PHYC 581: High Energy Astrophysics
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Bursting Stars:

Two particular types of explosive events stand out in high-energy astrophysics. One of these, so far detected from within our galaxy, is the sudden release of powerful bursts of X-rays from neutron stars. The second one is known to occur in distant galaxies and defined principally by the γ-rays that are put out. The X-ray and γ-ray bursts are among the most interesting dynamical phenomena in astronomy as they teach us about stellar evolution and large scale structure, as well as fundamental physics.

Although the X-ray and γ-ray bursts share an explosive identity, they differ in important ways. X-ray bursts barely damage the underlying star. Thus the stars not only survive the event in this case, but also repeat it. In contrast, γ-ray bursts completely destroy the underlying object in a spectacular display of cosmic fireworks not seen in other physical contents.

X-ray Bursts:

X-ray bursts were discovered independently by several groups in 1975. Of the ~200 X-ray binaries known, about 100 are low-mass systems, over half of which are accreting neutron stars. Most of these neutron stars are known to produce X-ray bursts. The mean quiescent source luminosity of these objects is $L_0 \sim (0.3-2)\times 10^{37}$ erg s^{-1}, which is roughly $\frac{1}{10}$ of the Eddington limit. When an X-ray burst goes off, it typically has a rise time $\lesssim 1s$, lasts $3-1000$ s, and recurs on a timescale of $\sim (10^{3}-10^{6})$ s.

The bursts have luminosities $L_b \sim 10^{39}$ erg s^{-1} and total energies $E_b \sim 10^{39}-10^{40}$ erg. Note that L_b is near or above L_{edd}.

Of the X-ray burst sources, ~ 35 exhibit photospheric expansion, which is consistent with the view that neutron star's atmosphere is blown away when the luminosity exceeds L_{edd}. The primary evidence for the thermonuclear interpretation of X-ray bursts comes from a comparison between the time-integrated quiescent and burst fluxes: $\frac{L_b}{L_0} \sim 20-300$.

The thermonuclear flash model has been very successful in reproducing the basic features of the X-ray burst phenomenon, which include the short rise time, the recurrence timescales, the luminosities, the energies released, the spectral softening as the burst decays, and the $\frac{L_b}{L_0}$ ratio.

X-ray bursts are caused by the unstable burning of freshly accreted H/He on the surface of the neutron star, which is accumulated over a period of a few hours to form a layer that is ~10m thick. As the accretion continues, the nuclear fuel is compressed and heated hydrostatically. There fore both the density and temperature of the accreted layer increases (the highest increase occuring at the bothom) until the Hydrogen starts burning into Helium. This first happens in a thin shell via the pp-chain as temperature is initially low. At high temperatures H burns into He via the CNO-cycle, and He can in turn burn to C via the triple-α reaction.

Explosions eventually occur because these processes are thermally unstable. As the temperature increases, the rate of collisions between the various nuclear species also increase, which enhance the reaction rate. By releasing more energy, this further raises the temperature thereby initiating a runaway process. These situations will lead to various combinations of H and He "flashes" that are observed as X-ray bursts. The burst spectrum is essentially a blackbody. Under the assumption that the emitting surface is spherical, one derives a photospheric radius that is smaller than the neutron star radius. This suggests that only a portion of the neutron star surface burns and radiates at any given time during the event. The neutron star's magnetic field may play an important role in this respect.

It has been long thought that a strong magnetic field stabilizes the nuclear burning by funneling H and He onto the polar caps where enhanced temperature causes the nuclear fuel to burn more rapidly, and hence avoiding the pileup of the matter that will produce a thermonuclear explosion. Recent discoveries show that the flash still occurs but at the magnetic poles of of the neutron star, which then propagates around the star. A very important question arises that how the nuclear burning actually propagates across the stellar surface. This is a subject of considerable interest in computational astrophysics, where these processes are modeled with high resolution grids and state-of-the art nuclear reaction network and equation of state.

As an aside, we note that in X-ray bursts the flame propagates within 1cm of the surface, and hence is easily observable. This is very different, for example, from the case of type Ia supernova where burning takes place deep inside the star, which makes it impossible to see the process from the outside. Also, a typical neutron star rotates at few hundred revolutions per second. Therefore, we are provided with hundreds of snapshots of the neutron star per burst during the process.

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 forthest such event, known as GRB 090429B has a redshift $z = 9.4$, which corresponds to an epoch when the universe was ~ 500 million years old.

Gamma-ray bursts (GRB's) are short, intence 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 quadropole moments in their distribution, thus ruling out all possible origins other than a truly 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 first characteristic deduced from the electromagnetic signal of GRB's is that their typical spectrum is non-thermal. It consists of two power-law distributions connected at a break energy $E_b \sim$ 100-400 keV. At energies below 1 MeV, the spectral index is ~1, while it considerably steepens (spectral index ~2-3) toward higher energies. The GRB light curve may be described as erratic, with a smooth, fast rise and a quasi-exponential decay, through many peaks and substructure on a millisecond timescale. The duration of bursts spans 6 orders of magnitude from 10^{-3} s to 10^{3} s, with a well-defined bimodal distribution;

those lasting longer than ~2s (long bursts), and others ending earlier (short bursts). It turns out that short bursts are harder, with only rare exceptions, while long bursts are softer.

The time-integrated flux of GRB's ranges from $\sim 10^{-7}-10^{-4}$ erg cm^{-2}, which corresponds to an isotropic luminosity of $\sim 10^{51}-10^{54}$ erg s^{-1}. However, the high-energy emission from these sources is believed to be beamed, lowering their actual power by on to two orders of magnitude. This still makes them more powerful than a typical supernova.

The light-travel time arguments based on the millisecond variability suggests that the GRB energy is released inside regions of ~300 km in size. GRB's are inherently relativistic phenomena, and hence we expect an intense and highly localized explosive release that involves a rapid and 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 1. It then challenges us to understand why we see photons with energies $E \gg 1 MeV$.

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

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

Therefore, the smaller the angle θ is, the larger the photon energies need to be. This can be intuitively understood since two photons moving in parallel ($\theta=0$) never interact as they are just following each 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 that emitted photons are beamed in the forward direction; $\theta \lesssim \frac{1}{\gamma}$. Photons with energies E_a and E_b can therefore not produce e^-e^+ pairs if:

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

It is seen that for $\gamma \gtrsim 100$, two photons with energies $E_a = 10$ GeV and $E_b = 1$ MeV 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 indicate 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 to kinetic energy of baryons instead of radiative luminosity. Moreover, the medium woulb be optically thick, which would give rise to a quasi-thermal spectrum instead of the observed power-law spectrum.

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 radiations.

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 Consesus view how 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 explaining the prompt emission prior to the afterglow activity. The observed GRB lightcurves are variable down to a timescale as short as a millisecond, even when the burst lasts tens of seconds. This is difficult to rationalize on the basis of a variable central engine, since the evidence points to a catstrophic destruction of the progenitor. In addition, the variability would tend to get washed away 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 material.

It is important to underline the role of relativistically moving outflow in this regard. Consider a γ-ray emitting front that moves at speed v. The emission (by the front) and absorption (by a distant observer) times are related to each other according to:

$$\Delta t_{obs} \approx \frac{1}{2\gamma^2}\Delta t_{emiss} \qquad \left(\gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}}\right)$$

For a strong relativistic shock $\gamma \gg 1$, and hence $\Delta t_{obs} \ll \Delta t_{emiss}$.

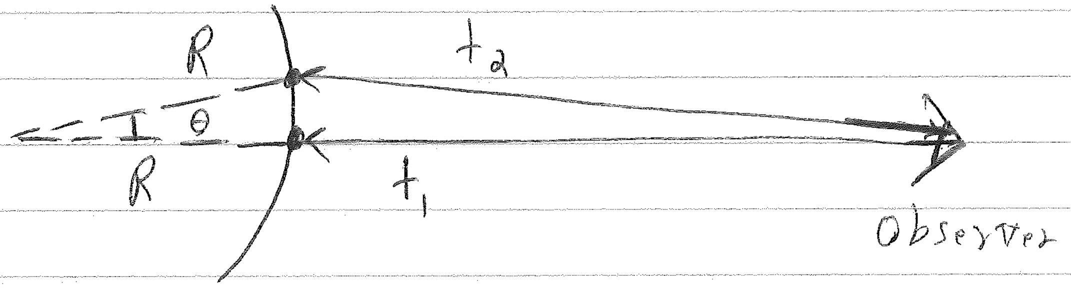
For example, for $\gamma \approx 100$, even a fluctuation with $\Delta t_{emiss} \sim 10\,s$ wold appear as $\Delta t_{obs} \sim 1$ ms to a distant observer.

One may also wonder how the overall duration of the burst can be so short ($\lesssim 1000$ s) when the charteristic timescale related to the size of the afterglow $\sim \frac{10^{17}\,\text{cm}}{c}$ is about a month. Here, too, relativistic effects due to beamed emission are responsible.

Emissions from parts of a shell moving at an angle θ from the line of sight (as shown below) arrive later than that along the line of sight with a delay time as follows:

$$t_{del} \equiv t_2 - t_1$$

$$t_{del} \simeq \frac{R(1-\cos\theta)}{c}$$



Since the radiation is beamed with an effective angle $\theta \sim \frac{1}{\gamma}$, the observer primarily sees a patch with opening angle $\theta \simeq \frac{1}{\gamma}$, which results in a characteristic burst duration:

$$\Delta t_{burst} \sim \frac{R}{2c\gamma^2}$$

For $\gamma \sim 100$, a γ-ray emitting front moving for ~1 month results in a burst that lasts ~300 s.

Although 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 $\gtrsim 10^{51}$ erg, 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 GRB's vs ~100 years per galaxy for supernova.

The pivotal event that brought the GRB-supernova connection into focus was the object GRB 980425 (at redshift $z=0.0085$). It was almost 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 2003 dh, which occured nearly simultaneously with GRB 030329. 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 some stars should produce ordinary Core-Collapse supernova explosions, while some others follow the GRB path. It appears that rotation may be the distinguishing feature, 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 thereby 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 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 collapsar and binary mergers.

This was observationally confirmed in 2005, with the detection of two short γ-ray bursts. The Swift satellite detected the short burst GRB 050509B, but no afterglow in the optical part was seen. This was consistent with many earlier attempts to detect long-wavelength emission from such short events, which all failed. A few months later, the HETE satellite detected another short burst GRB 050709.

In this case, an X-ray afterglow as well as an optical afterglow was seen. However, the total energy released in the afterglow was about two orders of magnitude smaller than that seen during typical long bursts. Moreover, no evidence of supernova explosion was found at any time before or after the prompt γ-ray emission. This supported the suspicion that the short GRB's have a different origin than their longer counterparts. They are lower energy explosions with less energetic relativistic blast wave occuring at significantly smaller distances.