GRBs from rotating black holes

Maurice H.P.M. van Putten (MIT)

Eve C. Ostriker (Maryland)
Amir Levinson (Tel Aviv)
Gerald E. Brown (SUNY Stony Brook)
Abhinanda Sarkar (IBM)
David Coward and Ronald R. Burman (UWA)
Stephen Eikenberry (Cornell)
Hyun Kyu Lee (Hanyang)
$< Z > \approx 1.25$

$< V / V_{\text{max}} > = 0.338 \pm 0.008$

$<1/2$ (Euclidean value)
Clustering-spread in GRB energies and opening angle

Frail et al., 2001
GRB supernova association

GRB 011121 (z=0.36)  
HST similar to GRB 1998bw

GRB 011211 (z=2.41)  
XMM detection of light elements

Bloom et al. 2002  
Reeves et al. 2002
GRBs: what’s in the black box?

Baryon-poor beamed outflows
Compact and energetic source
Long-duration (some 20 s, or $10^4$ dynamical time-scales)

Method:

Study all energy emissions (in grb, gws, thermal and nu-emissions)
Study progenitors and remnants

Rees & Meszaros ‘92,94
Rees, this morning
Piran, '98,'99
Frail et al. ’01
...
Most favored GRB progenitors

1. Woosley-Paczynski-Brown hypernovae

- Core-collapse in rapidly spinning magnetized star in a binary
- Rapid/slow black hole spin from close/wide progenitor binaries

2. NS/BH binary coalescence

- Black hole plus disk or torus systems

References:
- Woosley 1993
- Paczynski 1998
- Brown et al. 2000
- Woosley, this morning
- Lee, Brown & Wijers, 2002
- Paczynski 1991
Black hole mass $3-15 M_{\odot}$ in SXTs

Some of SXTs may be relics of GRBs

- Israeli et al., 1999
- Orosz et al., 2001
- Brown et al., 2000
Kerr black holes

Baryon-free objects
Frame-dragging of spacetime
Compact energy reservoir in angular momentum
Outline

- Bimodal distribution of durations from two accretion modes
- Minor output: BPJ from differential frame-dragging in a dissipative gap
- Major output: gravitational radiation from a torus around a black hole
- Searches for gravitational wave bursts in hypernovae
“A tango between a torus and a black hole”
Equivalence in poloidal topology to pulsars (a)

\[ \Omega_{PSR} = \Omega_T \]
Equivalence in poloidal topology to pulsars (b)

PSR spun-up as infinity wraps around it
PSR spun-down by losses to infinity

cpt infinity

=> Causal interactions

Long durations from a suspended accretion state
Coupling in lowest energy state of black hole

\[ E = \frac{1}{2} C q^2 - \mu H B \]

Capacitance  \[ C = \frac{1}{r H} \]

Carter (1968) \[ \mu H = \frac{q J H}{M} \quad \text{``no fourth hair''} \]

Approximately uniform and maximal horizon flux at all spin-rates

H.-K. Lee et al., MNRAS, 2001
Net charge from symmetries \( l=1, m=0 \) a surrounding force-free magnetosphere

\[
even = odd \ast even \div odd
\]

\[
E_r = -E_\theta \quad B_\theta / B_r > 0
\]

Charge on a sphere from \( Y_{l=1, m=0} \)
Suspended accretion state for the life-time of rapid spin

Black hole-torus coupling at high spin-rate by $\mu_H^e$

As torus catalyzes spin-energy, the black hole slows down by conservation of total energy and angular momentum

Maxwell stress on the horizon of the black hole

$$t_{spin} = 88s\left(\frac{M_H}{10M_{sun}}\right)\left(\frac{M_H/M_d}{100}\right)\left(\frac{\delta E_k/\delta E_B}{100}\right)g2(\theta)$$
Hyper-accretion onto slowly rotating black holes

Magnetic torque: \( \delta \tau_B = \Omega \sin^2 \theta (f \ m \ Af) \delta Af, \ \mu = \cos \theta \)

Inertial balance: \( \delta \tau_B = \frac{1}{2} \Omega \ RR \delta M \)

\( \ddot{\omega} = R/R_0 : \quad \omega(\tau;Af) = (1-t/\tau_f) a \)

\( \alpha = \begin{cases} 
\frac{1}{2} & \text{in split monopole geometry (SMG)} \\
2 & \text{in toroidal field geometry (TFG)} 
\end{cases} \)

\( t_f^{TMG} > 0.011s \left( \frac{R_d}{1000\text{km}} \right)^2 \left( \frac{MH}{10M_{\odot}} \right)^{-1} \delta E_k \frac{\delta E_B}{\delta E_B} \quad g(\theta) \)

\( t_f^{SMG} < 0.057s \left( \frac{R_d}{1000\text{km}} \right)^2 \left( \frac{MH}{10M_{\odot}} \right)^{-1} \delta E_k \frac{\delta E_B}{\delta E_B} \)

\( \delta E_k / \delta E_B \sim 10-100 \) produces \( t_f \sim \) few seconds
Two accretion modes: suspended- and hyperaccretion for long and short GRBs

*Bimodal distribution in durations when $Md << MH*
Evidence for a suspended accretion state?

“turbulent shear flow in the torus resulting from the powerful torques acting on it"

Excess heating of inner accretion disk, in broad iron emission lines

XTE J1650-500

MCG-6-30-15

Van Putten, Science, 1999

Miller et al., submitted

Wilms et al., 2001
Li-Xin Li 2002
Formation of baryon-poor outflows along open flux-tubes
$\mu H$ supports open flux tubes

B-topology
Geometry: flat versus twisted

``Woman with a mirror''
(II-III BC)

Differential frame-dragging around a Kerr black hole

©Van Putten 2001
Equivalence in poloidal topology to pulsars (c)
Differential Frame-dragging on an open flux-tube
Differential rotation of open flux tube

“Current continuity enforces a dissipative gap”

Low-sigma baryon poor jets

Current continuity over open flux-tube
\[(\Omega H - \Omega +)Af = \Omega - Af\]

Global current closure over outer flux-tube
\[\Omega - Af = \Omega T Af \quad (\Phi_i + \Phi_T = 0)\]

Output from a differentially rotating gap
\[P = I \Delta V/2 = I(\Omega + - \Omega -)Af/2\]

\[Lp = \frac{1}{2} \Omega T (\Omega H - 2\Omega T)Af^2\]
Clustering-spread in BPJs

\[ \theta_j = \frac{L_j}{L_{cw}} \]

(a) standard  (b) variable

\[ L_p = \frac{1}{2} \Omega T (\Omega H - 2\Omega T)A_f^2 \]

(a) \( \theta_H \sim 2^{1/2} \left( \frac{E_{\text{rot}}}{E_{\text{grb}}} \right)^{1/4} \left( \frac{\Omega T}{\Omega H} \right)^{1/4} \varepsilon^{-1/4} \sim 35^o \)

(b) \( E_{cw} \sim (2f_b)^{-1/2} E_{\text{grb}} \varepsilon^{-1} \sim 1052 \text{ erg} \)

\[ \theta_j < 35^o \]

Test:
Positive correlation true GRB energy \( \sim M \), and durations \( \sim M^p \) (p=1-2)
Energy paradox in long GRBs:
true GRB energies 0.01% E-rot
Suspended accretion state converts all E-rot

Unseen emissions in GWs emitted in all directions
LIGO sensitivity curve

Thorne (1996)
Suspended accretion with gravitational radiation

Balance in angular momentum and energy transport for a torus around a black hole with a quadrupole mass moment

\[ \tau_+ = \tau_- + \tau_{rad} \]

\[ \Omega_+ \tau_+ = \Omega_- \tau_- + \Omega \tau_{rad} + P \]

with the constitutive ansatz for dissipation

\[ P \approx A_r^2 (\Omega_+ - \Omega_-)^2 \]

by turbulent MHD stresses, into thermal emissions and (conceivably) neutrino emissions
\[ \begin{align*}
\frac{L_{GW}}{L_H} & \approx \frac{\alpha}{\alpha + f_w^2} \approx O(1) \\
\frac{\Omega_T}{\Omega_H} & \approx \frac{f_H^2}{\alpha + f_H^2 + f_w^2} \approx \frac{2}{(R/M)^{3/2} + 1} \\
\frac{\delta m_T}{M} & \approx 0.15\% \\
\end{align*} \]
True energy budget in emissions from a Kerr black hole

\[
\frac{E_j}{E_{rot}} \approx \eta \frac{1 - 2\eta}{1 - \eta} \left( \frac{\theta_H^2}{2} \right)^2 \quad \text{as input to GRBs (}\theta_H \approx 35^\circ\text{)}
\]

\[
\frac{E_{GW}}{E_{rot}} \approx \eta / 2 \text{ in gravitational waves (}\eta = \Omega_T / \Omega_H\text{)}
\]

\[E_{GW} \approx 100 E_j\]
A sample of 12 GRBs with measured redshifts and durations

Expected distribution of durations in LIGO/VIRGO detections

Mean duration ~ 25 s
Event rate ~ 1/yr within 100Mpc
Observational test for Kerr black holes

\[ 2\pi \int_{0}^{E_{GW}} f_{GW} \, dE > 0.005 \]

Black hole-torus system

Neutron star limit

Van Putten & Levinson, Science, 2002
A MAJOR fraction of $E_{\text{rot}}$ of a Kerr black hole is emitted in gravitational radiation (some 10-20%)

A MINOR fraction of $E_{\text{rot}}$ of a Kerr black hole is emitted in BPJ as input to GRBs (some 0.1-0.2%)

These emissions are simultaneous and for the same duration (about 25 s)

Events $2\pi E_f > 0.005$ indicate the presence of a Kerr black hole

Strategy:
LIGO/VIRGO searches in hypernovae, ~1 per year within D=100Mpc

S/N ~ 2 advanced LIGO (single detector operation)
S/N > 2 using dual recycled interferometers

Conclusions

Cutler & Thorne gr-qc/0204090
Harry et al. 2002