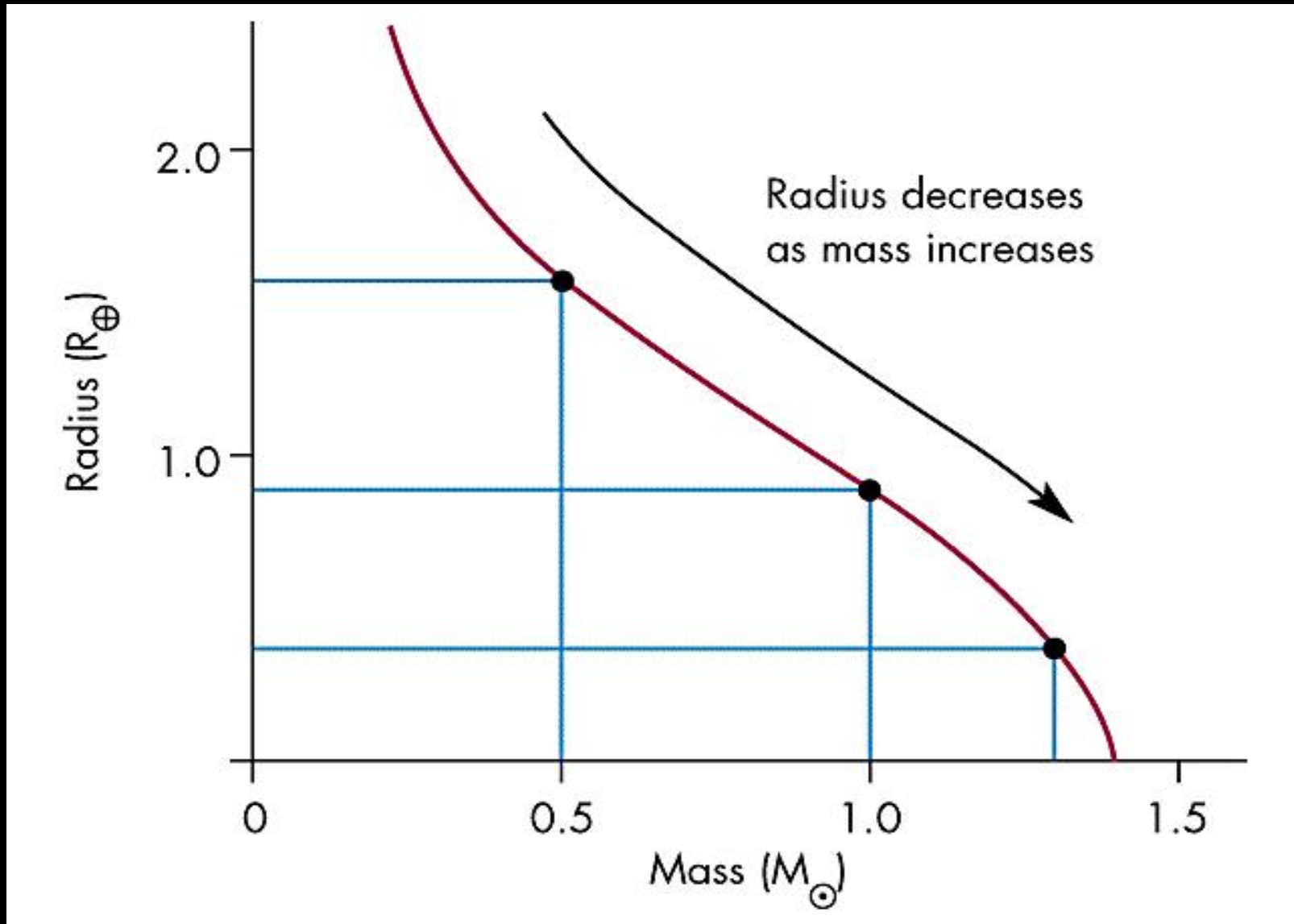
- Find R by minimizing E :

$$\frac{dE}{dR} \approx -\frac{\hbar^2 M^{5/3}}{m_e m_p^{5/3} R^3} + \frac{GM^2}{R^2} = 0$$

- Radius decreases as mass increases:

$$R \approx \frac{\hbar^2 M^{-1/3}}{G m_e m_p^{5/3}}$$

Mass vs radius relation



$$r \rightarrow M^{-\infty} = 0$$

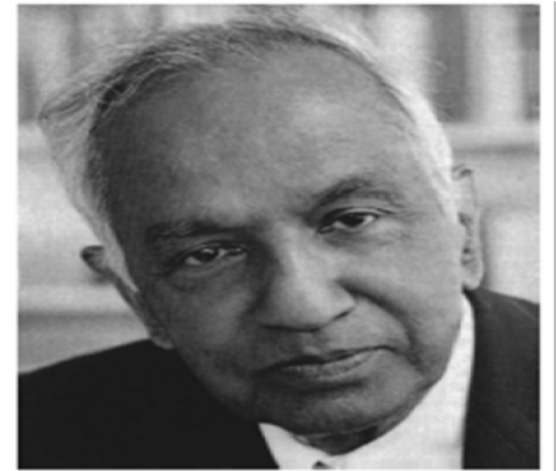
What does it mean?

At masses so high that electrons become ultra-relativistic, the electron pressure is unable to support the star against gravity.

If the density is high enough, degeneracy pressure due to protons and neutrons begins to operate. Stops collapse and produces a neutron star.

Chandrasekhar Mass:

The maximum stellar mass that can be supported by electron degeneracy pressure.



Subrahmanyan Chandrasekhar (1910–1995)

Estimate Chandrasekhar Mass

Start with virial theorem

$$\bar{P}V = -\frac{1}{3}E_{\text{gr}}$$

Substitute the ultra-relativistic electron degeneracy pressure and self gravity

$$P_e = \left(\frac{3}{8\pi}\right)^{1/3} \frac{hc}{4m_p^{4/3}} \left(\frac{Z}{A}\right)^{4/3} \rho^{4/3}$$

$$\left(\frac{3}{8\pi}\right)^{1/3} \frac{hc}{4m_p^{4/3}} \left(\frac{Z}{A}\right)^{4/3} \rho^{4/3} V \sim \frac{1}{3} \frac{GM^2}{r}$$

Simplify:

$$M \sim 0.11 \left(\frac{Z}{A}\right)^2 \left(\frac{hc}{Gm_p^2}\right)^{3/2} m_p$$

$$\rho \sim \frac{M}{V}$$

$$V = \frac{4\pi}{3} r^3$$

Full Solution using Equations of Stellar Structure:

$$M_{\text{ch}} = 0.21 \left(\frac{Z}{A}\right)^2 \left(\frac{hc}{Gm_p^2}\right)^{3/2} m_p$$

Accurately calculated value is $1.4 M_{\text{sun}}$.

As electron velocities increase, the rates at which momentum transfers approaches c . So, we need to modify the EOS for degenerate electron gas.

$$P_e = \left(\frac{3}{8\pi}\right)^{1/3} \frac{hc}{4m_p^{4/3}} \left(\frac{Z}{A}\right)^{4/3} \rho^{4/3}$$

EOS for an ultra-relativistic degenerate spin-1/2 fermion gas

Compare to non-relativistic case:

$$P_e = \left(\frac{3}{\pi}\right)^{2/3} \frac{h^2}{20m_e m_p^{5/3}} \left(\frac{Z}{A}\right)^{5/3} \rho^{5/3}$$

EOS for a degenerate non-relativistic electron gas

Notes: **The power index changes.**

The electron mass disappears.

For ultra-relativistic particles, the rest mass is negligible.

As we go from small to large white dwarf masses, we transition gradually from non-relativistic to ultra-relativistic.

Notes:

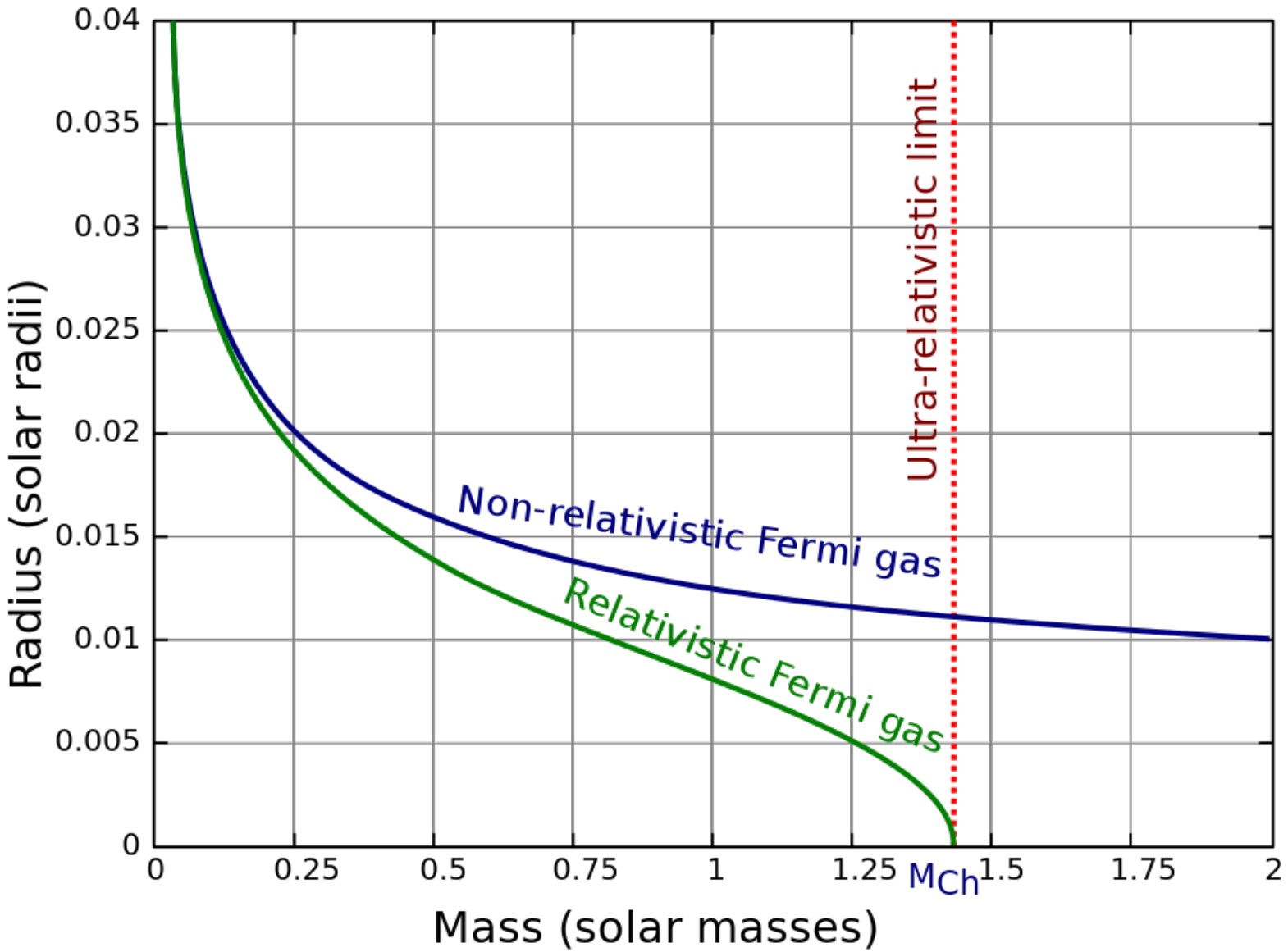
The accurately calculated Chandrasekhar mass is $1.4 M_{\text{sun}}$.

No white dwarfs with masses greater than M_{ch} have ever been found.

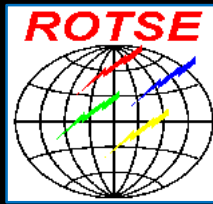
The lower bound of isolated white dwarfs found is $0.25 M_{\text{sun}}$.
Why is there a lower bound?

The universe is too young! Stars that have mass $< 0.8 M_{\text{sun}}$ could produce smaller white dwarfs. However, even if they were formed in the early universe, they have not yet gone through their main sequence lifetime.

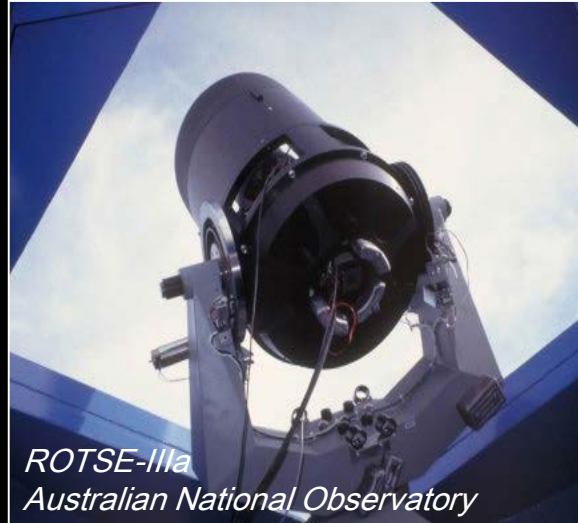
Mass vs radius relation



ROTSE

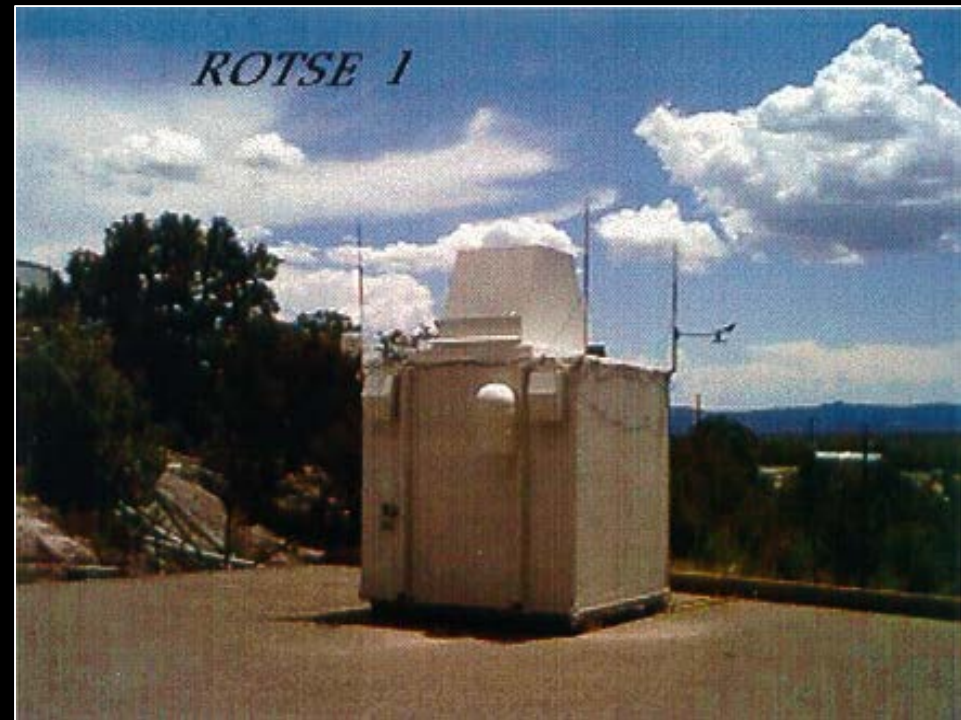


- Robotic Optical Transient Search Experiment
- Original purpose: Observe GRB optical counterpart (“afterglow”)
- Observation & detection of optical transients (seconds to days)
- Robotic operating system
 - Automated interacting Linux daemons
 - Sensitivity to short time-scale variation
 - Efficient analysis of large data stream
 - Recognition of rare signals
- Current research:
 - GRB response
 - SNe search (RSVP)
 - Variable star search
 - Other transients: AGN, CV (dwarf novae), flare stars, novae, variable stars, X-ray binaries



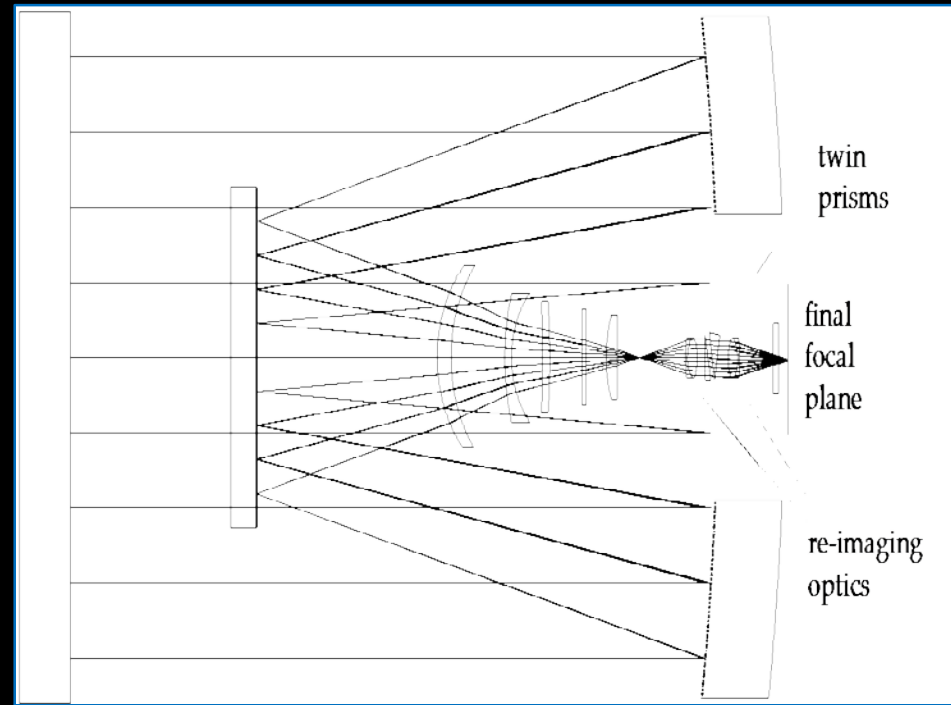
ROTSE-I

- 1st successful robotic telescope
- 1997-2000; Los Alamos, NM
- Co-mounted, 4-fold telephoto array (Canon 200 mm lenses)
- CCD
 - 2k x 2k Thomson
 - “Thick”
 - Front illuminated
 - Red sensitive
 - R-band equivalent
 - Operated “clear” (unfiltered)
- Optics
 - Aperture (cm): 11.1
 - f-ratio: 1.8
 - FOV: $16^\circ \times 16^\circ$
- Sensitivity (magnitude): 14-15
 - Best: 15.7
- Slew time (90°): 2.8 s
- 990123: Observed 1st GRB afterglow in progress
 - Landmark event
 - Proof of concept



ROTSE-III

- 2003 – present
- 4 Cassegrain telescopes
- CCD
 - “Thin”
 - Back illuminated
 - Blue-sensitive
 - High QE (UBVRI bands)
 - Default photometry calibrated to R-band
- Optics
 - Aperture (cm): 45
 - f-ratio: 1.9
 - FOV: $1.85^\circ \times 1.85^\circ$
- Sensitivity (magnitude): 19-20
- Slew time: < 10 s



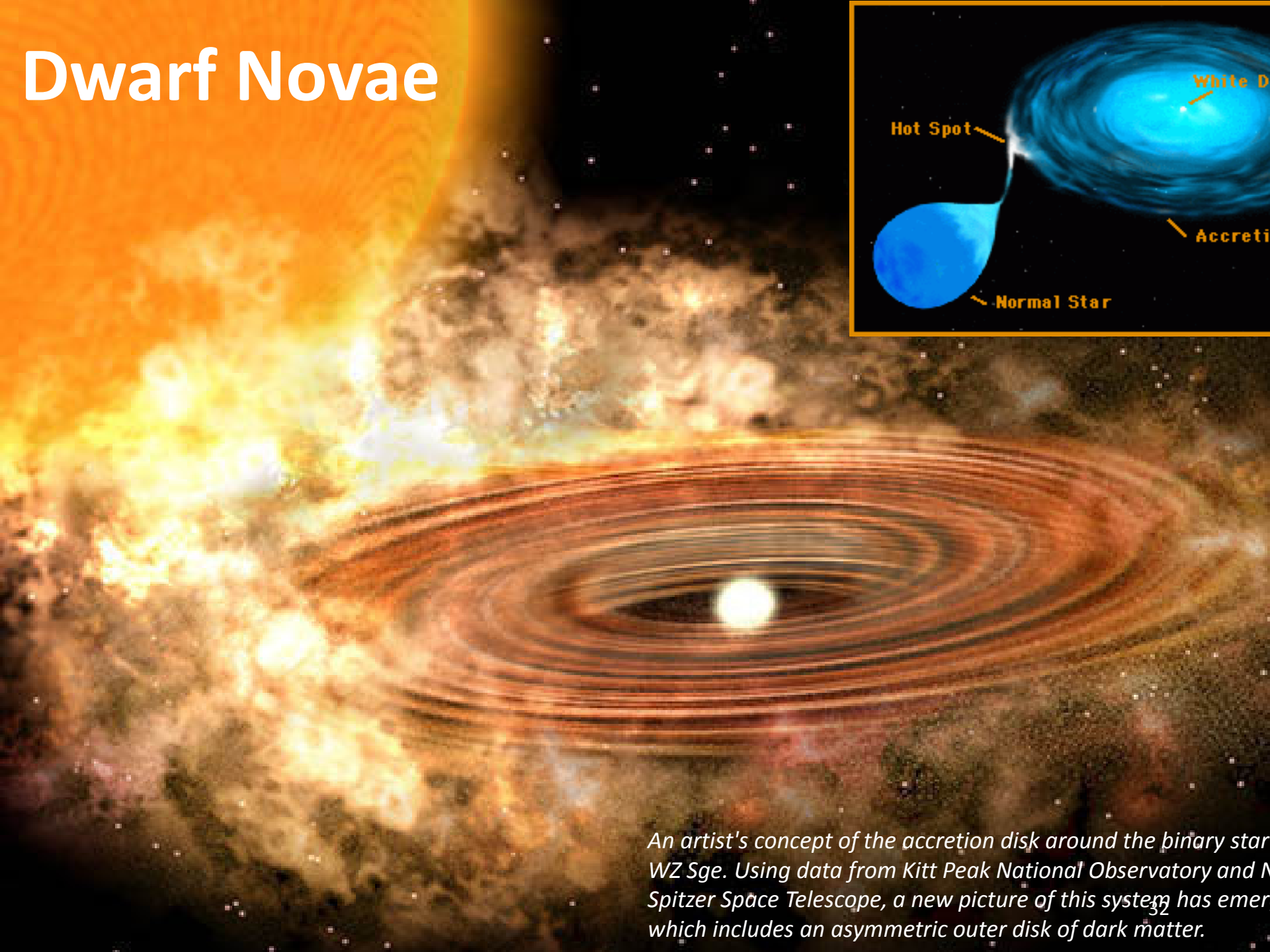
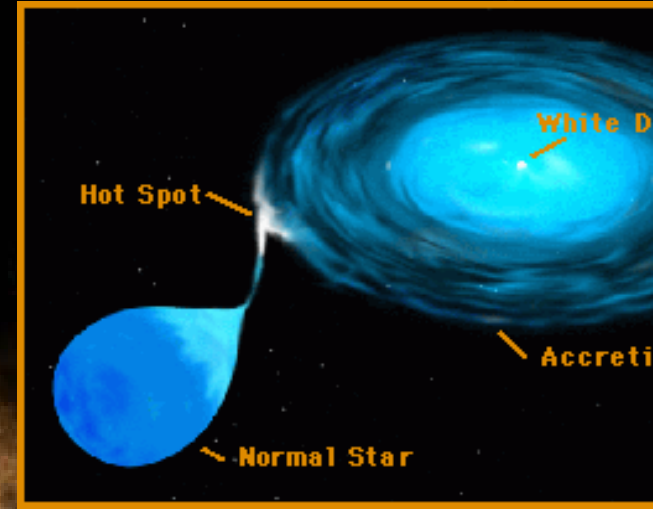
SMU PHYSICS



ROTSE-IIIb

McDonald Observatory
Davis Mountains, West Texas

Dwarf Novae

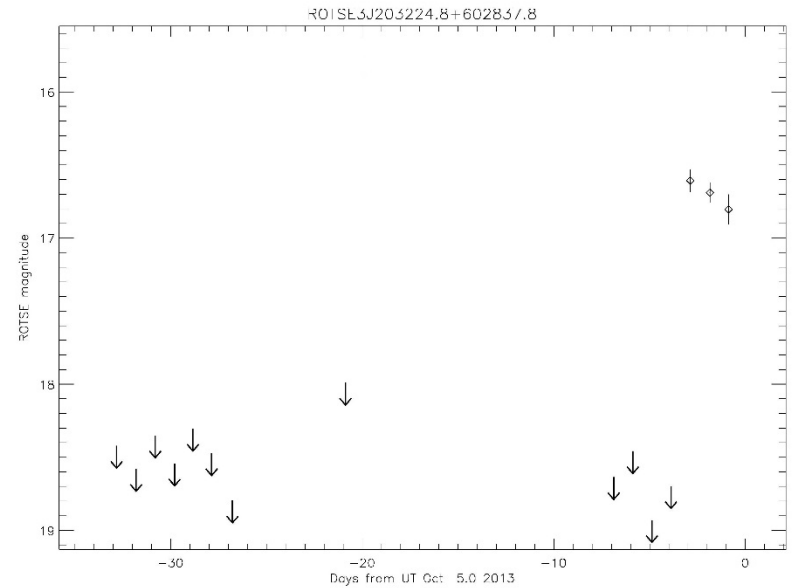


An artist's concept of the accretion disk around the binary star WZ Sge. Using data from Kitt Peak National Observatory and the Spitzer Space Telescope, a new picture of this system has emerged, which includes an asymmetric outer disk of dark matter.

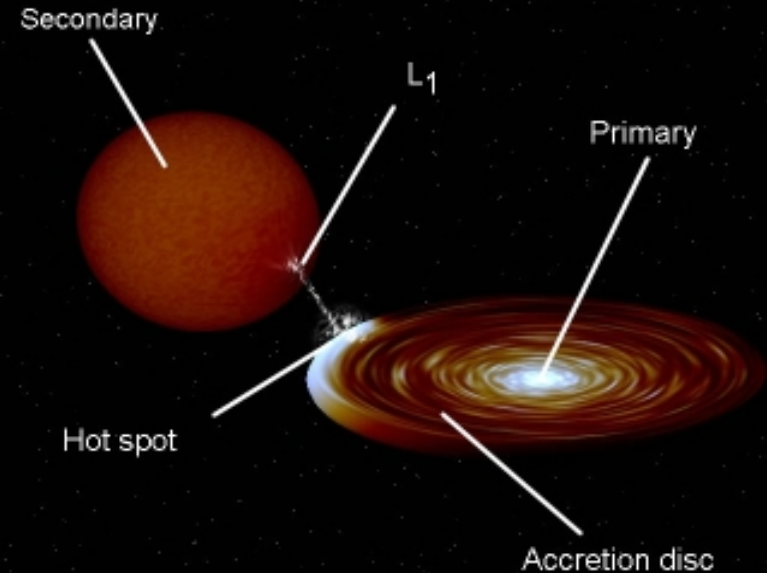
ROTSE3 J203224.8+602837.8

- 1st detection (110706):
 - ROTSE-IIIb & ROTSE-IIIc
 - ATel #2126
- Outburst (131002 – 131004):
 - ROTSE-IIIb
 - ATel #5449
- Magnitude (max): 16.6
- (RA, Dec) = (20:32:25.01, +60:28:36.59)
- UG Dwarf Nova
 - Close binary system consisting of a red dwarf, a white dwarf, & an accretion disk surrounding the white dwarf
 - Brightening by 2 - 6 magnitudes caused by instability in the disk
 - Disk material infalls onto white dwarf

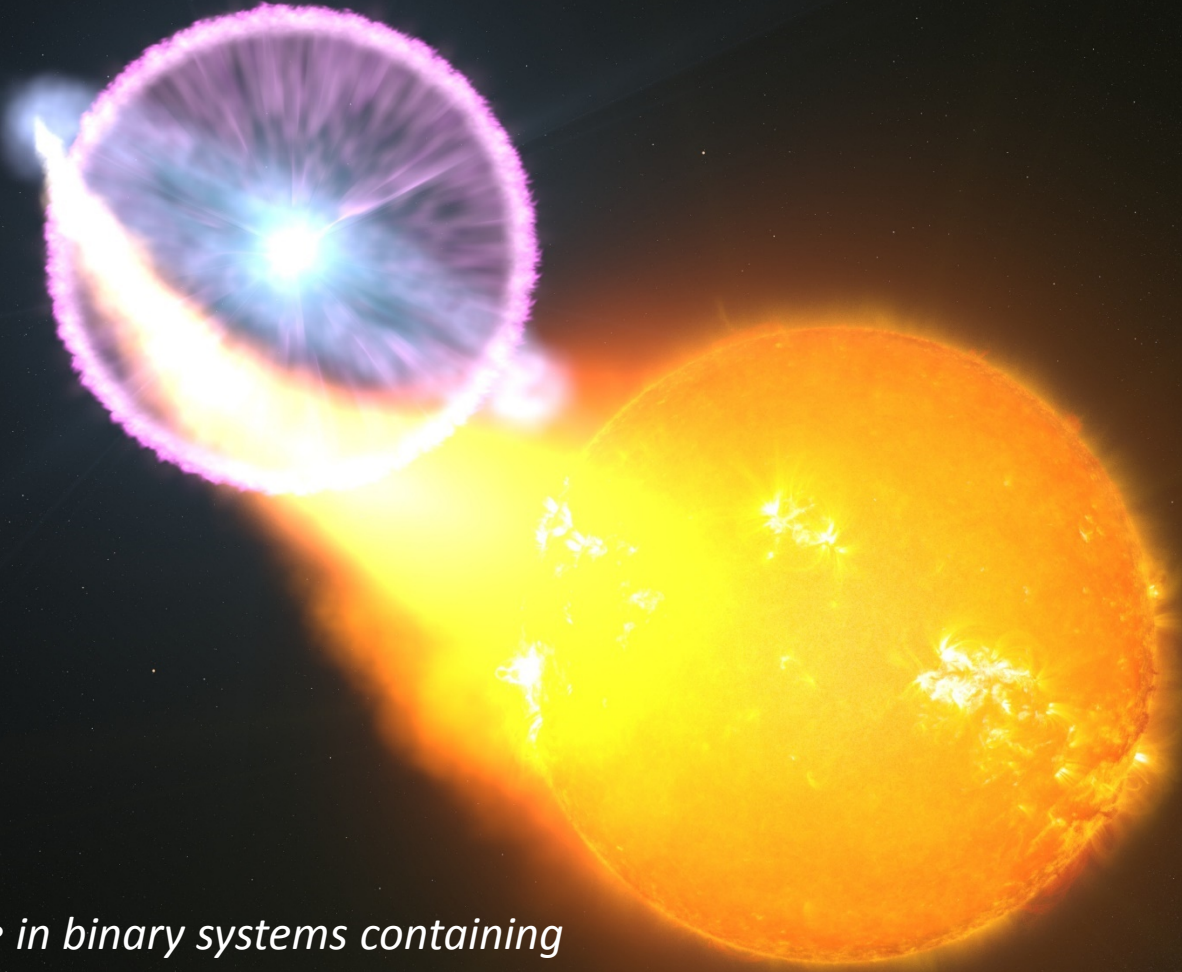
“Damien”



10. 2.2013 2:28:14 mlim = 17.60 ; fwhm = 3.2	10. 2.2013 3:12:25 mlim = 17.37 ; fwhm = 3.3	7.24.2007 5:50:52 mlim = 18.98 ; fwhm = 2.2												
subtraction 1 	subtraction 2 	<p>RA: 20:32:25.01 Dec: +60:28:36.59 (308.10422 60.47683)</p> <p>This candidate does not match a galaxy or a star</p> <table border="1"> <thead> <tr> <th>Mag</th> <th>S/N</th> <th>FWHM</th> <th>Motion</th> <th>% change</th> <th>Before?</th> </tr> </thead> <tbody> <tr> <td>16.49</td> <td>24.4</td> <td>3.66</td> <td>0.53</td> <td>258</td> <td>26**/0423</td> </tr> </tbody> </table> <p>Check SIMBAD objects <input type="button" value="Check SDSS"/></p> <p><input type="button" value="MPCChecker"/> <input type="button" value="Check 2MASS"/> <input type="button" value="FITS"/> <input type="button" value="Get DSS"/></p> <p><input checked="" type="radio"/> Junk <input type="radio"/> Asteroid <input type="radio"/> Variable Star <input type="radio"/> Interesting!</p> <p>Please add any comments you might have here:</p> <p><input type="button" value="Submit your Contribution"/></p>	Mag	S/N	FWHM	Motion	% change	Before?	16.49	24.4	3.66	0.53	258	26**/0423
Mag	S/N	FWHM	Motion	% change	Before?									
16.49	24.4	3.66	0.53	258	26**/0423									



Novae (classical)



Novae typically originate in binary systems containing sun-like stars, as shown in this artist's rendering.

M33N 2012-10a

- 1st detection: 121004 (ROTSE-IIIb)
- (RA, Dec) = (01:32:57.3, +30:24:27)
- Constellation: Triangulum
- Host galaxy: M33
- Magnitude (max): 16.6
- $z = 0.0002$ (~0.85 Mpc, ~2.7 Mly)
- Classical nova
 - Explosive nuclear burning of white dwarf surface from accumulated material from the secondary
 - Causes binary system to brighten 7 - 16 magnitudes in a matter of 1 to 100s days
 - After outburst, star fades slowly to initial brightness over years or decades
- CBET 3250

10. 4. 2012 4: 7:44

mlim = 17.37 ; fwhm = 3.4

10. 4. 2012 4:41:18

mlim = 17.36 ; fwhm = 3.3

7.24.2007 9:53:45

mlim = 20.05 ; fwhm = 2.1

subtraction 1

subtraction 2

RA: 01:32:57.28 Dec: +30:24:27.29 (23.23865 30.40758)

This candidate does not match a galaxy or a star

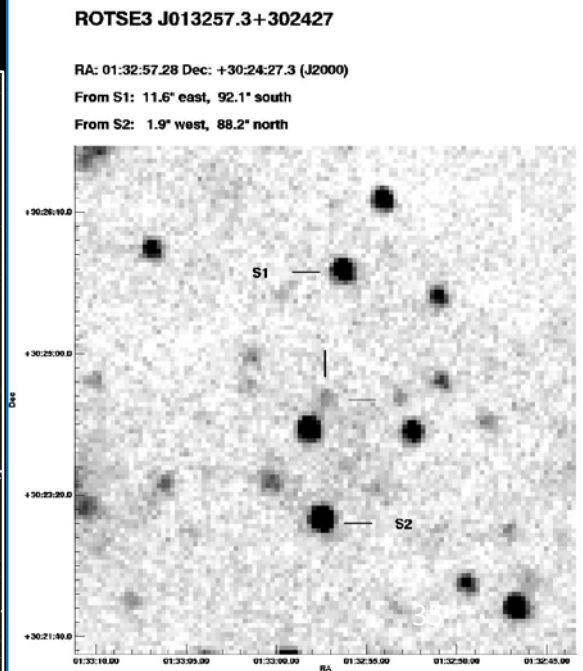
Mag	S/N	FWHM	Motion	% change	Before?
16.68	12.4	4.64	0.32	166	0/**/0000

[Check SIMBAD objects](#)

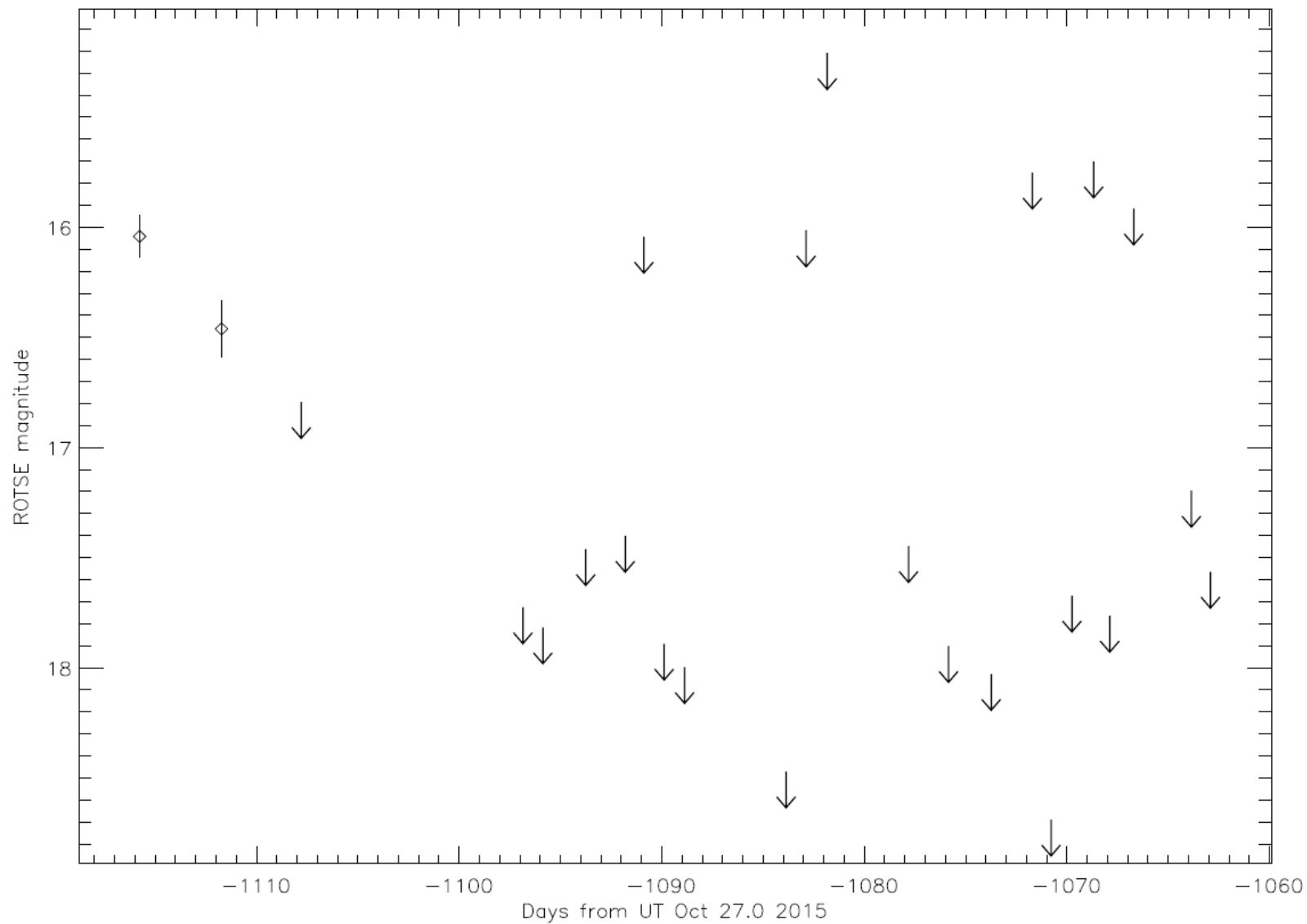
FITS

Junk Astroid Variable Star Interesting!

Please add any comments you might have here:



M33N_1012-10a



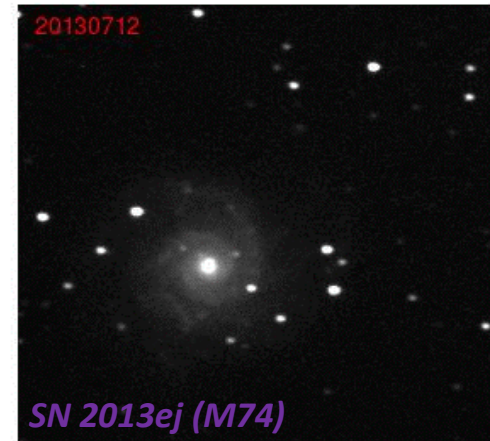
Supernovae



SN 1994D (NGC 4526)



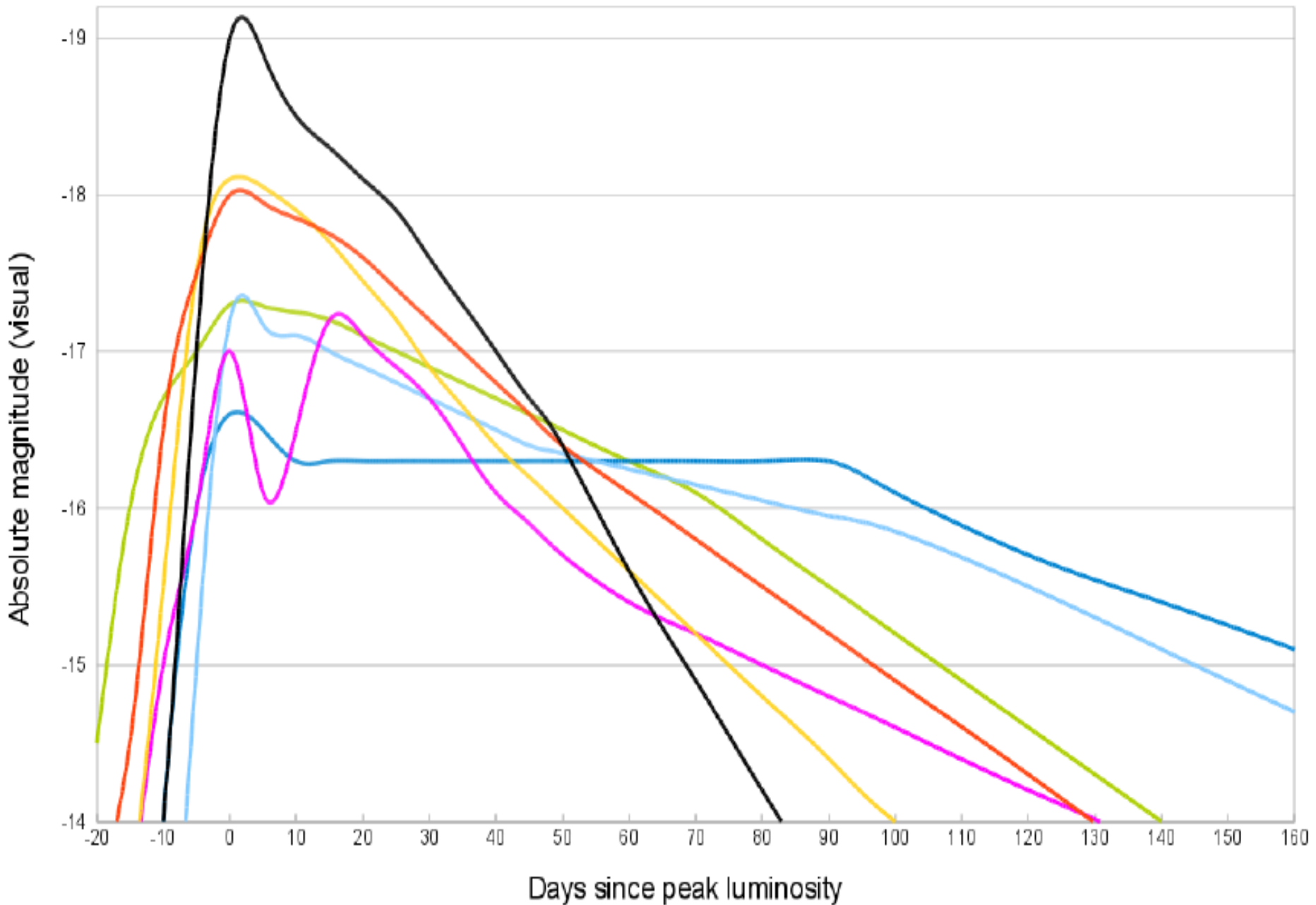
SN 2011fe

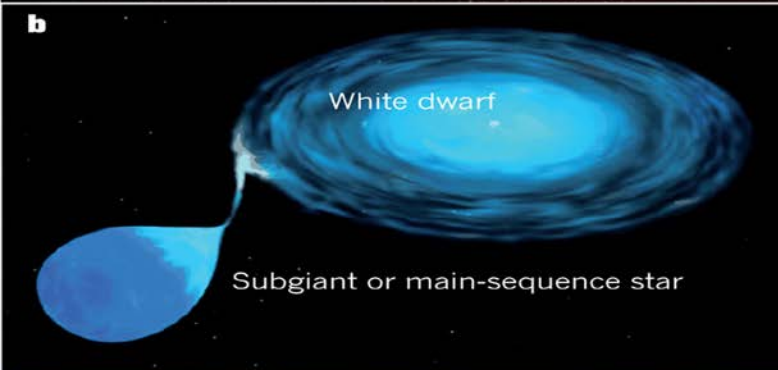
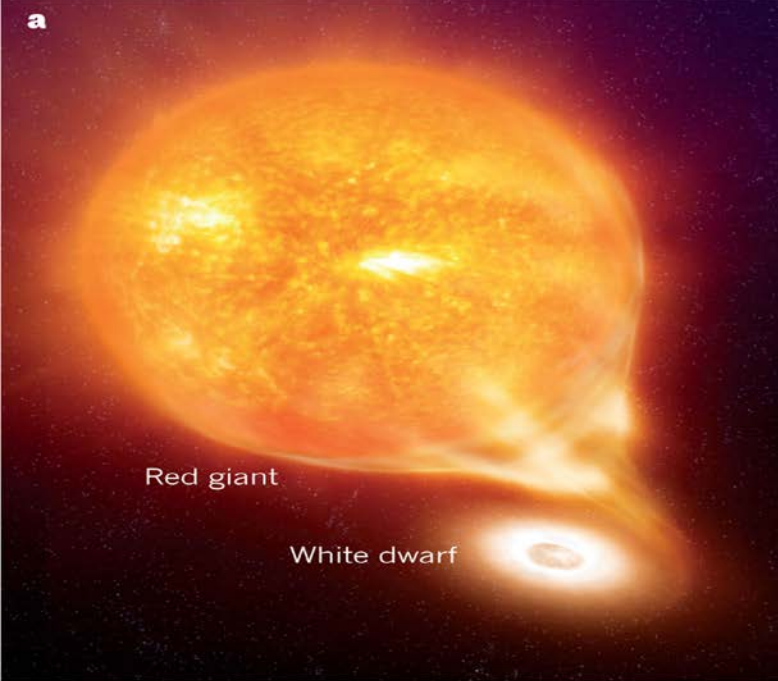


20130712

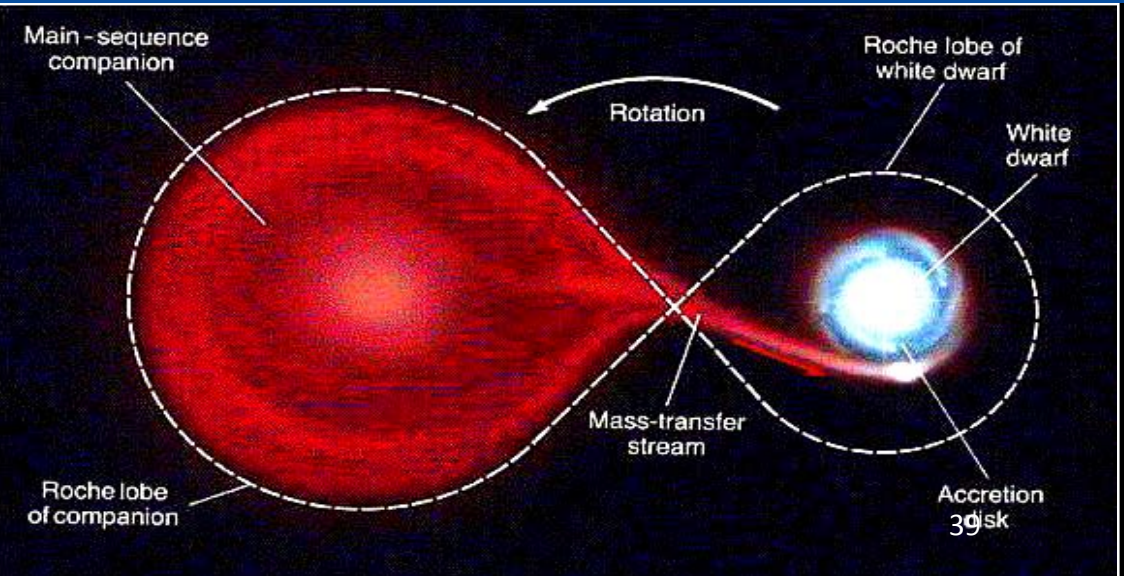
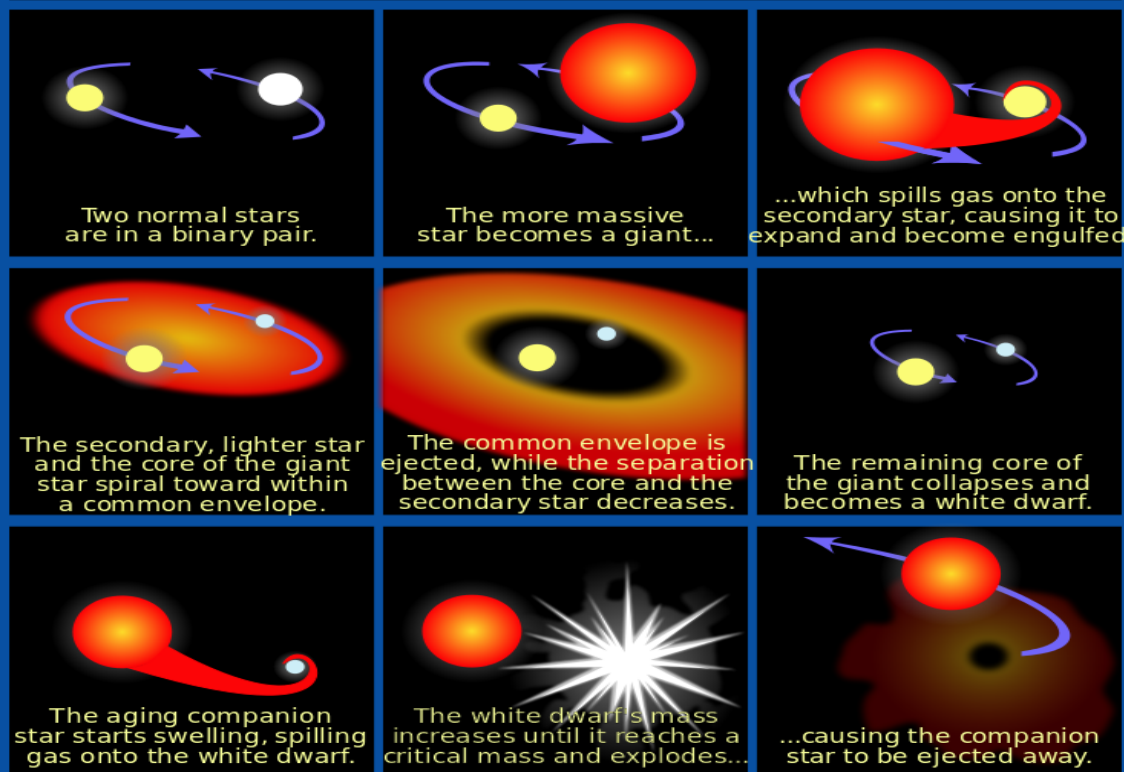
SN 2013ej (M74)

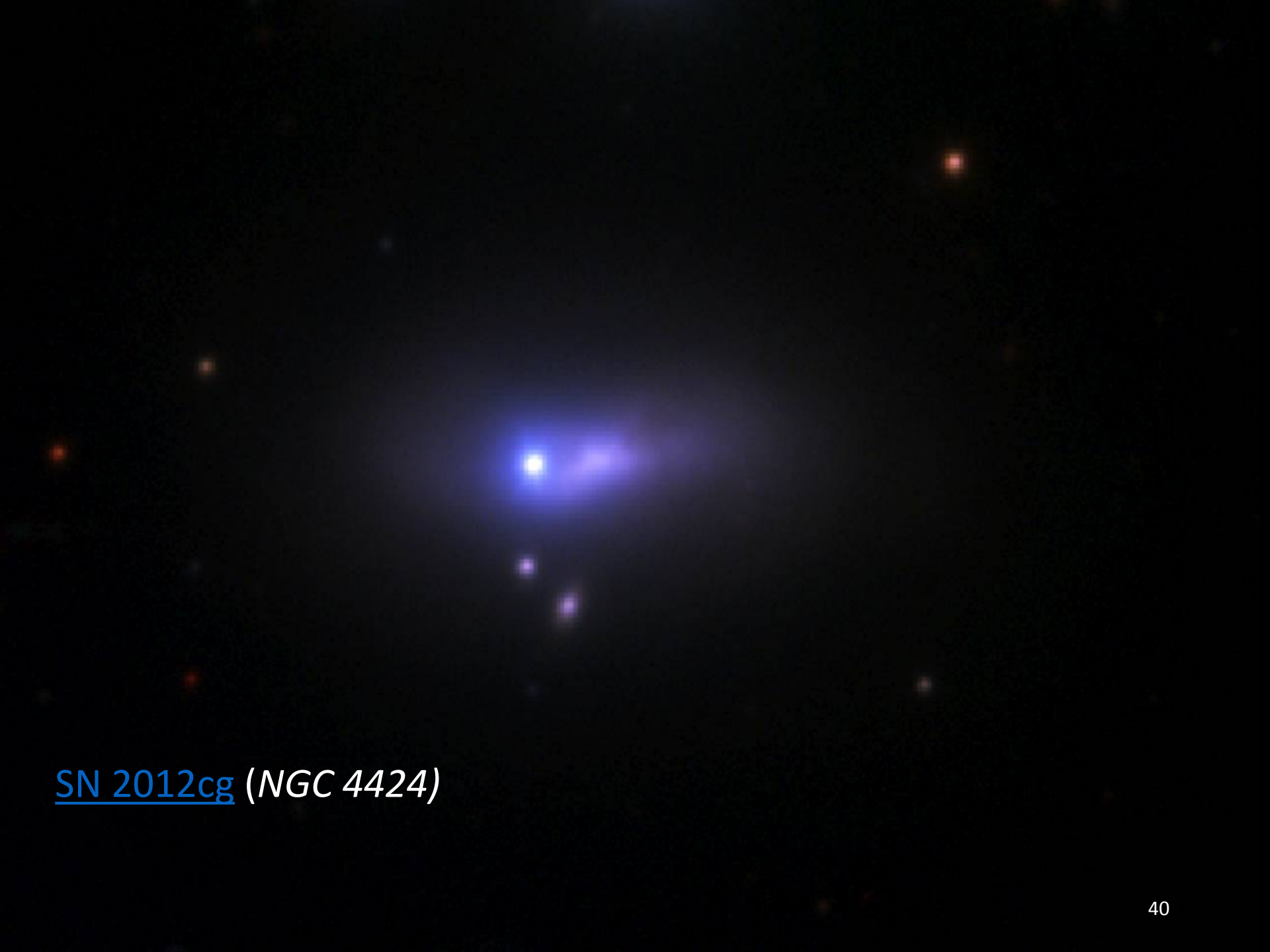
— Type Ia — Type Ib — Type Ic — Type IIb — Type II-L — Type II-P — Type IIn





The progenitor of a Type Ia supernova



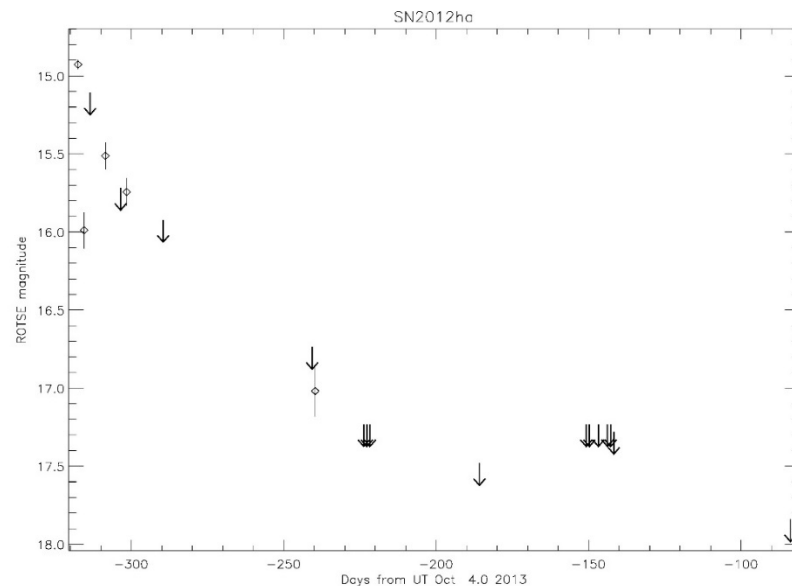
The image shows a dark field of space with a central bright blue-white point source, likely the supernova SN 2012cg. To its right is a larger, diffuse blue-white nebula. Several other stars are visible, including a prominent reddish-orange star in the upper right and several fainter stars in the lower left and center. The overall scene is a deep-field astronomical observation.

SN 2012cg (NGC 4424)

SN 2012ha ("Sherpa")

- 1st detection: 121120 (ROTSE-IIIb)
- Type: Ia-normal
 - Electron degeneracy prevents collapse to neutron star
 - Single degenerate progenitor: C-O white dwarf in binary system accretes mass from companion (main sequence star)
 - Mass → Chandrasekhar limit ($1.44 M_{\odot}$)
 - Thermonuclear runaway
 - Deflagration or detonation?
 - Standardizable candles
 - acceleration of expansion
 - dark energy

- Magnitude (max): 15.0
- Observed 1 month past peak brightness
- (RA, Dec) = (13:00:36.10, +27:34:24.64)
- Constellation: Coma Berenices
- Host galaxy: PGC 44785
- $z = 0.0170$ (~75 Mpc; ~240 Mly)
- CBET 3319



11.20.2012 11:46:41
mlim = 17.06 ; fwhm = 3.5

11.20.2012 11:49:0
mlim = 17.04 ; fwhm = 3.6

2.11.2008 10:54:54
mlim = 20.23 ; fwhm = 2.2

subtraction 1

subtraction 2

RA: 13:00:36.10 Dec: (195.15041 27.57351)
+27:34:24.64

This candidate matches a known galaxy core or edge

Mag	S/N	FWHM	Motion	% change	Before?
15.99	12.8	8.18	0.88	37	0/**/0000

Check SIMBAD objects Check SDSS

MPChecker Check ZMASS FITS Get DSS

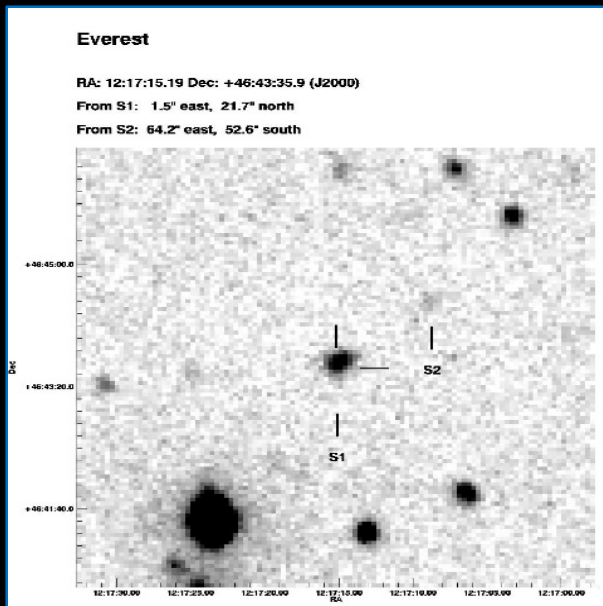
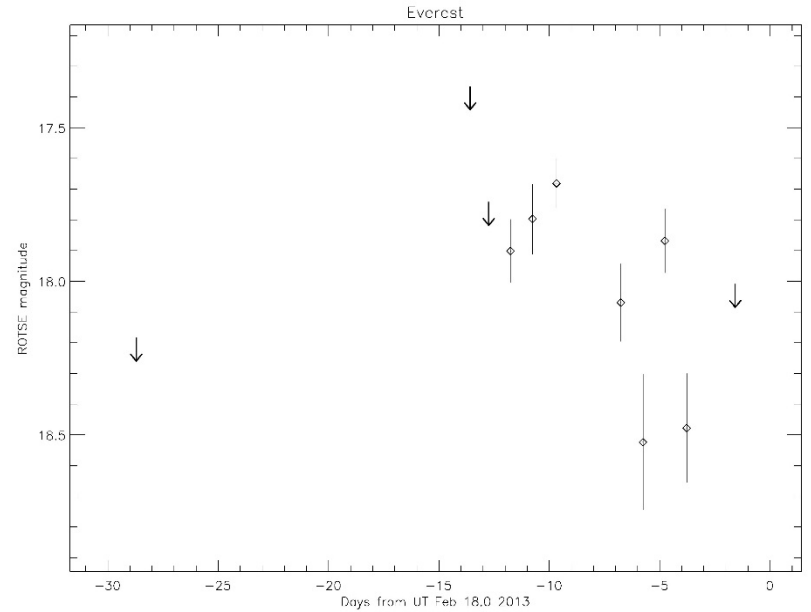
Junk Astroid Variable Star Interesting!

Please add any comments you might have here:

Submit your Contribution

SN 2013X ("Everest")

- Discovered 130206 (ROTSE-IIIb)
- Type Ia 91T-like
 - Overluminous
 - White dwarf merger?
 - Double degenerate progenitor?
- Magnitude (max): 17.7
- Observed 10 days past maximum brightness
- (RA, Dec) = (12:17:15.19, +46:43:35.94)
- Constellation: Ursa Major
- Host galaxy: PGC 2286144
- $z = 0.03260$ (~140 Mpc; ~450 Mly)
- CBET 3413



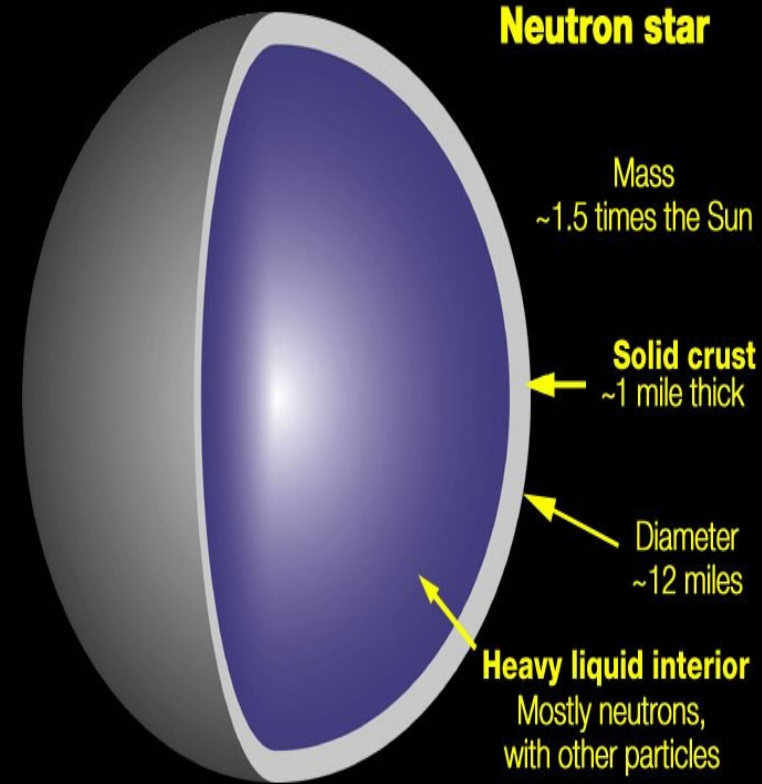
<p>2. 8.2013 5:29:18</p> <p>mlim = 18.46 ; fwhm = 4.1</p>	<p>2. 8.2013 10:0:50</p> <p>mlim = 18.41 ; fwhm = 3.8</p>	<p>1.20.2008 7:57:39</p> <p>mlim = 19.82 ; fwhm = 2.4</p>												
<p>subtraction 1</p>	<p>subtraction 2</p>	<p>RA: 12:17:15.19 Dec: +46:43:35.94 (184.31328 46.72665)</p> <p>This candidate matches a known galaxy but not at the core</p> <table border="1"> <thead> <tr> <th>Mag</th> <th>S/N</th> <th>FWHM</th> <th>Motion</th> <th>% change</th> <th>Before?</th> </tr> </thead> <tbody> <tr> <td>17.25</td> <td>17.5</td> <td>5.35</td> <td>0.21</td> <td>39</td> <td>4**/0207</td> </tr> </tbody> </table> <p>Check SIMBAD objects <input type="button" value="Check SDSS"/></p> <p><input type="button" value="MPChecker"/> <input type="button" value="Check 2MASS"/> <input type="button" value="FITS"/> <input type="button" value="Get DSS"/></p> <p><input checked="" type="radio"/> Junk <input type="radio"/> Asteroid <input type="radio"/> Variable Star <input type="radio"/> Interesting!</p> <p>Please add any comments you might have here:</p> <p><input type="button" value="Submit your Contribution"/></p>	Mag	S/N	FWHM	Motion	% change	Before?	17.25	17.5	5.35	0.21	39	4**/0207
Mag	S/N	FWHM	Motion	% change	Before?									
17.25	17.5	5.35	0.21	39	4**/0207									

What happens to a star more massive than 1.4 solar masses?

1. There aren't any
2. They shrink to zero size
3. They explode
4. They become something else

Neutron Stars

- Extremely compact: ~ 10 km radius
- Extreme density: 1 teaspoon would weigh $\sim 10^9$ tons (about as much as all the buildings in Manhattan)
- Spin rapidly: up to 600 *rev/s*
- Pulsars
- High magnetic fields ($\sim 10^{10}$ T): Compressed from magnetic field of progenitor star

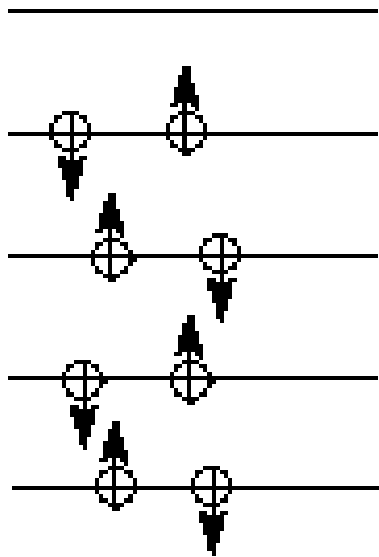


Neutron Stars

- Degenerate stars heavier than 1.44 solar masses collapse to become neutron stars
- Formed in supernovae explosions
- Electrons are not separate
 - Combine with nuclei to form neutrons
- Neutron stars are degenerate Fermi gas of neutrons

Near the center of the Crab Nebula is a neutron star that rotates 30 times per second. Photo Courtesy of NASA.

Neutron Energy Levels



Degenerate gas: all lower energy levels filled with two particles each (opposite spins). Particles **locked** in place.

- Only two neutrons (one up, one down) can go into each energy level
- In a degenerate gas, all low energy levels are filled
- Neutrons have kinetic energy, and therefore are in motion and exert pressure even if temperature is zero
- Neutron stars are supported by neutron degeneracy

Neutron Stars

Similar to white dwarfs - basic physics is degenerate fermion gas. However, we have neutrons, not electrons. Replace m_e with m_p .

$$r_{\text{ns}} \approx 2.3 \times 10^9 \text{ cm} \frac{m_e}{m_n} \left(\frac{Z}{A}\right)^{5/3} \left(\frac{M}{M_\odot}\right)^{-1/3} \approx 14 \text{ km} \left(\frac{M}{1.4M_\odot}\right)^{-1/3}$$

Note: the Z/A factor is one, since almost all nucleons are neutrons.

Important Effects (we neglected):

1. Nuclear interactions play an important role in the EOS. The EOS is poorly known due to our poor understanding of details of the strong interaction.
 2. The star is so compact that the effects of GR must be taken into account.
-

Compare gravitational and rest mass energies of a test particle of mass m .

$$E_{gr} = \frac{GMm}{2r} \quad \text{and} \quad E = mc^2$$

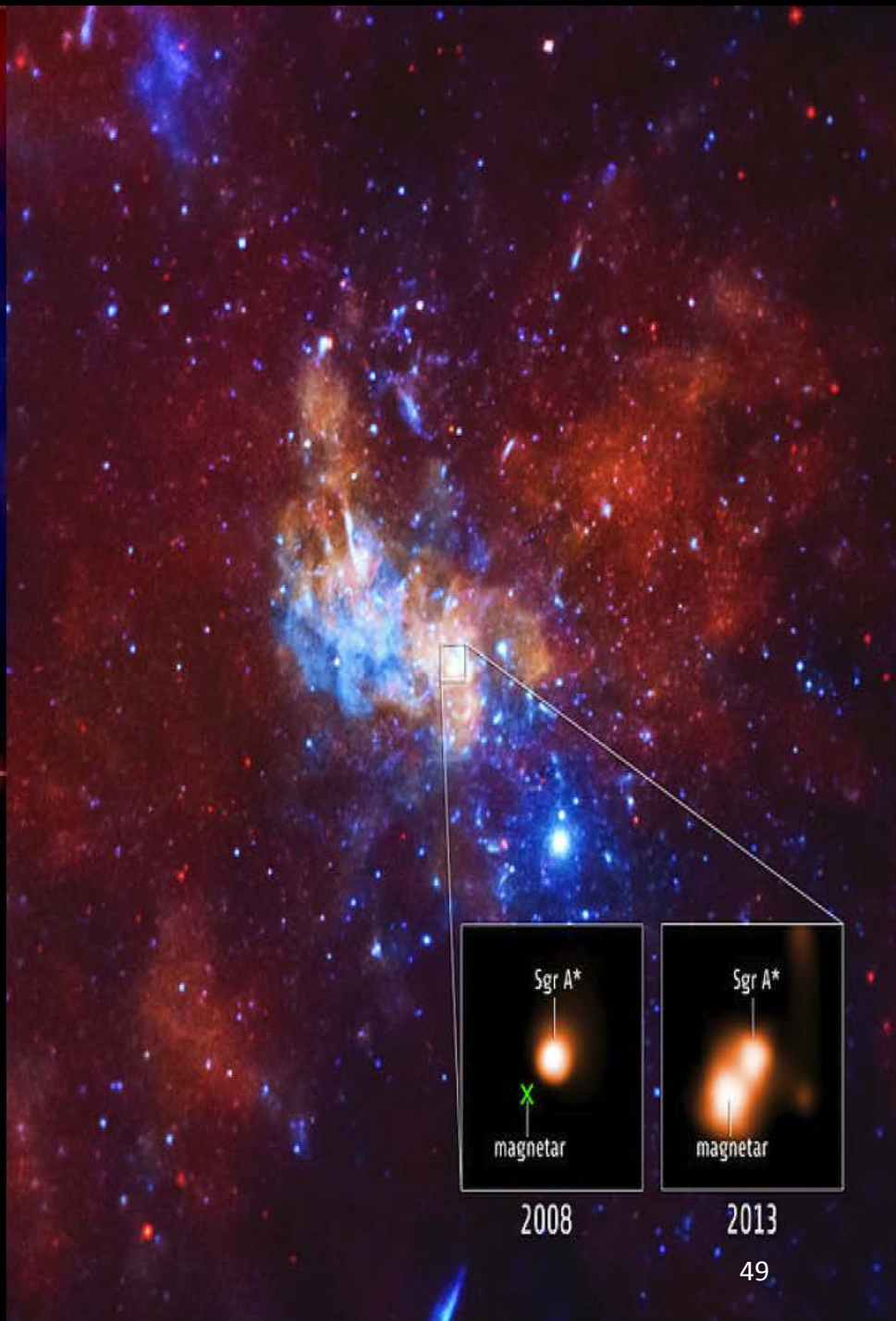
$$\frac{E_{gr}}{mc^2} = \frac{GM}{rc^2} \approx \frac{6.7 \times 10^{-8} \text{ cgs} \times 1.4 \times 2 \times 10^{33} \text{ g}}{10 \times 10^5 \text{ cm} (3 \times 10^{10} \text{ cm s}^{-1})^2} \approx 20\%$$

Matter falling onto a neutron star loses 20% of its rest mass and the mass of the star as measured via Kepler's law is 20% smaller than the total mass that composed it!

Detailed calculations that take into account GR and nuclear interactions give a radius of 10 km for a neutron star of $1.4M_{\text{sun}}$.

Limiting mass of a neutron star is not accurately known. The value is between $2M_{\text{sun}}$ and $3.2M_{\text{sun}}$.

Magnetars



BBC TWO

