Special lecture: short gamma-ray bursts

Initial question: What can radiative processes and gravitational waves tell us about short gamma-ray bursts?

In 1967, the Vela spy satellites from the United States started detecting bursts of gamma rays. The satellites had been placed in orbit in order to detect Soviet nuclear tests in space, so the observation of the gamma rays was rather alarming! However, after a few years and more satellite observations, it was determined that the distance had to be significantly greater than the distance to the Moon. If the Soviets had tests that far out, we were goners anyway, so the existence of these gamma-ray bursts was revealed publicly in 1973. Observations using many subsequent satellites, particularly the Burst and Transient Source Experiment (BATSE) aboard the Compton Gamma-ray Observatory, showed that although there was a remarkable diversity of properties between the bursts, some of the general trends were:

- The flux tended to peak at high energies, around hundreds of keV in many cases. One source had a single photon at 18 GeV; later observations with the Fermi gamma-ray observatory have seen even higher-energy photons.
- The peak flux at Earth from the bursts had a huge range, from about 10^{-8} erg cm^{-2} s^{-1} to about 10^{-3} erg cm^{-2} s^{-1}.
- The durations ran from a few hundredths of a second to maybe a thousand seconds. There were two peaks in the distribution: at a few tenths of a second and at maybe 20 seconds. When it was discovered that these populations differed in other properties as well, they were lumped into the categories of short (sometimes short-hard) gamma-ray bursts and long (sometimes long-soft) gamma-ray bursts.
- The sky distribution appeared nearly isotropic. However, although you might have expected the number of sources above some flux F to scale as $F^{-3/2}$ (because if all sources are the same, a source at distance d has a flux $F \propto 1/d^2$ and the volume is $V \propto d^3$, so if the number scales as V then $N \propto F^{-3/2}$), in fact the slope flattened at lower fluxes.

Based only on that information, what would you conclude about gamma-ray bursts?

In 1997, the Beppo-SAX mission, which had been designed mainly to look at active galactic nuclei, had a breakthrough when it was able to localize the fading X-ray emission from a gamma-ray burst sufficiently well that optical follow-up of the region was possible. Soon, multiple fading counterparts and their host galaxies were discovered. Thus the redshifts were as well. Long bursts commonly have redshifts $z \sim 2$ (the record holder has $z = 8.3$), and short bursts are closer, more like a redshift of a few tenths in many cases.

Given a flux of 10^{-4} erg cm^{-2} s^{-1}, what would this imply about the luminosity of a source at a redshift of $z = 1$ (distance of $\sim 10^{28}$ cm)? What would that tell you about the nature of the source? When you combine this information with the existence of multi-GeV photons from a number of bursts, what else can you suggest about these sources?

Another key observation (which is, as with so much about gamma-ray bursts, murky when you look at it in detail) relates to the afterglow of the burst. That is, a huge amount of energy is released in some interstellar medium. The ejected matter and energy thus run into the medium and produce energy that is seen in X-rays, UV, optical, IR, and radio emission. This is the "afterglow" because it happens from seconds to months (depending on the wavelength) after the initial burst. The flux tends to decay as a power law, but sometimes (at a time after the burst that depends on the wavelength and the environment of the source) the power law steepens; that is, the flux was decaying at a certain rate, then that rate increases. What does this suggest to you?

Enough long bursts have been associated with supernovae of a special type (these are thought to be core collapses in which the pre-SN star had lost its hydrogen and helium envelopes) that they are thought to be caused by core collapse in a massive star. The short bursts, however, have been tougher to pin down; they aren't associated with supernovae, so something else has to provide the energy. What are some ways that you can imagine that would have as much energy as is needed to explain these events?

The way that has received the most attention involves the inspiral and merger of either two neutron stars or a neutron star and a black hole. The problem is that it is difficult to think of a signature of this mechanism that is definitive and rules out other possibilities. One idea that had been proposed is that if the merger isn't perfectly clean then some of the very neutron-rich material that makes up neutron stars will go into a high-speed outflow. Because very neutron-rich material isn't stable at low density (remember our Fermi energy discussion!), the neutrons will either decay or will combine with protons to make alpha particles. This releases a huge amount of energy with time. The initial studies of these events, which were dubbed "kilonovae" because they were expected to have about a thousand times as much energy as a classical nova (recall that those are thermonuclear explosions on accreting white dwarfs), suggested that most of the energy would come out in optical light on ~ 1 day timescales.

However, those initial studies assumed that the relevant opacities would be those from iron group elements (i.e., elements with atomic numbers close to the $Z = 26$ of iron). Instead, when there are so many neutrons around, they can capture rapidly onto nuclei (thus r-process, for rapid-process) and they end up creating elements that are more likely to be rare earths. These have an extra electron shell compared to the iron group elements. What effect do they expect that this would have on the opacities? As a result, what effect do they expect that this would have on the time over which the energy is released, and the wavelength of peak emission?

A possible kilonova event has in fact been seen (see Berger et al. 2013, Tanvir et al. 2013). It has *roughly* the expected properties, but there are still some ways around this interpretation.

Finally, can you think of ways that gravitational wave observations could help elucidate the nature of short gamma-ray bursts?