Black-Hole Binaries as relics of GRBs/HNe.

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Outline

- Collapsar Model.
- Binary Evolution.
- Galactic BHBs as Relics of GRBs/HNe.
- Gamma-Ray Bursts and Their Energies.
- Conclusions.

Collapsar Model

Gamma-Ray Bursts

- Energy (Beamed luminosity): $\sim 10^{51}$ergs($= 1$ foe$= 1$ bethe).
- Gamma-Ray Bursts have a double peaked distribution in duration: Two populations.
- Short-Hard Gamma-Ray Bursts:
  - Below 2-second duration.
  - Hard-Gamma Rays.
  - Compact Objects Merger.
- Long-Soft Gamma-Ray Bursts:
  - Few-hundred-seconds duration.
  - Soft-Gamma Rays.
  - May have accompanying Hypernova Type I$_{bc}$.
  - Collapsar.

Hypernova Explosions

- Collapsar Model.
- Energy: $\sim 3 \times 10^{52}$ ergs($= 30$ bethes!!)
- Collapsars are rotationally and magnetohydrodynamically powered.
- Material ejected at velocities as high as $30,000$ km s^{-1}.
- The explosion, being type I$_{bc}$, is usually associated to WRs.

Collapsar Model

MacFadyen and Woosley (1999):

- Unsuccessful supernovae, in which the Fe core does not produce an energetic enough outgoing shock will form a black hole of a few $M_\odot$.
- The progenitor star has a certain amount of angular momentum, so the first part of the core of the star to collapse are the poles, which are not centrifugally supported. This clears a path along the rotational axis.
- The rest of the core (highly ionized metals) of the star will produce an accretion disk.
- The rotational energy of the BH is used, first, as a central engine to power up a GRB through the poles, and second, to heat the disk up and eventually expel it in a HN explosion, disrupting the central engine.

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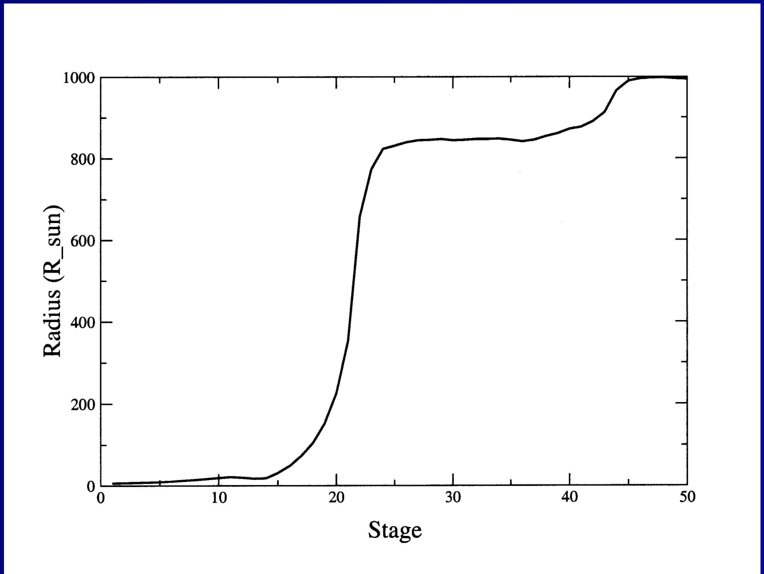
A couple of problems:

- Hypernovae are Type I$_{bc}$.
- Is there enough angular momentum in the rotation of massive stars, especially after the end of He burning?

Binary Evolution

The A, B, C of Mass Transfer

- Case A: Occurs during Main Sequence (H burning)
- Case B: Begins at H-shell burning; continues during He burning.
- Case C: Occurs at the later stages of He burning.



Binary Evolution with Case C Mass Transfer

- In order to evolve a BH we need $20M_\odot \leq M_{ZAMS} \leq 40M_\odot$, below this limit the collapsing core will not be massive enough, above this limit the stellar winds become too strong and the star loses too much mass.
- Common envelope evolution must begin until He-core burning is finished, else, too much mass is lost for a BH to be formed.
- The BH-progenitor star (primary) will be $\sim 850R_\odot$ at the end of He-core burning, and $\sim 1,000R_\odot$ at the beginning of CO-core burning (for a $M_{ZAMS} = 25M_\odot$ star), the Roche Lobe of the primary must be in this range for Case C mass transfer to occur.
- The distance, a_i, between the two stars will decrease to a few $R_\odot$.
- Stellar winds will end the common-envelope evolution phase, and Roche Lobe Overflow will be over.
- Metallicity (Population Type) may be an important factor for the winds to be strong enough to detach the two stars in common-envelope evolution.

Tidal Locking and Kerr Parameter

- The post-common envelope evolution tidally locks the two stars.
- Given that the material in the He star is highly ionized and that there is a strong magnetic field traversing the star we expect the black hole to acquire most of the angular momentum of the infalling He-star.
- Given the tidal lock at such a late evolutionary phase it is possible to have a good estimation of the angular momentum of the pre-collapse-primary star and therefore obtain the Kerr parameter of the black hole at the time it was formed (right before the GRB/HN event).
- $a_\star$ can be further increased by transferring mass from the companion star to the black hole.

Kerr Parameter and Mass Accretion

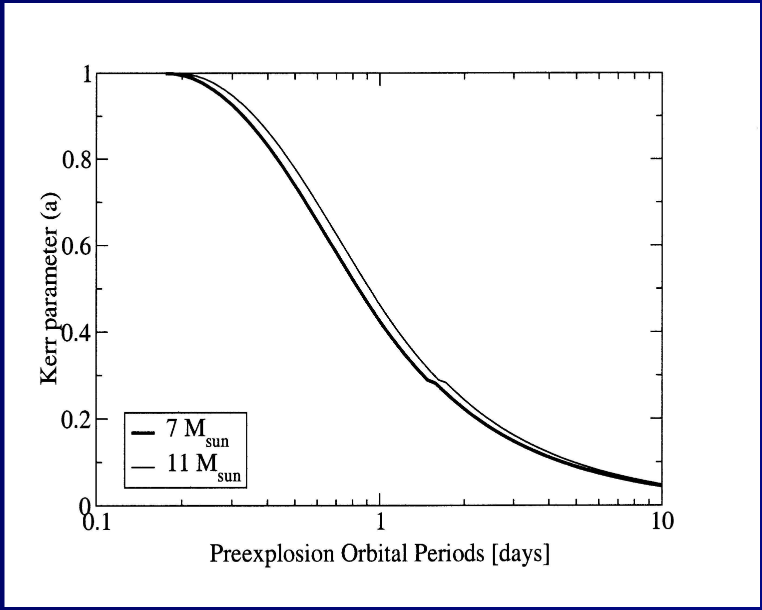


Figure 1: The Kerr parameter of the black hole, at the time of formation, from the collapse of a tidally locked He star, as a function of the orbital period. The result has little dependance on the mass of the He star (Lee et al., 2002)

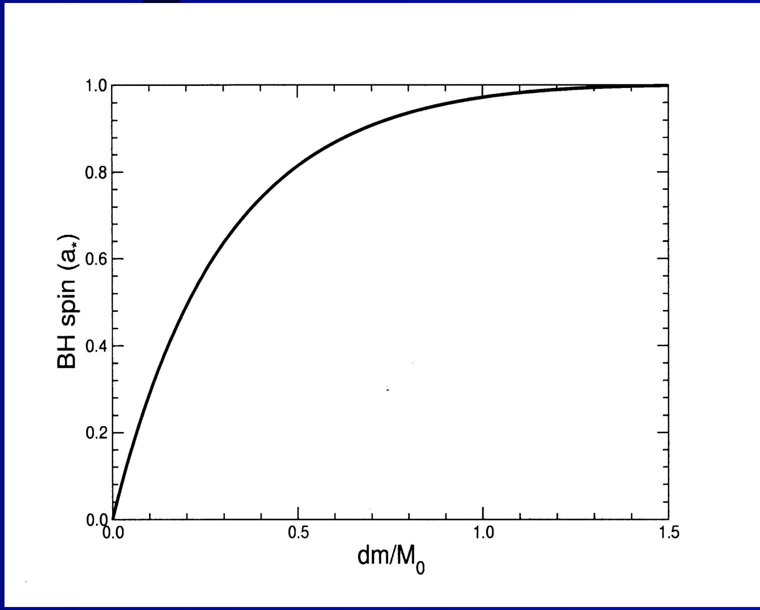
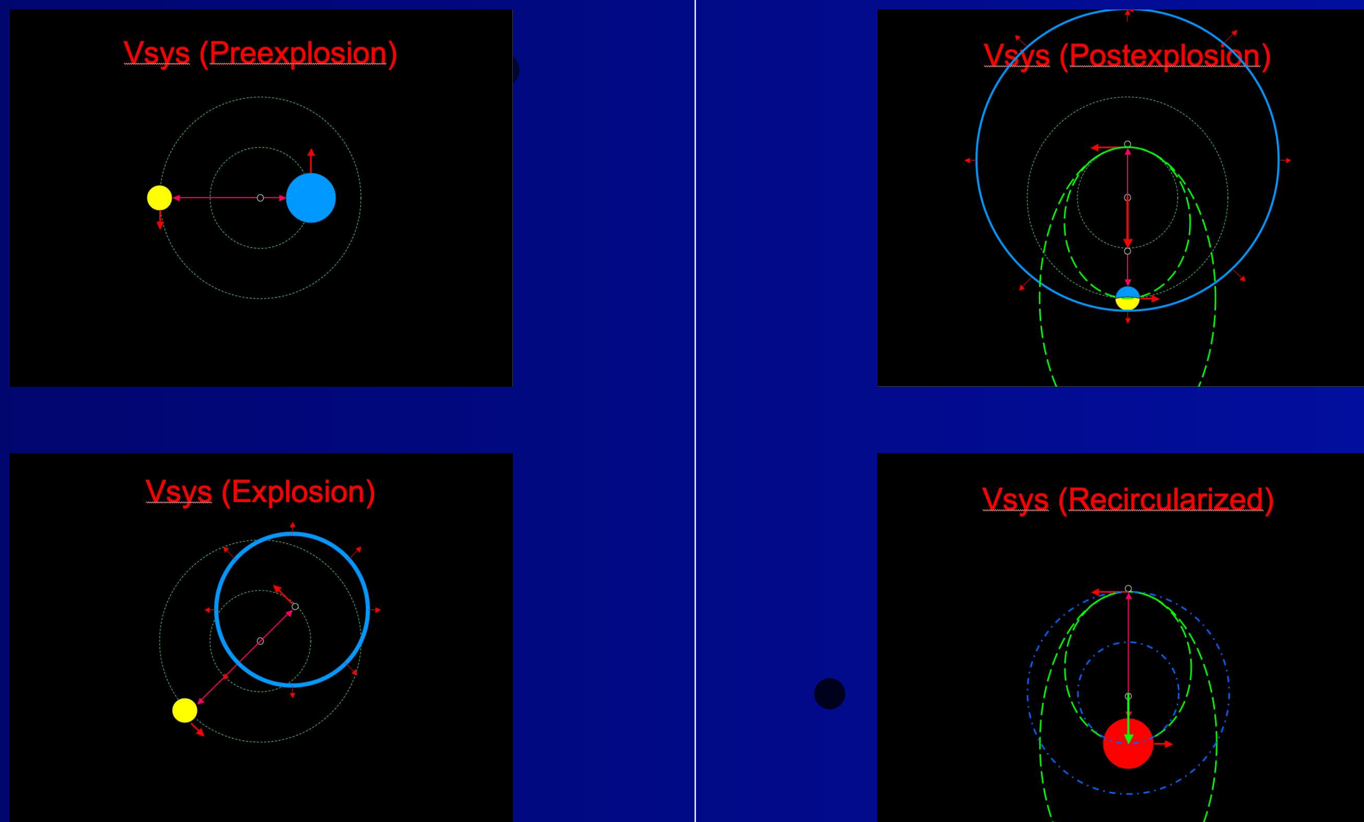


Figure 2: Black hole spin $a_\star$ is given in units of $[GM/c^2]$ and δm is the total rest mass of the accreted material. Note that M_0 is the mass of the non-rotating initial black hole. Here we assume that the last stable orbit corresponds to the marginally stable radius (Brown et al. 2000).

System Velocity



- Blaauw-Boersma Kick:

$$v_{sys} = \left(\frac{\delta M}{M_{BH}+m}\right) v_{He}.$$

- The HN's "sudden" mass loss shifts the C.O.M. of the binary, thus it acquires a velocity.

Galactic BHBs as Sources of GRBs/HNe

Galactic BHBs

- There are 15 known Galactic Black-Hole Binaries (BHBs) with well measured masses.
- 8 of them are Angular Momentum Loss (AMLs) sytems (the donor or secondary star is in Main Sequence).
- 7 of them are systems with evolved donors (Nu’s), so a model for their evolution can be estimated.
- We can estimate the energy stored in the angular momentum in the Galactic BHBs and evaluate their potential as gamma-ray bursters and hypernovae.

Blandford-Znajek Mechanism

- The magnetic field $\vec{B}$ rotates along with the forming black hole.
- Electrically-charged plasma from the collapsing core cannot keep up with the fast rotation of the BH-anchored $\vec{B}$ field.
- The resulting energy from the Faraday Law generator comes out in the direction of the Poynting vector. Its average points in the direction of the rotational axis.

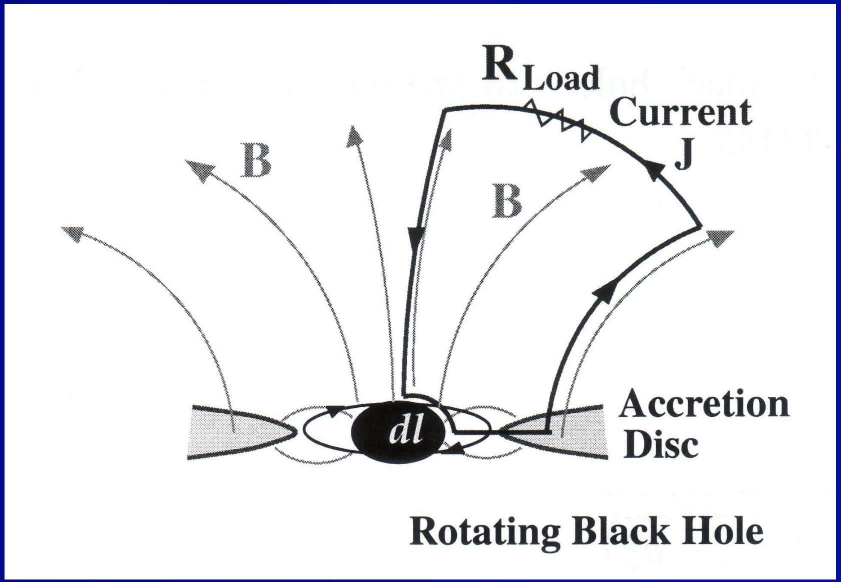


Figure 3: Lee et al., 2000. The black hole and the accretion disk work like an electric motor with the armature (the infalling material) going around the black hole.

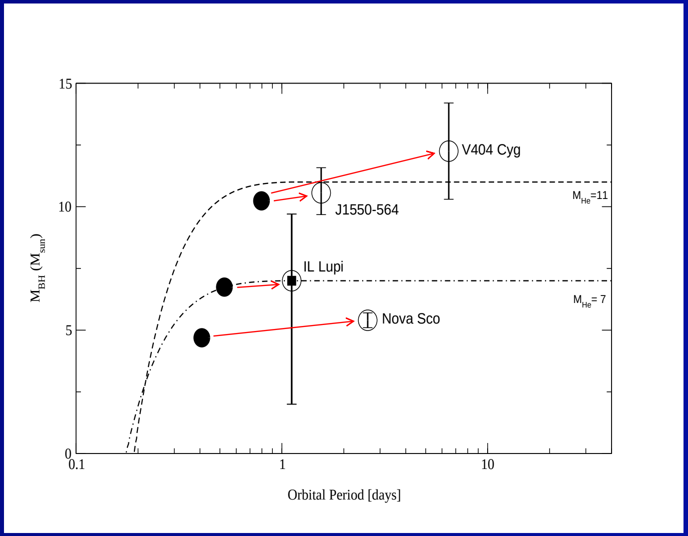
Gamma-Ray Bursts and Their Energies

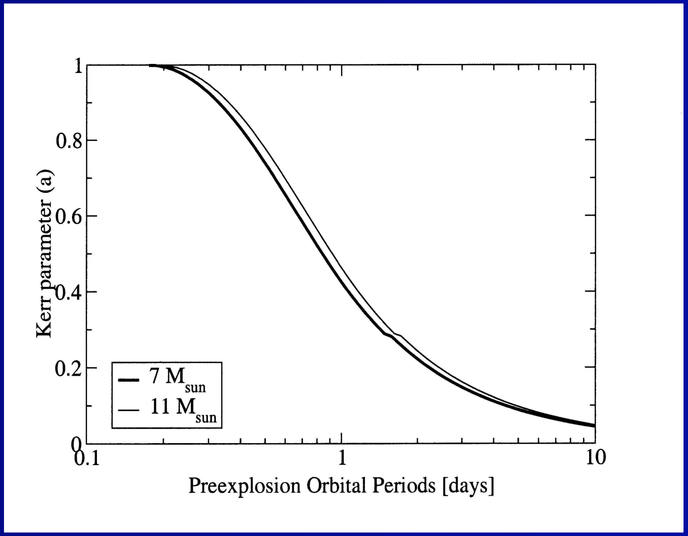
- Rotational energy of a BH is a fraction of its mass: $E_{\rm rot} = f(a_\star) M_{\rm BH} c^2$
- $f(a_\star) = 1 - \sqrt{\frac{1}{2}\left(1 + \sqrt{1 - a_\star^2}\right)}$
- For $a_\star = 1$, $f(a_\star) = 0.29$.
- In the BZ mechanism the efficiency is given as the ratio of angular velocities of the magnetic field and the BH: $\epsilon_\Omega = \Omega_F / \Omega_{BH}$.
- For optimal extraction $\epsilon_\Omega \simeq 0.5$.
- An analytical expression for the extracted energy is given by: $E_{BZ} = 1.8 \times 10^{54} \epsilon_\Omega f(a_\star) \frac{M_{BH}}{M_\odot} \mathrm{erg}$

Galactic Examples

Reconstructed pre-explosion orbital period vs. black hole masses of SXTs with evolved companions. The reconstructed pre-explosion orbital periods and black hole masses are marked by filled circles, and the current locations of binaries with evolved companions are marked by open circles. The solid lines are ideal polytropic He stars, but both IL Lupi and Nova Scorpii were evolved from $11 M_\odot$ He stars. (Lee et al. 2002).

We can then calculate the Kerr parameters: $a_\star = 0.8$.





BHBs

Name	M_2 [$M_\odot$]	m_2 [$M_\odot$]	M_{now} [$M_\odot$]	m_{now} [$M_\odot$]	Model $a_{\star,2}$	Meas. $a_\star$	P_{now} [days]	E_{BZ} [10^{52} ergs]
AML: with main sequence companion								
J1118+480	~ 5	< 1	$6.0 - 7.7$	$0.09 - 0.5$	0.8	-	0.170	~ 43
Vel 93	~ 5	< 1	$3.6 - 4.7$	$0.50 - 0.65$	0.8	-	0.285	~ 43
J0422+32	$6 - 7$	< 1	$3.4 - 14$	$0.10 - 0.97$	0.8	-	0.213	$50 - 60$
1859+226	$6 - 7$	< 1	$7.6 - 12$		0.8	-	0.380	$50 - 60$
GS1124−683	$6 - 7$	< 1	6.95	$0.56 - 0.90$	0.8	-	0.433	$50 - 60$
H1705−250	$6 - 7$	< 1	$5.2 - 8.6$	$0.3 - 0.6$	0.8	-	0.521	$50 - 60$
A0620−003	~ 10	< 1	11.0	0.68(18)	0.6	-	0.323	~ 44
GS2000+251	~ 10	< 1	$6.0 - 14$	$0.26 - 0.59$	0.6	-	0.344	~ 44
Nu: with evolved companion								
GROJ1655−40	~ 5	$1 - 2$	$5.1 - 5.7$	$1.1 - 1.8$	0.8	$0.65 - 0.75$	2.61	~ 43
4U1543−47	~ 5	$1 - 2$	$2.0 - 9.7$	$1.3 - 2.6$	0.8	$0.75 - 0.85$	1.12	~ 43
XTEJ1550−564	~ 10	$1 - 2$	$9.7 - 11.6$	$0.96 - 1.64$	0.5	-	1.55	~ 30
GS2023+338	~ 10	$1 - 2$	$10.3 - 14.2$	$0.57 - 0.92$	0.5	-	6.47	~ 30
XTEJ1819−254	$6 - 7$	~ 10	$8.7 - 11.7$	$5.50 - 8.13$	0.2		2.81	$1 \sim 1.2$
GRS1915+105	$6 - 7$	~ 10	14(4)	1.2(2)	0.2	> 0.98	33.5	$1 \sim 1.2$
Cyg X−1	$6 - 7$	$\gtrsim 30$	~ 10.1	17.8	0.15	-	5.60	$.5 \sim .6$
Extragalactic								
LMC X−1	~ 40	~ 35	$9.0 - 11.6$	30.6 ± 3.2	0.05	$0.81 - 0.94$	3.91	$< .2$
LMC X−3	10.25	4	$5 - 11$	6 ± 2	0.43	< 0.26	1.70	~ 16
M33 X−7	~ 90	~ 80	$14.2 - 17.1$	70.0 ± 6.9	0.05	0.77(5)	3.45	$.3 - 1.1$

Table 1: Parameters at the time of formation of BH and at present time. Subindex 2 stands for values at the time BH is formed, whereas subindex now stands for recently measured values. The AML binaries lose energy by GWs, shortening the orbital period whereas the Nu binaries will experience mass loss from the donor star to the higher mass BH and, therefore, move to longer orbital periods.

M33 X—7

- $M_{BH} \sim 15 M_{\odot}$.
- $M_{sec} \sim 70 M_{\odot}$.
- Low metallicity.
- $P = 3.45$ days.
- Low natal $a_{\star} \lesssim 0.05$.
- Fast present $a_{\star} \sim 0.77$.
- Hypercritical Accretion!!
- Not enough energy for a GRB/HN.

LMC X—1

- $M_{BH} \sim 10 M_{\odot}$.
- $M_{sec} \sim 31 M_{\odot}$.
- Low metallicity.
- $P = 3.91$ days.
- Low natal $a_{\star} \lesssim 0.05$.
- Fast present $a_{\star} \sim 0.90$.
- Hypercritical Accretion!!
- Not enough energy for a GRB/HN.

Conclusions

Conclusions I

- Case C mass transfer is essential to produce BHs.
- Without tidal locking the He-Star model does not have the rotational energy to produce GRB/HN explosions.
- Black Hole Binaries produce GRB/HN explosions during the collapse of the primary star into a black hole.
- Our model supports the Collapsar model by supplying the rotational energy in a natural way and explains the Subluminous GRBs.
- We can observe 14 Galactic relics of (mostly subluminous) GRB/HN explosions.
- There is 1 Galactic source of dark explosions.
- There is one nearby known extragalactic BHB which is a likely cosmological GRB/HN relic.
- Hypercritical accretion is suggested by LMC X−1 and M33 X−7.

- Thank you!

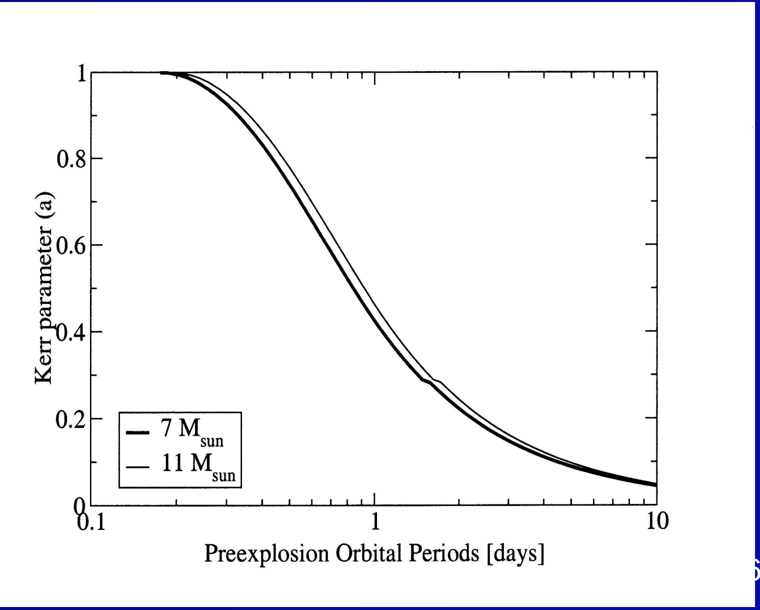
References

Selected References

- Moreno Méndez, Brown, Lee and Walter. Kerr Parameters for Stellar Mass Black Holes and Their Consequences for GRBs and Hypernovae, 2007, arXiv:astro-ph/0612461 *In progress*.
- Brown, Lee, Moreno Méndez. LMC X—3 May Be A Relic of a GRB Similar to Cosmological GRBs, 2008, *ApJ* 685, 1063.
- Brown, Lee, Moreno Méndez. GRBs and Hypernova Explosions of Some Galactic Sources, 2007 *ApJ* 671, L41.
- Moreno Méndez, Brown, Lee. The Case for Hypercritical Accretion in M33 X—7, 2008, arXiv:0809.2146, *ApJ* accepted, .
- Bethe, Brown, Lee. Formation and Evolution of Black Holes in The Galaxy.
- Shafee, McClintock, et al. Estimating the Spin of Stellar Mass BHs by Spectral Fitting of the X-Ray Continuum, 2006.
- McFadyen, Woosley. Collapsars: GRBs and Explosions in "Failed" SNe, 1999, ApJ, 524:262-237.

Donor Mass to Kerr parameter

- From $M_{He} = 0.08 \left[\frac{M_{giant}}{M_\odot}\right]^{1.45} M_\odot$ LBW found that
  $$a_f = \left(\frac{M_d}{M_\odot}\right) \left(\frac{M_{Giant}}{M_\odot}\right)^{-0.55} a_i.$$
- From Kepler: $\frac{\text{days}}{P_b} = \left(\frac{4.2 R_\odot}{a_f}\right)^{3/2} \left(\frac{M_d + M_{He}}{M_\odot}\right)^{1/2}.$
- So $\frac{\text{days}}{P_b} = \left(\frac{4.2 R_\odot / a_i}{M_d / M_\odot}\right)^{3/2} \left(\frac{M_d + M_{He}}{M_\odot}\right)^{1/2} \left(\frac{M_{giant}}{M_\odot}\right)^{0.83}.$
- a_i is, for practical purposes, close to being constant of value of the radius of the supergiant plus an extra $\sim 50\%$. So $P_b \propto M_d^{3/2}$ for small M_d, and $P_b \propto M_d$ for large M_d.



Kerr Parameter

- $J = I\Omega$.
- $a = Jc/GM$ =Specific Angular Momentum.
- $a_\star = a/M = Jc/GM^2$ =Kerr Parameter.
- $a_\star = 0$ for a Schwarzschild BH.
- $a_\star = 1$ for an extreme Kerr BH.
- $a_\star$ is the ratio of the speed of the rotation of the equator of the BH to the speed of light (Ω/c).