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SHORT GAMMA RAY BURST CENTRAL ENGINES

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RESUMEN

Reseño posibles escenarios del origen de los discos densos calientes alrededor de hoyos negros y su papel en la producción de destellos cortos de rayos gamma. La estructura y evolución de estos discos impacta directamente en la energía disponible para extracción y determina las escalas de tiempo de interés en el sistema. La misión SWIFT, actualmente en curso, ya ha localizado con exactitud los primeros GRBs cortos y ha dado indicaciones que las fusiones binarias pueden estar relacionadas a estos poderosos eventos.

ABSTRACT

I review the possible scenarios that could give rise to hot dense disks around black holes, and their role in the production of short gamma ray bursts. The structure and evolution of these disks directly impacts upon the energy available for extraction, and sets the relevant time scales in the system. The on-going SWIFT mission has already accurately localized the first short GRBs, and provided indications that binary mergers may indeed by linked to these powerful events.

Key Words: **DENSE MATTER — GAMMA RAYS: BURSTS — HYDRODYNAMICS — STARS: NEUTRON**

1. INTRODUCTION

Gamma ray bursts (GRBs) are some of the most violent and powerful events in astrophysics, releasing $10^{50} - 10^{51}$ erg in a matter of seconds. Discovered in the late 1960s, and announced in the 1970s (Klebesadel et al. 1973), GRBs remained one of the biggest puzzles in high–energy astrophysics (see Piran 2004, Zhang & Mészáros 2004 for theoretical reviews). By the 1990s, through the results of the BATSE instrument onboard the Compton Gamma Ray Observatory it became clear that at least two separate populations were present in the data (Kouveliotou et al. 1993): long/soft bursts (with duration longer than about 2 seconds) and short/hard events (less than 2 seconds in duration, and typically a few tenths of a second). On statistical grounds, it appeared also as if the progenitors were at cosmological distances (Fishman & Meegan 1995).

It was only in the 1990s with the advent of the Beppo–SAX mission and its localization capability for long GRBs that the predicted long–wavelength afterglows were detected (in X–rays, optical and radio, Metzger et al. 1997, see also van Paradijs et al. 2000 for a review), allowing for the identification of host galaxies. These proved to lie at redshifts $z \simeq 1 - 4$, confirming their cosmological origin. Additionally, the progenitors were in regions of active star formation, indicating a link with the evolution of massive stars, and a handful of events now have definite supernova associations. The collapsar model (Woosley 1993, MacFadyen & Woosley 1999), in which the collapse of a massive rotating stellar core produces a black hole and a centrifugally supported accretion disk, has become widely accepted as an explanation for the long GRBs.

The identification of the progenitors of short GRBs, however, has proved very difficult, precisely because of their duration. The on–going SWIFT mission (Gehrels et al. 2004) was designed to specifically address these issues, with a rapid on-board response and X–ray follow-up capability. Theoretical expectations have linked these events to the coalescence of compact binaries driven by gravitational wave emission for many years (Eichler et al. 1989), but it is only now that observations are finally being able to discriminate between possible models. I summarize here recent calculations of the final stages of evolution of such systems and their remnants as possible GRB central engines.

2. DISK FORMATION IN MERGERS

Despite the general belief that compact object mergers may lead to the formation of an accretion disk (Lattimer & Schramm 1974), the question is not fully resolved. The difficulty stems from the fact that the merger is an intrinsically three-dimensional event, which does not allow one to use symmetry arguments (e.g., azimuthal symmetry) to make it more tractable. It must be addressed with accurate, high resolution dynamical simulations. The strong grav-

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itational fields in the vicinity of neutron stars and particularly black holes play an important role in the dynamical merger. Pseudo-Newtonian (Janka et al. 1999, Rosswog 2005) calculations have been performed, but the final answer will clearly require a fully relativistic calculation. In addition, the equation of state at nuclear densities is important, as the compressibility of the material, and thus the response of the star to tidal stretching and mass transfer, critically affects the dynamical evolution during merger, and thus the final outcome (Kluźniak & Lee 1998, Lee & Kluźniak 1999, Lee 2001).

2.1. *Binary neutron star mergers*

Binary neutron star systems are known to exist (Hulse & Taylor 1975, Burgay et al. 2003), and the time until final merging for PSR 1913+16 and PSR J0737-3039 is less than the Hubble time. Thus it is reasonable to assume that this kind of event will be fairly frequent, and it must certainly give rise to an electromagnetic signal, in addition to a gravitational wave burst.

The merger itself will produce a supra-massive neutron star, which would collapse to a black hole if it were cold and non-rotating. However, this post-merger remnant may be temporarily stabilized by differential rotation. Collapse would only come after the excess energy had been eliminated, perhaps through the emission of gravitational waves.

After collapse, a small amount of mass could remain in orbit around the newborn black hole, and subsequently drain on an accretion timescale, determined by the efficiency of angular momentum transport. Recent calculations indicate that a torus of $\approx 10^{-3} - 10^{-2} M_{\odot}$ may be thus formed (Shibata 2005).

The outcome may be quite sensitive to the binary mass ratio, $q = M_1/M_2$. For $q = 1$ a point–symmetric structure ($m = 2$) forms, with large expanding tidal arms on either side of the central remnant. Small deviations from unity, however, as small as about 10%, can affect the structure of the remnant significantly, inducing a single-armed structure ($m = 1$). In this case, one of the stars is essentially disrupted and wrapped up around the companion, which is affected to a much lesser degree. Whether all kinds of structure lead to a similar final configuration is a matter that still requires further investigation.

2.2. *Black hole neutron star mergers*

No black hole neutron star binaries are yet known, although population synthesis estimates suggest they do in fact occur, probably with lower frequency than double neutron star systems (Bloom et al. 1999). A black hole is already present, so the question is whether a torus will form as the neutron star plunges in because of gravitational radiation reaction. As stellar mass black holes will contain more than approximately three solar masses, the mass ratios $q = M_{\rm NS}/M_{\rm BH}$ will be smaller than 0.5 (for a canonical neutron star mass of 1.4 $M_{\odot}$). The horizon radius grows faster than the tidal radius with increasing black hole mass. Thus, for massive holes, the neutron star will be engulfed whole (Miller 2005), before it can be tidally disrupted and thus a torus is unlikely to form (although the black hole spin may affect this, since the horizon radius shrinks with increasing spin angular momentum). Low-mass black holes, giving mass ratios greater than about 0.1, are thus more likely to lead to tidal disruption of the neutron star. In this context, it is interesting to note that for the 18 galactic black hole binaries, mass determinations indicate that ≈45% of the black holes within them have masses between 6 and 8 solar masses (McClintock & Remillard 2004), and thus in the range likely to lead to the complete tidal disruption of a neutron star companion.

Numerical studies of black hole neutron star interactions with these mass ratios, with their limitations, show that a disk frequently forms (Lee 2001), containing $10^{-3} - 10^{-2}$ $M_{\odot}$. Large, one–sided tidal tails are also common, with some of the material attaining escape velocities. This could potentially lead to interesting nucleosynthesis of heavy elements through the r–process.

3. MICROPHYSICS

We have performed numerical calculations of the evolution of post–merger accretion disks using a Smooth Particle Hydrodynamics (SPH) code in cylindrical coordinates in two dimensions (r, z), assuming azimuthal symmetry. The disk evolves in the central potential well produced by the black hole, typically harboring 3-4 $M_{\odot}$, and we model the evolution during ≈ 0.4 s. The equations of motion and the energy equation include all terms arising from the viscous stress tensor, and the magnitude of the viscosity coefficient is computed through the prescription of Shakura & Sunyaev with the α parameter, ranging from $10^{-1} - 10^{-3}$ (Lee et al. 2005a).

The equation of state considers the contribution to the pressure and internal energy from free nucleons and α particles, a relativistic Fermi gas of arbitrary degeneracy (Blinnikov et al. 1996), radiation and neutrinos. The degree of neutronization is determined self-consistently by assuming equilibrium of weak interactions from capture of electrons and positrons onto free protons and neutrons respectively (the accretion time scale is much longer than the weak interaction time scale, so this assumption is entirely reasonable). Over the encountered range in density and temperature, ideal gas pressure of free nucleons dominates at the 85% level over the other terms.

The fluid cools through neutrino emission (photons are entirely trapped), and we consider pair annihilation, $e^{\pm}$ capture onto free nucleons, nucleon–nucleon bremsstrahlung and plasmon decays. In practice, pair capture completely dominates the cooling rate. We use fitting functions and tables valid over a wide range of temperatures and densities whenever possible (Itoh 1996, Langanke & Martínez–Pinedo 2001).

Since, as mentioned before, the density is high enough for the fluid to become opaque to its own neutrino emission, we compute the neutrino optical depths from coherent scattering off free nucleons (this provides the dominant contribution to the opacity), and suppress the local cooling rate by a factor $\exp(-\tau_{\nu})$. In practice, the surface of last scattering, or neutrino–surface, lies at $\rho \approx 10^{11}$ g cm^{-3}.

4. ENERGETICS

Two main mechanisms provide natural options to tap the energy of the disk: neutrino emission and magnetically powered outflows.

Neutrino emission is the main source of cooling, with e$^{\pm}$ pair annihilation and capture of electrons and positrons by free nucleons providing most of the energy release. The available energy comes primarily from the store of internal energy in the disk, and viscous dissipation. As the disk is partially opaque to its own neutrino emission (this occurs at densities above $\approx 10^{11}$ g cm^{-3}), the energy is released over a longer time scale, given by $t_{cool} \approx E_{\rm int}/L_{\nu} \approx 0.1$ s. This time scale is comparable to the characteristic duration of short GRBs. Figure 1 shows the neutrino luminosity for calculations with various disk masses and effective viscosities. If the viscosity is very high, the disk drains into the black hole so quickly that it becomes entirely transparent to its own neutrino emission within a few tens of milliseconds. Otherwise the opaque region persists in the inner disk throughout the calculations.

Numerical simulations of disks under the physical conditions appropriate for short GRBs have been performed in the past few years, although to date none of them include magnetohydrodynamical effects. Thus, any arguments about magnetically driven outflows must rely on inferences and extrapolations (accurate MHD simulations have been carried out in the Schwarzschild and Kerr metrics –

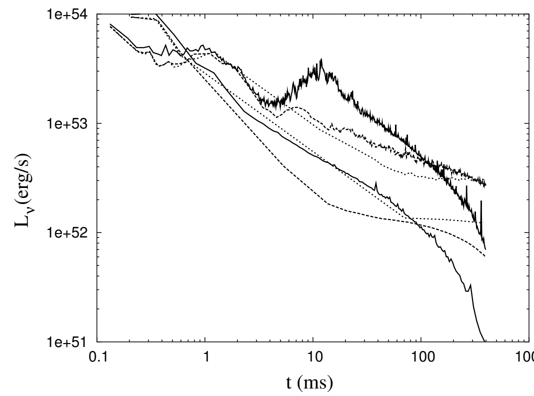

Fig. 1. Neutrino luminosities L_{ν} for calculations with $\alpha = 0.1$ (solid), 0.01 (long–dashed), 0.001 (short–dashed) and initial disk masses $m_d = 0.3, 0.06$ M$_{\odot}$ (upper and lower of each pair respectively). The decay occurs on a cooling timescale $t_{cool} \approx E_{\rm int}/L_{\nu}$ where $E_{\rm int}$ is the internal energy reservoir of the disk.

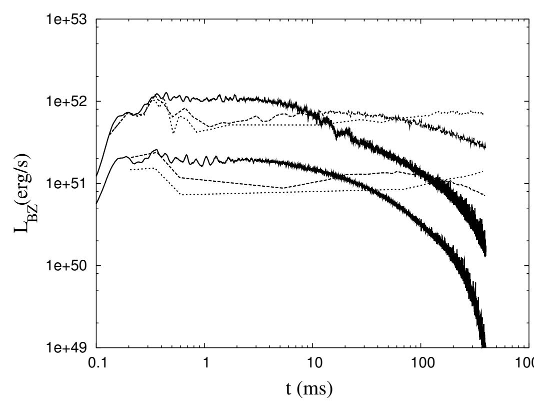

Fig. 2. Blandford–Znajek luminosities L_{ν} for calculations with $\alpha = 0.1$ (solid), 0.01 (long–dashed), 0.001 (short–dashed) and initial disk masses $m_d = 0.3, 0.06$ M$_{\odot}$ (upper and lower of each pair respectively). The decay occurs on an accretion time scale t_{acc}.

see Balbus 2003 — but they use a simplified hydrodynamical treatment and none of them include detailed microphysics of the type necessary to consider the role of neutrino emission and neutronization). Very roughly, if the magnetic field energy density within the rotating plasma reaches some fraction of equipartition with the thermal energy density, then the outflow power will scale in time with the maximum (equatorial) density in the inner disk. The accretion time scale is given by the efficiency of angular momentum transport. For $t < t_{acc}$ the density remains roughly constant, and subsequently falls rapidly. Thus the natural duration of a magnetically driven flow (if no external agent feeds the disk with mass) is $t_{burst} \approx t_{acc}$. Figure 2 shows the magnetically powered luminosity (assuming full equipartition and that the Blandford-Znajek mechanism powers the outflow) for the same calculations as displayed in Figure 1.

The energies of the emitted neutrinos are $E_\nu \simeq$ 8 MeV. The spectrum may be especially relevant as the neutrino interaction cross-sections scale with the square of the energy. Thus, for a given total energy release, the shape of the spectrum may affect the driving of a neutrino powered outflow (Ramirez-Ruiz & Socrates 2005).

5. CONCLUSIONS AND DIRECTIONS FOR FUTURE WORK

There are clearly a number of unresolved issues concerning the calculations we have briefly described here. The two most important shortcomings are the lack of explicit magnetic field effects in the hydrodynamics and the fact that the computations are not done in General Relativity. Our treatment of neutrino diffusion effects is simple and attempts only to capture the essential behavior of the system. The necessary and obvious step is to consider the appropriate modifications to take these effects into account. On the other hand, a substantial effort has been done to capture the microphysics correctly, in what concerns the equation of state, neutronization and neutrino emission.

Clearly, there is a long way to go from modeling the structure and evolution of the inner disk at the heart of the GRB central engine to the observed electromagnetic signal, but the former is a necessary first step. Simple, global variables such as energetics and durations, and possible correlations between them, may already be obtainable from the growing data set of short GRBs being compiled by SWIFT. The first short/hard burst for which an accurate localization was obtained, GRB050509b (Bloom et al. 2005), has already provided a hint that a compact binary merger origin is possible (Lee et al. 2005b). Indeed, a giant elliptical galaxy at at redshift $z = 0.22$ lies only 10" away from the X-ray afterglow. If the association is real, the projected distance is 40kpc and the isotropic energy release is $E_{\gamma,iso} \approx 3 \times 10^{48}$ erg. The offset from the center of the galaxy, which contrasts with that of numerous long GRBs found directly within star–forming galaxies, indicates that the system may have traveled far from its birthplace before producing the burst, in agreement with delays of a few hundred million years expected from population synthesis estimates of gravitational radiation driven compact binaries.

As SWIFT continues to detect and successfully localize short GRBs, we may hope to finally pin down the progenitor systems.

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