Lec 27: 04/25/2012

Bursting Stars (Cont'd):

Gamma-ray Bursts:

Gamma-ray bursts radiate immense power that, integrated over several seconds, is equal to the total energy emitted by our entire galaxy over many years. The furthest such event, known as GRB 050904, has a redshift $z = 6.39 \pm 0.12$, which corresponds to an epoch when the universe was ~900 million years old.

Gamma-ray bursts (GRB's) are short, intense pulses of γ rays lasting from a fraction of a second to several hundred seconds. They arrive from random directions and from cosmological distances. This was first demonstrated by the Compton Gamma Ray Observatory, which saw no significant dipole or quadrapole moments in the distribution of GRB's, thus ruling out all possible origins other than a truely cosmological population. Later, the Beppo-SAX satellite identified sources (from 0.1 to 10 keV) to within ~1 arcmin accuracy. This made it possible for other telescopes to follow the GRB afterglows at optical and radio wavelengths.

The current redshift record ($z = 6.39 \pm 0.12$) belong to GRB 050904 as mentioned. The object GRB 980425 has the nearest measured redshift ($z = 0.0085$). The burst with measured intrinsic brightness would be detectable with current instrumentation to redshifts as large as $z \sim 15$. This could provide information on the physical state of pregalactic gas at much earlier epochs than any other objects we know.

The first characteristic deduced from their electromagnetic signal is that the typical GRB spectrum is nonthermal.

It consists of two power-laws connected at a break energy E_b. At energies below $\lesssim 1$ MeV the spectral index is ~ 1, and the spectrum steepens considerably (spectral index ~ 2-3) toward higher energies. The distribution of observed values of E_b shows that for most bright bursts it falls in the range 100-400 keV. The GRB light curve may be described as erratic, with a smooth, fast rise and quasi-exponential decay, through many peaks and substructure on a millisecond timescale. The duration of bursts spans 6 order of magnitude from 10^{-3} s to 10^{3} s, with a well-defined bimodal distribution; those lasting longer than ~ 2 s (long bursts), and other ending earlier (short bursts). One can demonstrate convincingly that the long and short bursts reflect different demographics by invoking another statistical test. It turns out that short bursts are harder, with only rare exceptions, while long bursts are softer. The hardness ratio is defined as the ratio of the time-integrated fluxes from ~(100-300) keV and ~(50-100) keV.

The time-integrated flux of GRB's ranges from $\sim 10^{-7}-10^{-4}$ erg cm which corresponds to an isotropic luminosity of $\sim 10^{51}-10^{54}$ erg s^{-1}. However, the high-energy emission from these sources is believe to be beamed, lowering their actual power by one to tw orders of magnitude. This still makes them more powerfu than a typical supernova.

The light-travel-time arguments based on the millisecond variabilit suggests that the GRB energy is liberated inside regions of ~100 km in size. GRB's are inherently relativistic phenomena, and hence we expect an intense and highly localized explosive release that involves a rapid an extensive formation of e^+e^- pairs. The optical depth to $\gamma\gamma \rightarrow e^-e^+$ annihilations in such an environment would be much larger than one. It then challenges us to understand why we see photons with an energy $E \gg 1$ MeV.

For two photons with energies E_a and E_b, one can show that e^+e^- pair production happens at incident angles θ such that

$$E_a E_b \geq \frac{2(m_e c^2)^2}{1-\cos\theta}$$

Thus, the smaller the angle θ is, the larger the energies need to be. This is intuitively understandable: two photons moving in parallel $(\theta = 0)$ never interact; it is that one is just following the other.

Now, since the luminosity of GRB's is super-Eddington, the exploding material must undergo rapid expansion. This results in a relativistic outflow, which implies tha emitted photons are beamed in the forward direction accordin to $\theta < \frac{1}{\gamma}$. Photons with energies E_a and E_b therefore cannot produce e^+e^- pairs, provided that:

$$\gamma^2 \gtrsim \frac{E_a E_b}{4(m_e c^2)^2} \qquad \left(1-\cos\theta \simeq \frac{\theta^2}{2} \text{ for } \theta \ll 1\right)$$

This results in:

$$\gamma \gtrsim 100\left(\frac{E_a}{10\,\text{GeV}}\right)^{\frac{1}{2}}\left(\frac{E_b}{1\,\text{MeV}}\right)^{\frac{1}{2}}$$

For $\gamma \gtrsim 100$, two photons with corresponding energies 1 MeV an 10 GeV do not pair produce.

There is now ample evidence that the emitting plasma in a GRB is moving relativistically. The evidence includes radio scintillation measurements, which indicates that the size of the afterglow is $\sim 10^{17}$ cm two weeks after the burst. The implied speed of expansion is therefore $\sim c$. However, the picture is more complex than a simple fireball expansion. In that case, most of the GRB internal energy would be converted into kinetic energy of baryons instead of radiative luminosity. Moreover, the medium would be optically thick, which would give rise to a quasi_thermal spectrum instead of the observed power-law.

A simple extension to this scenario is based on the fact that a rapidly expanding outflow must eventually cause a shock. As we have seen, shocks are efficient accelerators of particles. If shocks form once the fireball has become optically thin, they could reconvert the kinetic energy of baryons back into non-thermal particles and into radiation.

Fireball shocks come in two varieties. When the GRB ejecta collide with the ambient medium they produce external shocks. The synchrotron and combined synchrotron-inverse-

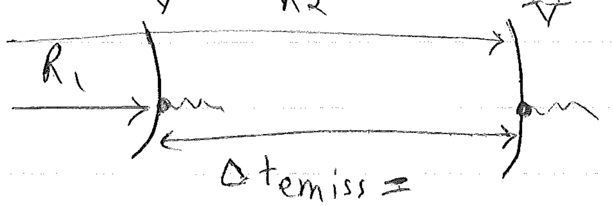
Compton emission by particles accelerated in this environment can account for the general characteristics of the typical GRB spectrum. The consensus view now is that the much longer-lasting afterglow is indeed emitted by such external shocks.

Internal shocks arise when the plasma expands nonuniformly. They do even better than external shocks when it comes to the prompt emission itself, i.e. the γ-radiation produced prior to the afterglow activity. The observed GRB lightcurves are variable down to a timescale as short as a millisecond, even whe the burst lasts tens of seconds. This is difficult to rationali on the basis of a variable central engine, since the evidenc points to a catastrophic destruction of the progenitor. In addition, the variability would tend to get washed awa within the optically thick material. On the other hand, the rapid flickering could be the radiative manifestation of multiple internal shocks jostling for dominance in the expanding optically thin remnant.

At first glance, it would seem that even internal shocks would have difficulty producing millisecond variability. This comes due to the fact that $c\delta t \sim 300$ km, while radio scintillation measurements suggest an overall remnant size of ~ 0.1 lyr. However, it is easy to show that:

$$\Delta t_{obs} \approx \frac{1}{2\gamma^2} \Delta t_{emiss}$$

Here Δt_{obs} and Δt_{emiss} are shown according to the figure:

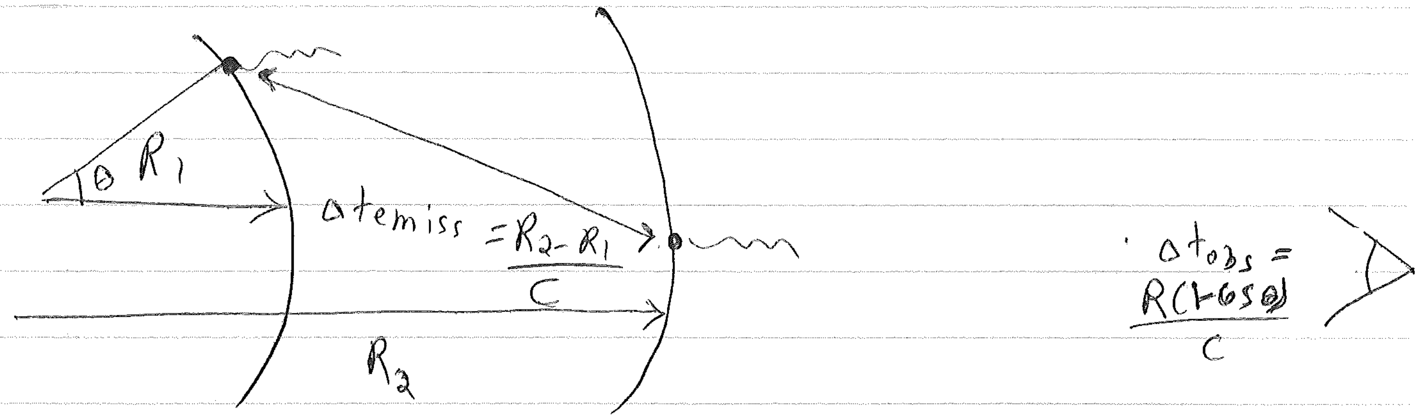


$$\Delta t_{emiss} = \frac{R_2 - R_1}{c}$$

$$\boxed{\Delta t_{obs} \approx \frac{R_2 - R_1}{2c\gamma^2}}$$

The Lorentz factor is given by $\gamma = \left(1-\frac{v^2}{c^2}\right)^{-\frac{1}{2}}$. For a strong relativistic shock $\gamma \gg 1$, and hence Δt_{obs} would be much smaller than Δt_{emiss}. For $\gamma \simeq 100$, even a fluctuation with $\Delta t_{emiss} \sim 10$ s would appear as $\Delta t_{obs} \sim 1$ ms to a distant observer.

One may wonder about emission from different parts of the moving shell since Δt_{obs} can be much larger in this case for parts moving at a large angle θ:



However, as mentioned earlier, the emission is highly beamed. This implies that the observer can only see emission from those parts of the shell that move at an angle $\theta \sim \frac{1}{\gamma}$. Again, this results in $\Delta t_{obs} \simeq \frac{R}{2c\gamma^2}$ as before.

Although the typical GRB duration and variability timescale may be easily reconciled with observations, the main question remains as what produces the explosion in the first place. Several clues indicate a possible GRB-supernova connection. The first is the total released energy $\gtrsim 10^{51}$'s, which is a significant fraction of the binding energy of a compact star. Second, most GRB's are collimated, with typical opening angles $1° < \theta < 20°$, known from a consideration of the burst afterglow. This partially accounts for a huge difference between the estimated GRB and supernova rates: 300,000 years per galaxy for GRBs vs ~100 years per galaxy for supernova.

The pivotal event that brought the GRB-supernova connection into focus was the object GRB 980425. It was nearly coincident with the explosion of **SN** 1998bw, a type IC supernova. A supernova origin for GRB's was confirmed in compelling fashion with the observation of another supernova SN 2003dh, which occured nearly simultaneously with GRB030329. In this case, the source spectrum evolved from a power-law continuum with narrow emission lines to the development of broad peaks characteristic of a supernova.

Such observations pose the question that why should some stars produce ordinary core-collapse supernova explosions, while other follow the GRB path. It appears that rotation may be the distinguishing features, and GRB's may be produced only by the most rapidly rotating and most massive stars, whereas about 99% of massive stars end their lives with an ordinary supernova explosion.

The model that best accounts for the inferred properties of the GRB explosion is the "Collapsar" scenario. In this scenario, a massive star with fast rotation collapses and forms a black hole that continues to accrete from a transient disk. The relativistic jet penetrates through the envelope of the collapsing star and breaks out into the surrounding medium. According to this model, the massive iron core of a massive star with $M > 30\,M_\odot$ collapses to a black hole, either directly or due to accretion phase following the core collapse. Because of the large angular momentum of the star's interior, a transient disk develops around the black hole, and a funnel emerges along the rotation axis. In numerical simulations of this process, the accretion disk has a mass of $\sim 0.1\,M_\odot$, and drains into the black hole over a period of several tens of seconds, powering the GRB.

The process of core collapse, accretion along the polar column, and the jet propagation through the stellar envelope take about ~ 10 s. The ensuing accretion onto the black hole takes another tens of seconds. The timing of these events is consistent with the measured properties of long bursts.

The short bursts appear to be associated with another class of progenitors, neutron-star binaries or neutron star-black hole binaries. These systems lose orbital angular momentum by radiating gravitational waves and undergo a merger. These catastrophic events also produce a black hole surrounded by a temporary debris torus, which provides a sudden release of gravitational energy due to accretion. The duration of the burst in binary mergers is related solely to the fall-back time of matter flowing into the black hole. The split between long and short bursts may therefore simply be the dichotomy between collapsars and binary mergers.