

GRBs from compact object mergers

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- accretion on to a black hole or neutron star yields 10^{20} erg/g
- this is the most efficient way of extracting energy from normal matter
- GRBs are (briefly) the brightest objects in the Universe

accretion must power GRBs

required mass

$$\Delta M = 10^{-20} E = 0.1 M_{sun} E_{52}$$

— a successful GRB model must explain why this mass accretes on to a black hole or neutron star on the observed timescale

- observed energy => *stellar* mass
- observed timescales: ~10s or more (long duration)
~ few seconds or less (short duration)
- need to choose accretor and mass reservoir for a GRB model

two basic possibilities

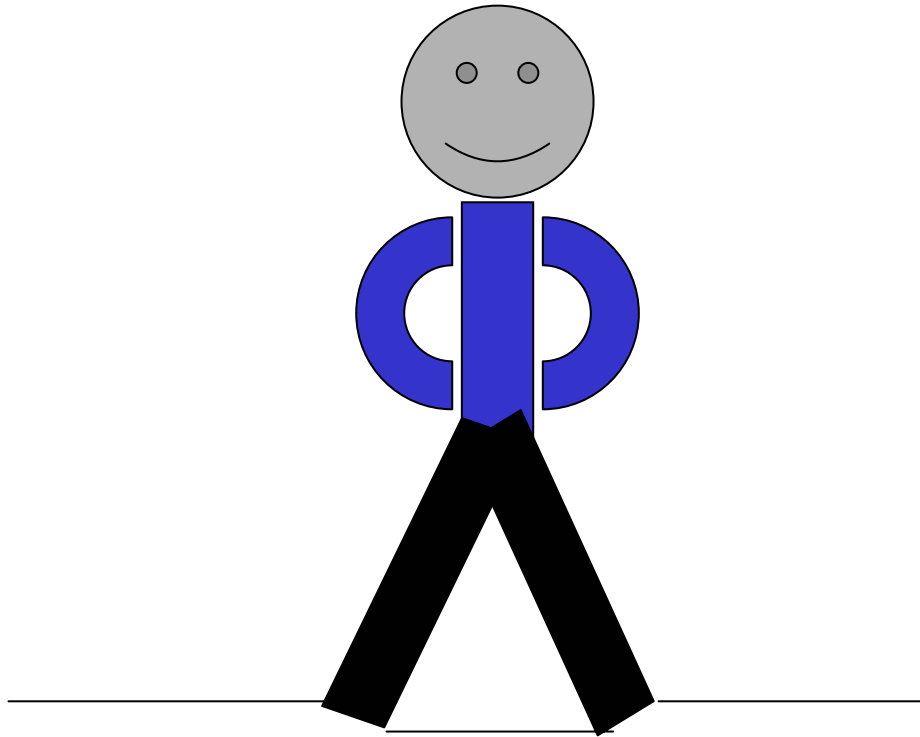
(a) same star is *both* accretor *and* reservoir

collapse of rapidly—rotating core \Rightarrow accretion disc with

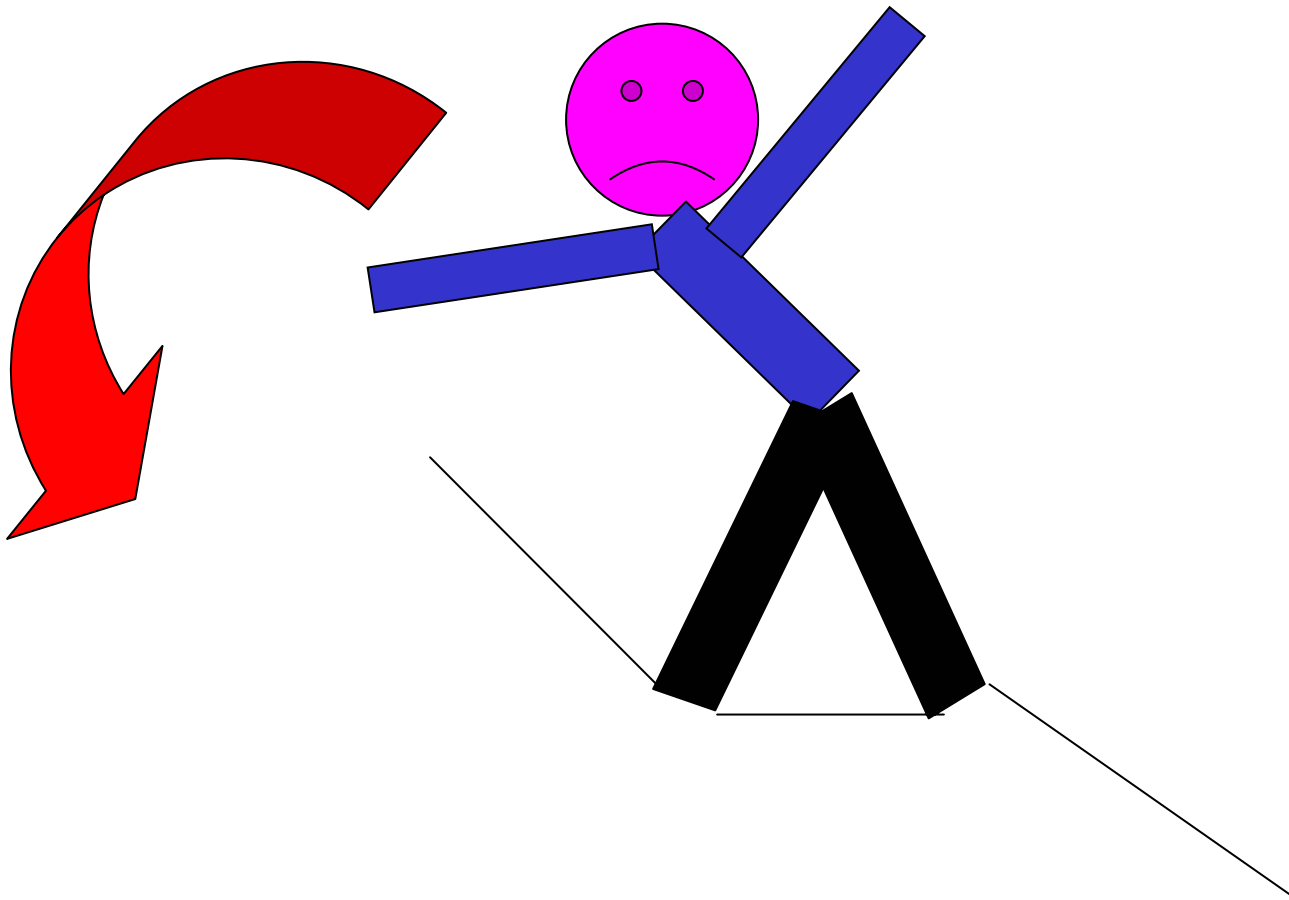
$$M_{disc} > \frac{H}{R} M_{accretor}$$

\Rightarrow *self—gravitating disc*

in 2D this is dynamically stable



stable 2D person



unstable 3D tightrope walker

\Rightarrow in 3D, *self-gravitating disc is subject to*

nonaxisymmetric instabilities \Rightarrow infall is *dynamical*, with

$$t \sim \text{few times} \left(\frac{R^3}{GM} \right)^{1/2}$$

in this case (a), accretor = forming BH, reservoir = core, so

$$M \sim M_{sun} \quad R \sim 10^9 \text{ cm}$$

$$t \sim 10 \text{ s}$$

collapsar

natural explanation for long—duration bursts

(b) second possibility: accretion in a *binary*

- accretor (star 1) must be neutron star or black hole
- reservoir = donor star (2), determined by timescale
- once star 2 fills its Roche lobe R_L we have

$$\frac{\dot{M}_2}{M_2} = \frac{1}{D} \frac{\dot{J}}{J}$$

where $t_J = -J / \dot{J}$ is the timescale for orbital angular momentum loss (usually via gravitational radiation),

and

$$D \equiv \left(\frac{5}{6} + \frac{\zeta}{2} - \frac{M_2}{M_1} \right)$$

with ζ the radius—mass index of star 2, i.e.

$$R_2 \propto M_2^\zeta$$

typical values $\zeta \sim 1$ (main sequence) and $\zeta = -1/3$ (white dwarf)

Importance of D: it gives the sign of

$$\dot{R}_L - \dot{R}_2$$

on a dynamical (mass transfer) timescale

Generally D is $O(1)$. If it is positive we have

$$\frac{\dot{M}_2}{M_2} \sim \frac{\dot{J}}{J}$$

i.e. mass transfer on the orbital angular momentum loss timescale

$$t_{GR} \sim -\frac{J}{\dot{J}} = \frac{5 c^5}{32 G^3} \frac{a^4}{M_1 M_2 (M_1 + M_2)}$$

where a is the orbital separation

Now since star 2 fills its Roche lobe,

$$R_2 \sim a / \text{few}$$

so

$$t_{GR} \sim 10^{10} (R / R_{MS})^4 \text{ yr}$$

hence

$$t_{GR} \sim 100 \text{ years,} \quad \text{white dwarf donor}$$

$$t_{GR} \sim 10^{-3} \text{ seconds,} \quad \text{neutron star donor}$$

conclude that NS + NS and BH + NS binaries are candidates for producing short—duration GRBs

but there are further possibilities: in some cases we have

$$D \equiv \left(\frac{5}{6} + \frac{\zeta}{2} - \frac{M_2}{M_1} \right) < 0$$

then *Roche lobe cuts into star on a dynamical timescale:*

feedback \Rightarrow mass transfer rate increases towards

$$\dot{M}_{dyn} \sim \frac{M_2}{t_{dyn}}$$

NB Roche lobe filling $\Rightarrow t_{dyn} \sim P =$ orbital period

Causes of dynamical instability

When is $D < 0$?

1. *violently expanding donor*: if $\zeta < -5/3$, $D < 0$ for any mass ratio M_2 / M_1 . This happens if a neutron star is reduced to $0.2M_{sun}$ by mass transfer

late flares?

Causes of dynamical instability

2. *very rapid mass transfer*: expression for D assumes tides feed angular momentum of transferred mass back to donor. If too rapid for this,

$$D \equiv \left(\frac{5}{6} + \frac{\zeta}{2} - \frac{M_2}{M_1} \right) - \alpha$$

with $\alpha = O(1)$

thus **even white dwarf donors may be unstable**

similar effect if mass transfer stream accretes directly without forming a disc, e.g. falls within ISCO

Causes of dynamical instability

3. *large mass ratio*. For a white dwarf, $\zeta = -1/3$, so

$$D \equiv \left(\frac{2}{3} - \frac{M_2}{M_1} \right)$$

i.e. unstable for mass ratios $> 2/3$.

For WD less than Chandrasekhar mass, $D < 0$ requires

$M_1 < 2.1M_{sun}$, so most likely for neutron star accretors.

If $M_1 = 1.4M_{sun}$ instability requires $M_2 > 0.9M_{sun}$

i.e. **neutron star + massive white dwarf**

Notes

1. some types of binary unstable in several ways, e.g. NS + NS
(all three)
2. once dynamical instability sets in, star(s) is(are) no longer
bound object(s) — many—body problem:

anything can happen!

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- are there systems like this? i.e. right mass ratio, merging in less than Hubble time?
- YES! PSR J1141—6545 (Kaspi et al., 2000)

pulsar (non—recycled) in relativistic 5—hour orbit with massive WD, eccentricity $e = 0.17$. Relativistic orbit allows very precise mass estimates

$$M_{ns} < 1.348M_{sun}, \quad M_{wd} > 0.968M_{sun}$$

i.e.

$$M_{wd} / M_{ns} > 0.718$$

- will merge under GR in $\sim 10^9$ yr
- evolutionary scheme, relevance to GRBs in Davies, Ritter & King (2002)
- estimated formation rate $5 \times 10^{-5} - 5 \times 10^{-4} \text{ yr}^{-1}$ in Galaxy
- more than half of such systems merge in 10^8 yr, and 95% within a Hubble time. Rapidly merging systems dominate rate.
- substantial fraction have kick velocities 50 — 100 km/s
- \Rightarrow many move < 5 kpc from birthplace

burst characteristics:

long duration

since

$$t_{dyn} \sim 10 \text{ sec}$$

supernova? unclear — but automatically no H or He if so

a long—duration burst from a host without star formation would be a candidate for this type of merger

summary

- BH + NS and NS + NS probably make short—duration GRBs.
Late flares as NS → WD?
- BH + WD and NS + *massive WD* probably make long—duration GRBs — can come from hosts without star formation
- NS + massive WD candidates exist, have significant rate, show some association with SFR, and may lie close to host
- if they produce supernovae, no H or He