Nuclear Physics I: Nuclear Astrophysics

PHYS 8801

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Agenda

Supernovae

Supernova Types

as Function of Mass and Metallicity

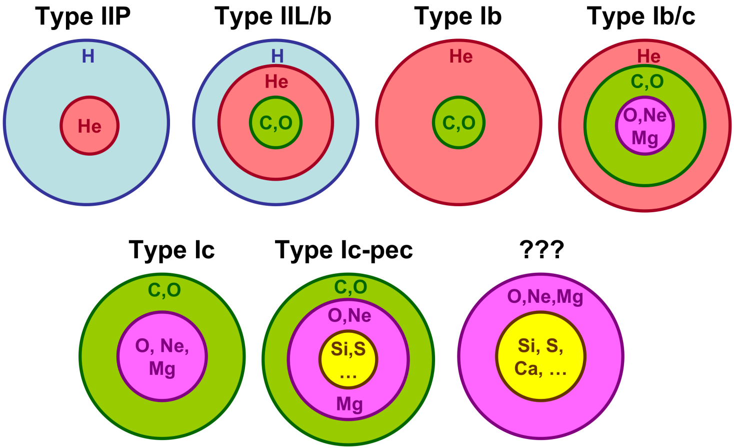
(single stars)

SN Type	pre-SN stellar structure
IIp	> 2 $M_\odot$ H envelope
IIL	< 2 $M_\odot$ H envelope
Ib/c	**no** H envelope

Type Ib/c He core mass at explosion	explosion energy	display
> 15 $M_\odot$	direct collapse	none
~15…8 $M_\odot$	weak	dim
~8…5 $M_\odot$	strong	dim
< 5 $M_\odot$	strong	bright

Supernovae

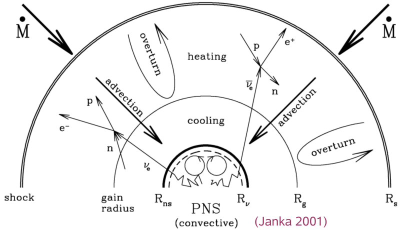
Sequence of increasingly stripped cc SNe



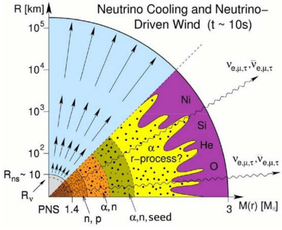
(adopted from Filippenko 2002) (SN 2002ap?) (SN 02ap?, 98bw?)

Supernovae

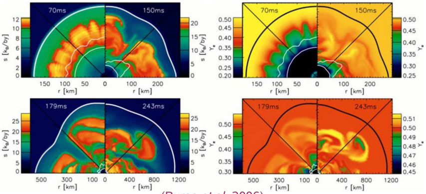
Core Collapse Supernovae



(Janka 2001)



(Woosley & Janka 2006)



(Buras *et al.* 2006)

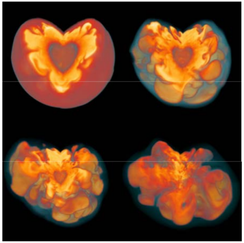
←Entropy and electron per baryon (Y_e) at different time snapshots in a core collapse supernova

(simulation: equatorial band)

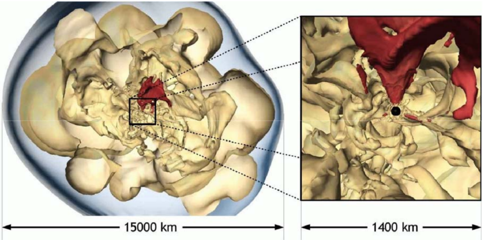
Supernovae

Core Collapse Supernovae – 3D

Cold inflow and **hot outflow** in 3D simulations ➔ similar to dipolar flow pattern observed in 2D rotationally symmetric simulations



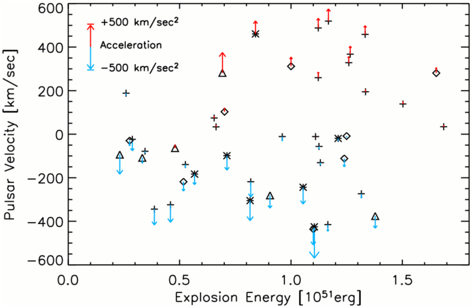
(Scheck, Janka, *et al.* 2006)

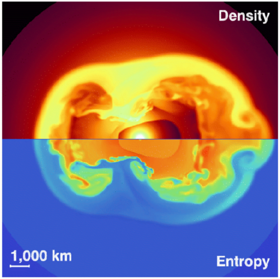


(Janka *et al.* 2005)

Supernovae

Neutron Star Kicks





(Janka 2004)

Dipolar oscillation may explain observed neutron star kicks of several 100 km/s.

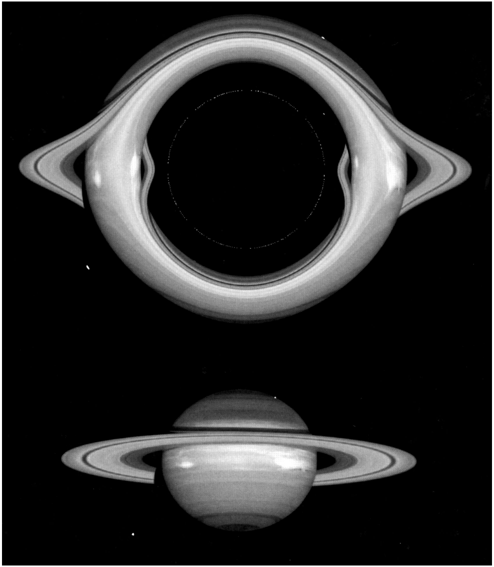
Supernovae

Explosive Nucleosynthesis

in supernovae

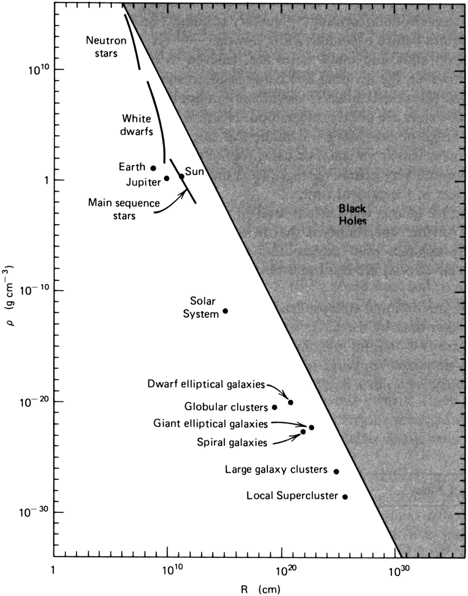
Fuel	Main Product	Secondary Product	T (10^9 K)	Time (s)	Main Reaction
Innermost ejecta	***r*-process**	**-**	**>10 low Y_e**	**1**	**(n,γ), β^-**
Si, O	**^{56}Ni**	**iron group**	**>4**	**0.1**	**(α,γ)**
O	**Si, S**	**Cl, Ar, K, Ca**	**3 - 4**	**1**	**$^{16}O + ^{16}O$**
O, Ne	**O, Mg, Ne**	**Na, Al, P**	**2 - 3**	**5**	**(γ,α)**
		p-process ^{11}B, ^{19}F, ^{138}La, ^{180}Ta	**2 - 3**	**5**	**(γ,n)**
		ν-process		**5**	**(ν, ν'), (ν, e^-)**

Black Holes



Saturn as seen through the gravitational lense of a black hole

Density and Radii of Astronomical Objects



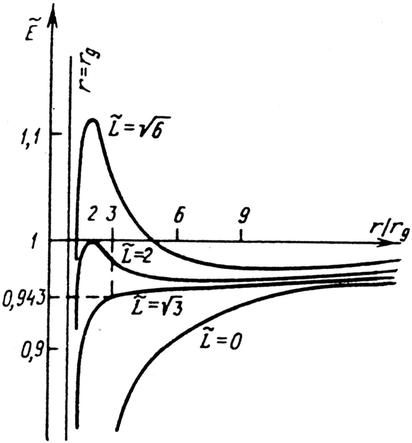
- comparison of average density of astronomical objects
- average density of black holes decreases with increasing mass

$$R_s \sim M$$

$$V \sim R^3$$

$$\bar{\rho} = M/V \sim M^{-2}$$

Black Holes - Angular Momentum and Orbits



in this figure the following conventions were used:

- "gravitational radius" $r_g = R_s$
- normalized angular momentum $\tilde{L} = l/cmr_g$ where l is the angular momentum of the particle
- specific *total* energy of the particle $\tilde{E} = E/mc^2$
  $E = mc^2 + E_{bind} + E_{kin}$

Black Holes - Energy and Orbits

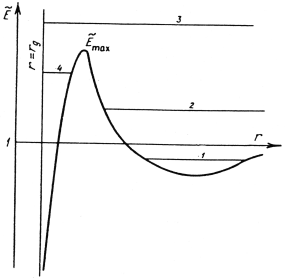


Fig. 3. Effective black hole potential. $1 - \tilde{E} = \tilde{E}_1$, $2 - \tilde{E} = \tilde{E}_2$, $3 - \tilde{E} = \tilde{E}_3$, $4 - \tilde{E} = \tilde{E}_4$

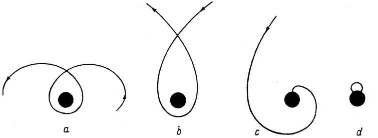


Fig. 4. Trajectories of particles with energies (a) $\tilde{E}_1$, (b) $\tilde{E}_2$, (c) $\tilde{E}_3$, and (d) $\tilde{E}_4$

Types of orbits

- **1/a**: bound/closed, $0 < \tilde{E} < \tilde{E}_{\rm max}$
- **2/b**: unbound/open, $\tilde{E} < 0$
- **3/c**: “unbound”/capture for $\tilde{E} > \tilde{E}_{\rm max} > 0$ (not in classical mechanics)
- **4/d**: closed capture loop $\tilde{E} < \tilde{E}_{\rm max}$, can be $\tilde{E} < 0$ or $\tilde{E} > 0$ (not in classical mechanics)

Kerr Black Holes

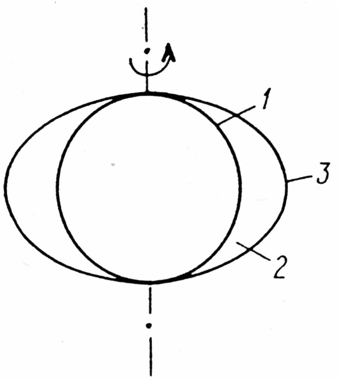
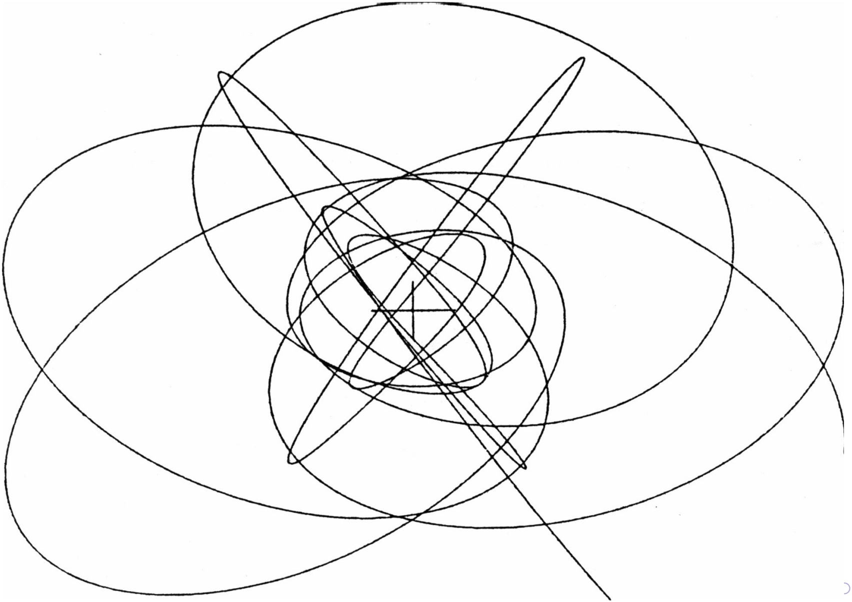


Fig. 7. A rotating black hole: 1—horizon, 2—ergosphere, 3—static limit

Particle Orbit around a Kerr Black Hole



Critical Radii in Black Holes

Orbit	$a=0$	$a=M$	
		$L>0$	$L<0$
r_{photon}	1.5	0.5	2.0
r_{bind}	2.0	0.5	2.92
r_{bound}	3.0	0.5	4.5

Schwarzschild Case

- photon circular orbit

$$r_{\text{bind}} = 1.5 R_s = 3\frac{GM}{c^2}$$

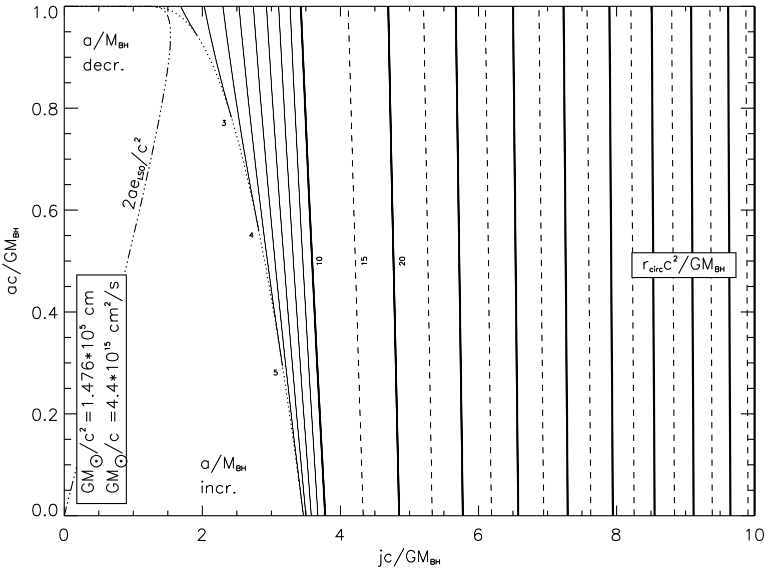
- last stable orbit

$$r_{\text{bound}} = 3 R_s = 6\frac{GM}{c^2}\ ,\ v = \frac{c}{2}$$

- last marginally stable circular orbit

$$r_{\text{bind}} = 2 R_s = 4\frac{GM}{c^2}\ ,\ v = v_{\text{esc}}$$

Orbits and Energies



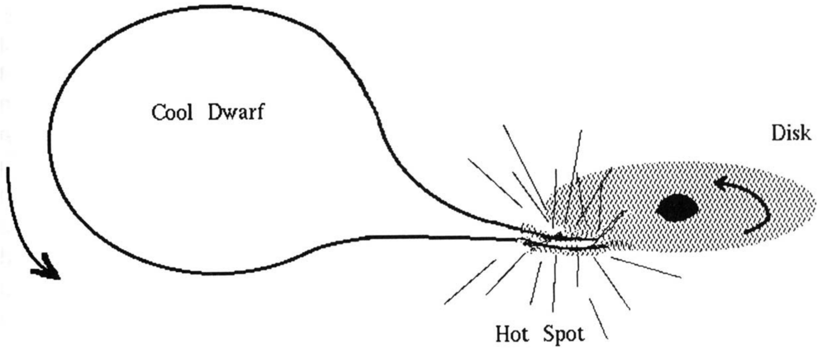
Summary - Comparison of Compact Remnants

Distinguishing Traits of Compact Objects

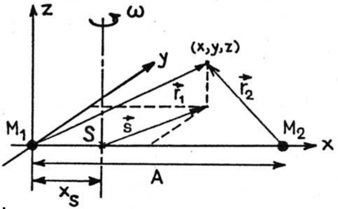
Object	Mass[a] (M)	Radius[b] (R)	Mean Density (g cm^{-3})	Surface Potential (GM/Rc^2)
Sun	$M_\odot$	$R_\odot$	1	10^{-6}
White dwarf	$\lesssim M_\odot$	$\sim 10^{-2} R_\odot$	$\lesssim 10^{7}$	$\sim 10^{-4}$
Neutron star	~ 1–$3 M_\odot$	$\sim 10^{-5} R_\odot$	$\lesssim 10^{15}$	$\sim 10^{-1}$
Black hole	Arbitrary	$2GM/c^2$	$\sim M/R^3$	~ 1

[a] $M_\odot = 1.989 \times 10^{33}$ g
[b] $R_\odot = 6.9599 \times 10^{10}$ cm

Binary Stars ('Binaries')



Roche Model



$$\phi(x,y,z) = -\frac{GM_1}{|\vec{r}_1|} - \frac{GM_2}{|\vec{r}_2|} \underbrace{- \frac{1}{2}|\vec{S}|^2\omega^2}$$

centrifugal potential

$$|\vec{r}_1| = (x^2+y^2+z^2)^{1/2} \quad , \quad |\vec{r}_2| = ((A-x)^2+y^2+z^2)^{1/2}$$

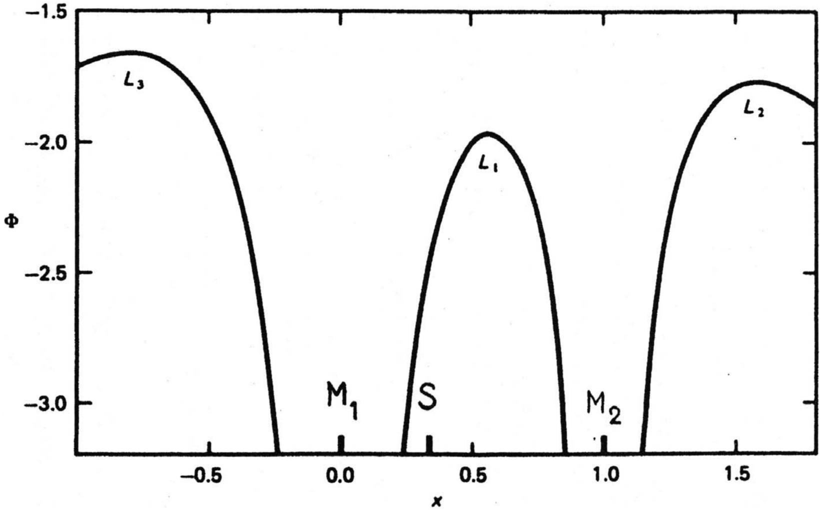
$$|\vec{S}| = ((x-x_s)^2+y^2)^{1/2} = \left[\left(x - \frac{M_2}{M_1+M_2}A\right)^2 + y^2\right]^{1/2}$$

$$\omega^2 = \frac{G(M_1+M_2)}{A^3}$$: **3rd Kepler's Law**

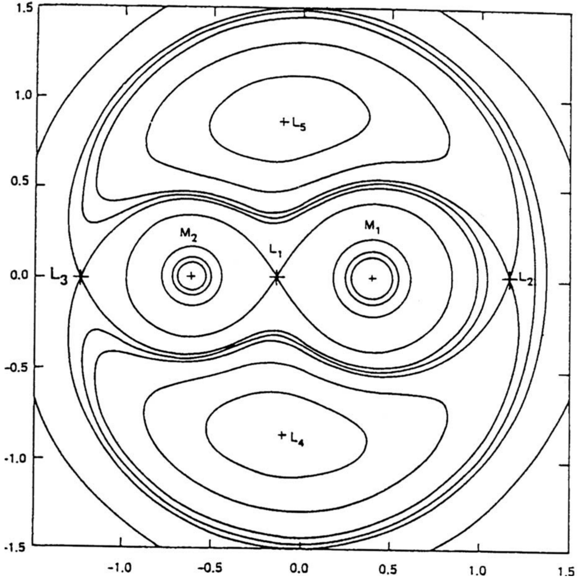
Introduce dimensionless variables: $\xi = \frac{x}{A}$; $\eta = \frac{y}{A}$; $\zeta = \frac{z}{A}$; $q = \frac{M_1}{M_2}$

- $$\phi_R(\xi,\eta,\zeta) = -\frac{GM_2}{A}\left\{\frac{q}{(\xi^2+\eta^2+\zeta^2)^{1/2}} + \frac{1}{[(1-\xi)^2+\eta^2+\zeta^2]^{1/2}} + \left[\left(\xi - \frac{1}{1+q}\right)^2 + \eta^2\right]\frac{(1+q)}{2}\right\}$$

Roche Potential



Lagrange Points

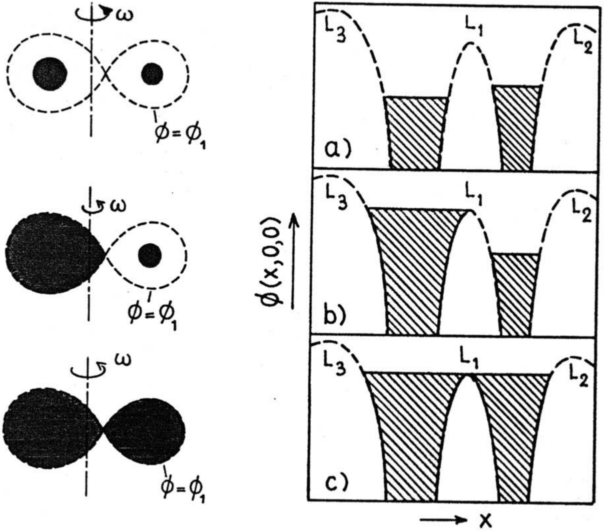


Five Lagrange points:

L1, L2, L3: unstable

L4,L5: stable

Contact Binaries



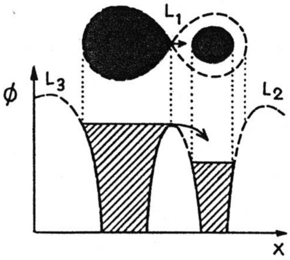
detached

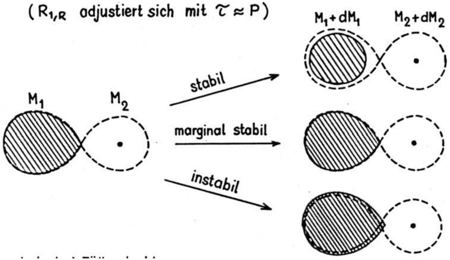
semi-detached

contact

Binary Mass Transfer

Stability of mass transfer depends on reaction of donor and receiving star





Compact Binary Types

Star + compact remnant + Roche-Lobe overflow: X-ray binaries

WD + companion:
Novae, Dwarf Novae, Type Ia supernovae

NS + companion:
X-ray bursts, millisecond pulsars, …

NS+NS: Binary pulsars

Binary Pulsar Production