Gamma-Ray Bursts, part 2: short bursts and soft gamma-ray repeaters

We now move on to the short gamma-ray bursts. For these, the origin is even less certain than it is for the long bursts, and that's saying something! We'll go over some of their properties, then consider possible origins.

Short bursts are just as diverse as long bursts, but short bursts are:

- Shorter (duh!), with typical durations of a few tenths of a second.
- Harder, meaning that a greater fraction of photons at higher gamma-ray energies (several hundred keV).
- Found in or near multiple types of galaxies, i.e., elliptical or spiral. Long bursts are only associated with actively star-forming galaxies.

Naturally, when examined closely, there is enough heterogeneity in the population that we can't be too categorical. Still, **Ask class:** what are some possible origins?

Black hole – neutron star mergers

Our first try will be mergers between black holes and neutron stars. The basic idea is that as the neutron star is disrupted, its matter forms something of an accretion disk. There is therefore a naturally clean axis along which one can imagine a jet flowing. More specifically, it has been proposed that in this type of merger, high-energy neutrinos and antineutrinos annihilate to form an electron-positron outflow.

To get a sense for the time scales involved, let's calculate the orbital time at the point when the neutron star is disrupted. Recall that Roche lobe overflow occurs when the average density inside the orbit is comparable to the average density of the donor. Thus

$$M/r^3 \approx m_{\rm donor}/R^3_{\rm donor}\ . \tag{1}$$

Note, though, that the orbital frequency is $\omega_{\rm orb} = \sqrt{GM/r^3}$. As a result, the frequency at which mass transfer begins basically depends only on the average density of the donor. For a neutron star, the characteristic time is then

$$T \sim 2\pi/\sqrt{G\rho} \approx 1\ {\rm ms} \tag{2}$$

for a star of mass 1.5 $M_\odot$ and radius 10 km (and thus an average density of 7×10^{14} g cm^{-3}).

Our next calculation is to estimate the maximum mass of a black hole that can disrupt a neutron star outside the horizon; obviously a disruption inside the horizon won't yield any observable effect! Suppose we focus on nonrotating black holes. Then the effective average density at the horizon is

$$\rho_{\rm eff} = M/[(4\pi/3)(2GM/c^2)^3]\ . \tag{3}$$

A quick comment here about strategy for solving such equations. We could set $\rho_{\rm eff} = 7\times 10^{14}$ g cm^{-3}, then cross-multiply and solve for M. However, it is easier to just pick a mass (we'll choose 1 $M_\odot$), solve for the density, then recognize $\rho \propto M^{-2}$ to solve for the mass. Adopting this procedure we find $\rho_{\rm eff} = 1.8\times 10^{16}(M/M_\odot)^{-2}$g cm^{-3}. This implies that we can go to a mass of about 5 $M_\odot$, which isn't much! More careful consideration would bring you to about 10 $M_\odot$ for a nonrotating black hole, and about 30 $M_\odot$ for a maximally rotating black hole for which the horizon radius is M instead of $2M$.

But wait **Ask class**: have we done this properly? Remember that we need the matter to spiral around for the process we have in mind. If the neutron star is disrupted outside the horizon, but then plunges straight in, that doesn't help. As a result, our condition is really to match the average density inside the ISCO, not the horizon. For a nonrotating black hole, that's an extra factor of three in distance, leading to a factor of 4-5 in mass. This already takes us down to about 2 $M_\odot$ for nonrotating black holes. In addition, even outside the ISCO, losses of angular momentum to gravitational radiation can be rapid enough to extend the effective required radius for disruption a bit more.

Adding spin can in principle improve things, because the ISCO moves in for high-spin spacetimes and prograde orbits. However, it isn't obvious how much this helps, given that at the relatively comparable masses of interest the neutron star itself contributes to the spin of the spacetime, in the sense of reducing the spin.

With all this in mind, I published a paper in 2005 suggesting that BH-NS mergers are not good candidates for short hard gamma-ray bursts. This is basically because I felt that the neutron star would be swallowed whole rather than allowing enough matter to spiral around to produce the observed behavior. Numerical simulations of these mergers are the most challenging mergers one can do, because they involve horizons as well as complicated hydrodynamics and an uncertain equation of state. Still, recent work tends to support the idea that NS-BH mergers are over and done with without much emission. The main issue remaining involves very rapidly rotating black holes. That will still require significant development of numerical techniques.

Neutron star – neutron star mergers

What about two neutron stars? Here you know that there will be a disk of some sort, because there is no horizon (at least at first!). There are, however, two apparent problems.

The first has to do with time scales. Recall that the dynamical timescale for NS disruption is about 1 ms. This is still true when the other object is also a NS. By itself, that doesn't mean much; after all, one might have hoped that even if the orbital time is 1 ms, the inspiral time could be much more than that, and hence be comparable to the few tenths of a second that is observed. However, this isn't the case. Indeed, for two neutron stars, the inspiral time due to gravitational radiation is about the same as the orbital time. This is too short by factors of hundreds!

The second issue relates to whether the combined object can survive. The lowest mass NS ever inferred has $M = 1.25\ M_\odot$. When two NS come together there will be some release of gravitational energy, but this implies that the total mass will be well above 2 $M_\odot$, and more typically above 2.5 $M_\odot$. This is above the standard maximum mass for a neutron star. Will the object collapse directly into a black hole?

The answer to both could be that when two neutron stars merge, they have a tremendous amount of angular momentum. This spin helps support the merged remnant against gravity, especially if the remnant is rotating differentially (i.e., not as a solid body). The support isn't unlimited, of course, but could extend to nearly 3 $M_\odot$, which is plenty for the NS pairs that have thus far been observed. See Figure 1 for a visualization.

Why, though, might this help with time scales? The key issue is in how rapidly the star can either redistribute its angular momentum (if the support relies on differential rotation) or shed it entirely (if the mass is low enough to survive when the star has locked into solid-body rotation). As with much else in the gamma-ray burst game, a full answer to this is probably pretty far away because the numerical relativity that is needed is pretty extensive (full GR MHD, good equation of state at high density, accurate neutrino transport). However, my guess is that magnetic fields will enforce uniform rotation pretty rapidly if there is differential rotation initially. The timescale for angular momentum *loss*, though, depends on the strength of the dipolar component of the magnetic field. Let's examine the latter in some more detail.

From our discussion of rotation-powered pulsars the rate of rotational energy loss from a neutron star of poloidal magnetic field B_p, radius R, and angular spin frequency Ω is

$$\dot{E} = -\frac{2}{3c^3}|\ddot{\mathbf{m}}|^2 = -\frac{B_p^2 R^6 \Omega^4}{6c^3}\ . \tag{4}$$

The rotational energy is $E = \frac{1}{2}I\Omega^2$, where $I \approx 10^{45}$ g cm^2 is the moment of inertia. This means that the characteristic time needed to slow down the neutron star is

$$T = E/|\dot{E}| = 3c^3 I/(B_p^2 R^6 \Omega^2) \approx 2\times 10^9\ \mathrm{s}(B_p/10^{12}\ \mathrm{G})^{-2}(\Omega/2\pi\times 10^3\ \mathrm{s}^{-1})^{-2}\ . \tag{5}$$

This is an extremely long time, indeed much longer than a short gamma-ray burst. Note that this is the time needed to roughly double the period, which would take the rotational support from dominant to essentially negligible, but the time required for just a 10-20% change is only a factor of a few less. If we were able to get the field to a strength of $B_p \sim 10^{17}$ G, the timescale would go back into the realm of short GRBs. Is this possible?

We can get a rough estimate of this by estimating the total mass-energy in the star if the average magnetic field is $B_p = 10^{17}$ G. The energy density in a magnetic field is $B^2/(8\pi)$, so over a volume of $(4\pi/3)R^3$ we have

$$E_{\rm mag} = (B^2/6)R^3 \approx 1.7 \times 10^{51}\ (B_p/10^{17}\ {\rm G})^2 {\rm erg}\ . \tag{6}$$

This is to be compared with the stellar mass-energy of $Mc^2 \approx 3 \times 10^{54}$ erg. Therefore, such a magnetic field would make only a small difference to the overall structure of the star, and in particular would not be likely to cause it to collapse. The field is legal.

As far as how the field would get to that strength, note that in many circumstances magnetic field lines act like elastic ropes, and as they are twisted and tangled the field strength increases. Turbulence in the merged remnant, plus significant differential rotation, might do the job. There are still, however, many issues to resolve.

Soft gamma-ray repeaters

As you may recall from the last lecture, there was an event on March 5, 1979 that sowed confusion in the GRB game for many years because it appeared similar to a standard GRB and was clearly from a relatively local source (the Large Magellanic Cloud in this case). A few other similar sources have now been detected, and their properties are now distinct enough from classic GRBs to merit their own source category: soft gamma-ray repeaters (SGRs). These sources:

- Peak in softer photons, with temperatures around $kT \sim 20 - 30$ keV.
- Are associated with supernova remnants. This is trickier than you might imagine, because there are so many visible supernova remnants in the Galactic plane, and SGR localization is often so poor (degrees to arcminutes), that the probability of chance coincidence is not all that small.
- Have long quiescent periods followed by surges of activity, in which we might observe dozens of bursts of a tenth of a second or less. The typical peak luminosity is 10^{41-42} erg s^{-1}.
- In three of the 4-5 sources (depending on how you classify them), there has been a single "superburst" in which the peak flux has been 10^{45-47} erg s^{-1}. These superbursts lasted hundreds of seconds (mostly at a much lower luminosity), and clear periodicity is seen in the emission. The period is typically 6–12 seconds.

- Quiescent observations show that the persistent emission is at around 10^{35} erg s^{-1}, and the same period is seen as in the superbursts. The period exhibits spindown that is rapid by the scale of most neutron stars.

Considering this evidence in 1995, Chris Thompson and Rob Duncan proposed that these are "magnetars", meaning neutron stars that have surface magnetic fields $B \sim 10^{14-15}$ G instead of the more typical birth fields $B \sim 10^{11-13}$ G. The most convincing of their arguments comes from energetics. If we assume, reasonably, that the 6–12 second period is rotational (nothing else could be that periodic!), the rotational energy is only about 10^{42} erg, much too small to explain the observations. In contrast, 10^{15} G gives about 10^{47} erg, which is plenty. The case was clinched with the observation of rapid spindown of the stars, which is consistent with fields of this strength.

The picture is that with fields this strong, the field "wants" to put itself in a lower-energy configuration, meaning that the field lines try to drag through the crust. The crust, however, resists, so pressure builds up in a way similar to how tectonic plates stick against each other. Occasionally the plates give way, usually in a series of relatively small blips, but every now and then in a major release of energy. This model has weathered the tests so far, although there are still plenty of puzzles (e.g., in the two most recent superbursts, quasi-periodic oscillations at several tens of Hertz to a few hundred Hertz were seen).

Returning finally to short gamma-ray bursts, is it possible that at least some of them might be the initial very high luminosity spike of a superburst? Yes, but either they would have to be super-superbursts (i.e., much more energetic than what we have seen so far) or fairly tightly beamed towards us, to give the observed fluxes. Overall, I have the somewhat pessimistic viewpoint that short GRBs will turn out to be an admixture of multiple categories of events, so it could be quite some time before we resolve their origin. One way that it might be done, though, is by observation of gravitational waves coincident with a short GRB. If they are visible at all, it must have been a merger of two compact objects, and we would be able to tell from the masses whether these are two neutron stars or a neutron star and a black hole. To understand more about this we need to discuss gravitational waves, which will occupy the last four lectures in our class.

Intuition Builder

10^{15} G is above the "quantum critical field" $B_c = 4.4 \times 10^{13}$ G at which $E_{\rm cycl} = m_e c^2$. People are often puzzled that stronger fields can exist, arguing that above twice that field, the virtual photons generated should pair-produce and thus cut the field down to at most $2B_c$. What do you think about this?

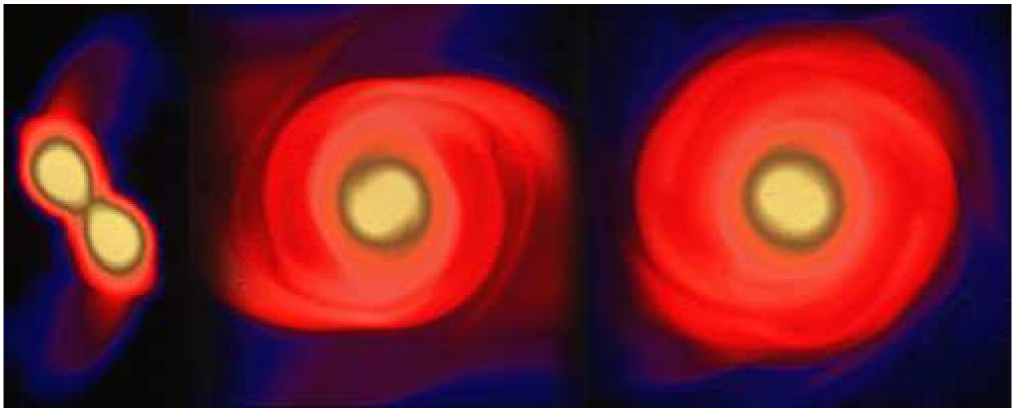

Fig. 1.— Slides from a simulation of two neutron stars merging. The rapid differential rotation keeps them from collapsing into a black hole, at least for a while. From http://ct.gsfc.nasa.gov/insights/vol3/images/neutcol.gif