The Biggest Explosions in the Universe

Biman Nath

Gamma ray bursts – which are first detected in energetic gamma rays and which then glow in X-ray, visible and radio wavelengths – are the result of the biggest explosions in the universe. Astronomers wonder what causes these violent events, and some of their ideas are discussed in this article.

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1. Serendipitous Discovery

The story of Gamma Ray Bursts (GRB) began in 1963 after USA and the then USSR signed a nuclear test-ban treaty. They agreed not to conduct any test of nuclear bombs above ground or under water. Then USA launched a series of spy sattelites to watch out for any nuclear tests being performed in secret by the USSR. These satellites were called *Velas* (Spanish for 'watchmen'), and they were designed to detect energetic gamma rays from earth, since nuclear reactions always proceed with the emission of gamma rays. But the scientists discovered something completely unexpected.

In July 1967, one of these satellites found a bright flash of gamma rays. Then it kept on detecting flashes of gamma rays from different directions, often brighter than any other sources of gamma rays in the sky for minutes on end. Soon the scientists realized that these bursts were not due to any secret experiments being carried on earth – they were from astronomical objects. But they wanted to be sure of it and it was not until 1973 that this discovery – of enigmatic gamma ray bursts – was announced by the defence establishment to the public and astronomers at large.

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Soon the theorists came up with a number of ideas for what might be at the root of these explosions. Some thought these were associated with neutron stars in our Galaxy. These stars are the remnants of supernova explosions which occur when a massive star runs out of nuclear fuel to shine. The core of these massive stars are made of neutrons (which are subatomic particles, with mass comparable to protons but without any electric charge), and possess very high magnetic field, almost a thousand billion times that of the earth. Perhaps, the theorists surmised, the magnetic field configuration had some glitches from time to time and released energy in the form of bursts. At the same time, some astronomers hypothesised that gamma ray bursts were associated with objects outside the galaxy.

2. How Far are the Bursts?

The biggest problem facing the astronomers at that time was the lack of knowledge of the *distance* of the gamma ray burst sources. Without this information one did not know the actual luminosity of the burst, and so no hypothesis could be ruled out easily. A distant bright star and a dim nearby star would both appear faint in our sky, and without knowing the distance one cannot root for one hypothesis over another. The distance factor has always been a handicap for astronomers, and time and time again in the history of astronomy it has made their task difficult.

Yet astronomers have always found a way out, and in this case too they had an idea of the distances of gamma ray burst sources within a few decades. But before the conclusive results came in, they had an indication of possible distance measures by just studying the distribution of sources in the sky. Our Galaxy, the Milky Way, has the shape of a thin disk with our sun (and the solar system) near the edge. So, from our point of view on earth, the Milky Way appears to be a luminous band cutting across the sky. If the majority of gamma ray bursts originated inside our Galaxy, then they would mostly appear to come from a band-like region in the sky.

Initially, the number of detected gamma ray bursts were not large enough for astronomers to do a proper statistical study, but by the year 2000, they had a large enough sample, thanks to a satellite named Compton Gamma-ray Observatory, launched by NASA to study astronomical gamma ray sources. An experiment done with a detector aboard this satellite, especially designed to detect flashes of gamma rays (called the Bursts and Transient Source Experiment) found about 2700 sources between 1991 and 2000. To the surprise of many astronomers, the

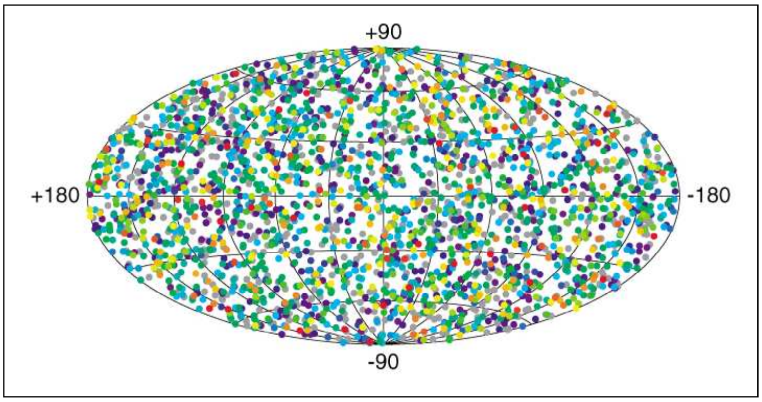


Figure 1. The distribution of gamma ray bursts in the sky is fairly uniform. The bursts whose positions are shown as dots in this plot were detected by Compton Gamma-Ray Observatory launched by NASA, by the Burst and Transient Source Experiment (BATSE) carried aboard it, between 1991 and 2000. The colours of the dots signify the intensity of the burst, with the intensity increasing from blue to red. This experiment ruled out the possibility of gamma ray bursts being associated with sources like neutron stars in our Galaxy, and prompted the astronomers to link them to sources outside our Galaxy.

distribution (see *Figure* 1) of gamma ray bursts in the sky looked anything but uneven – there was no way that sources within our Galaxy could have explained such a uniform distribution. So the typical distances must be larger than the extent of our Galaxy (which is about 40,000 light years in radius). Moreover, they could not be all coming from nearby galaxies, otherwise the plot would look clustered in certain parts, since galaxies are distributed very unevenly in the nearby universe.

The only explanation was that gamma ray bursts occurred in distant galaxies, spanning out to the edge of the known universe, so that their distribution in the sky would look uniform.

When astronomers stumble on a new class of luminous objects, they like to determine their distribution in space with a statistical study of the distribution of objects with different luminosities. Consider the case of uniformly distributed objects, all with the same brightness L, and consider the flux of such an object at a distance d: $f = L/4\pi d^2$. Suppose there are n objects per unit volume. Then, for an observer (put anywhere in this volume) the number of objects with flux *greater* than f would mean the number of objects in a volume $(4/3)\pi(L/4\pi f)^{3/2}$, which is given by $n \times (4/3)\pi(L/4\pi f)^{3/2}$. This shows that the number of objects greater than a given flux f should scale as $f^{-3/2}$, if objects are distributed evenly. Although we have assumed constant brightness for all objects, this argument can be easily made more sophisticated, and the same result holds.

Astronomers found that the flux distribution of gamma ray bursts follows the telltale $f^{-3/2}$ signature for large fluxes (apparently bright bursts), but for dimmer bursts, the distribution has a power index that is smaller than 3/2. Our derivation of the flux distribution assumed an Euclidean space, and the flux distribution will be different for curved space. This observation then implies that faint bursts, or sources at large distances, are distributed in curved space, which is expected in our expanding universe. Therefore this detailed statistical study confirmed the suspicion that gamma ray burst sources are very distant, some of them being at the edge of the observable universe.

But this confirmation immediately threw a challenge for the theoreticians. At large distances, the actual brightnesses of these objects or events must be very large, and astronomers wondered what sort of phenomenon could give rise to release of such gigantic amount of energy.

If the astronomers could associate the bursts with known objects then it would have helped the theorists. But the angular resolution of BATSE was poor, and it could not pin-point the bursts with an accuracy more than a degree or so. In such a large portion of the sky – larger than the apparent diameter of moon in earth's sky – there could be many distant objects, and it was not easy to find an association.

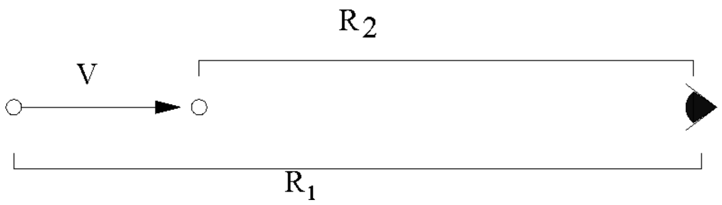
3. Fireball Model of Gamma Ray Bursts

In 1993, two theorists made a significant advancement in this regard. Martin Rees of Cambridge University, UK, and Peter Meszaros of Penn State University in the US argued that there would be 'afterglows' of these gamma ray bursts, in other wavelengths, and if one could follow them up, hopefully with better angular resolution, then the search might lead to the culprit object. They also predicted how these afterglows might evolve with time. They had the following scenario in mind: if an explosive event deposits a large amount of energy in a small amount of matter, then it would result in a fireball expanding rapidly, almost with the speed of light.

There are reasons why one needs expanding fireballs to explain gamma ray bursts. If it were a static phenomenon then the energy density of photons turns out to be too large. We will see later that typically the energy output in these bursts is about 10^{44} J. We can also get an idea of the size of the region in which this energy is concentrated – it could not be larger than ct where t is the duration of the burst. The typical duration is of order of a second or so (there are also bursts of shorter duration, which we will mention later). Now consider such a large amount of energy in gamma ray photons being concentrated in a region of size ct. One can show that these gamma ray photons would interact so strongly – because of being packed so compact – that they would degrade in energy quickly down to lower energy photons (by producing pairs of electrons and positrons, which would in turn interact with photons, and so on). Then, because of the strong interaction with matter particles, the resulting spectrum should be that of a blackbody (Planckian spectrum), which is not observed.

This problem is easily solved if motions with speed close to that of light, that is, relativistic motions are involved. Consider the case of bulk motion with Lorentz factor $\gamma = (1 - v^2/c^2)^{-1/2}$. Then, because of relativistic effects (see *Box* 1), what appears to an observer to be a duration t, would actually (in the rest frame of moving matter) correspond to a *longer* time – to be precise, a duration of $\sim \gamma^2 t$.

Box 1: Relativistic Effects in Gamma Ray Bursts



Consider an object moving along in a line towards the observer with a constant velocity v, which is very close to the speed of light c. This means that the Lorentz factor $\Gamma = \frac{1}{\sqrt{1-v^2/c^2}}$ is very large. Now consider two photons emitted by this object along its path, at distances R_1 and R_2 from the observer. The time taken by the object (in its rest frame) to move between these two positions is $(R_1 - R_2)/v$. Let us call this the time difference in its frame, Δt_e. It is easy to show (and left as an exercise for the reader) that the time difference of arrival of two photons at the observer is $\Delta t_o = \frac{(R_1-R_2)}{v} - \frac{(R_1-R_2)}{c}$. For large values of the Lorentz factor, this can be simplified in the following way:

$$\Delta t_o = \frac{(R_1 - R_2)}{v}(1 - \frac{v}{c}) = \frac{(R_1 - R_2)}{v}\frac{1 - \frac{v^2}{c^2}}{1 + \frac{v}{c}} \approx \frac{\Delta t_e}{2\Gamma^2}, \qquad \text{(i)}$$

where the last approximation follows from the fact that $v \sim c$. This means that what appears to be a duration t_o to the observer actually refers to a longer duration Δt_e in the frame of the moving object,

$$\Delta t_{e) \approx 2\Gamma^2 \Delta t_o}. \qquad \text{(ii)}$$

Then the corresponding length scale and volume would be much larger than that inferred without considering relativistic effects, and the problem of high energy density would disappear. The energy density will decrease (from the earlier, naive estimate) by a factor of γ^6. There are other relativistic effects which help further – for example, the radiation will be beamed in a narrow cone and the photon energy will appear to increase by Doppler effect. Taking all these effects into consideration, one can show that the high radiation energy density problem is alleviated if the Lorentz factor is larger than 100 (corresponding to a speed $v \gtrsim 0.99995c$).

This expanding fireball would lead to a powerful shock, sweeping up surrounding matter, and accelerating particles of matter to high energy. Electrons which are thus accelerated to high energy would spiral around magnetic field lines and emit radiation (called synchrotron radiation). This radiation would cover a large range of frequencies in the electromagnetic spectrum, and would cause the source to have an 'afterglow' in wavelengths other than gamma rays. Rees and Meszaros also predicted that the brightness of the afterglow would decrease quickly in the beginning, and then slowly as time progressed (so that they would appear to fade uniformly with logarithm of time). In other words, the brightness would be proportional to some power of time: $\propto t^{-\alpha}$.

It then remained for astronomers to look for these afterglows of gamma ray bursts quickly enough, before they faded away, and try to locate the position of the source accurately enough so that they could be associated with some known objects.

4. Afterglow of Gamma Ray Bursts

Their patience was rewarded in 1997, almost three decades after the initial discovery of gamma ray bursts. On 28th February 1997, astronomers used the Italian–Dutch satellite (named BeppoSAX) for X-ray observations to look at a direction in the sky where a burst had taken place eight hours earlier. They were hoping to catch a glimpse of the fading afterglow in X-ray wavelengths, and they were fortunate. The news of their discovery affirmed the idea of theorists, and it spurred further research in this topic.

Soon astronomers discovered gamma ray burst afterglows in other wavelengths– including visible and radio. These are difficult observations: astronomers have to quickly set up their telescopes–they are usually notified after a burst has been initially detected and located within a small portion of the sky – perhaps to arcminute resolution (one sixtieth of a degree). Then X-ray satellites, and later on, optical telescopes are used to track them down to further smaller portions of the sky. Typically, the X-ray and optical afterglows can be detected for about a week, and in radio wavelengths, for months.

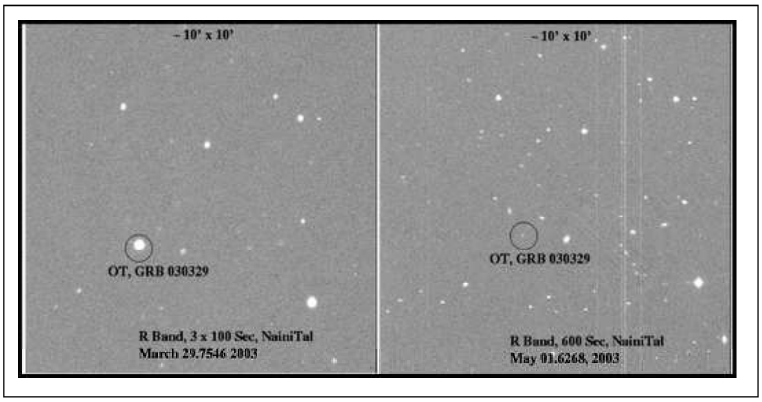
The Indian observatory UPSO at Nainital, with its modest 1 meter optical telescope is situated at a crucial position on the earth – it is one of the few observatories between Australia and Europe – and has participated in these exciting experiments. The Giant Meter-wave Radio Telescope near Pune has also detected some faint afterglows in radio wavelengths.

Astronomers' task has now been aided by a new satellite called Swift, which was launched by NASA in 2004. It has a burst detector and a multi-wavelength observatory in X-ray, ultraviolet and optical wavelengths, and can be used to quickly point the telescope towards any burst and detect even faint afterglows.

During their observations, astronomers take the spectra of the afterglows, and they often find absorption lines in these spectra. These lines are due to absorption of afterglow light by intervening matter – between earth and the source – at certain wavelengths. One usually finds that these lines have wavelengths that are shifted towards the red compared to standard values that are benchmarked from laboratory experiments. This 'redshift' is a general phenomena in our expanding universe – it was the discovery of redshift of spectra of galaxies that led Edwin Hubble to propose an expanding universe. When a source of light recedes from

Figure 2. The gamma ray burst afterglow in visible light fades away quickly and one must quickly mount a search to be able to catch the light from the burst. Shown here is the dimming of the optical afterglow of the gamma ray burst of 29th March 2003 (the image on the left was taken on 29th March and on the right, on 1st May 2004). The position of burst is shown by a circle.

Images were taken at the State Observatory, Nainital, India. (Courtesy : SO, Nainital)



the observer, the frequency of light becomes larger, or it shifts from blue to red. This is analogous to the shift in the pitch – from high pitch to low – of a siren from an ambulance speeding away from us.

The amount of redshift tells us the distance, since one knows how speed and distance correlate in our expanding universe. And these observations confirmed the initial suspicion of astronomers that gamma ray bursts typically occurred at very large distances – sometimes at the edges of the known universe. The most distant gamma ray burst that has been detected so far was seen on 5th September 2005, and from its spectrum, it was deduced that it originated when the universe was barely a billion year old – compared to its present age of about 14 billion years. The concept of distance in an expanding universe is a bit tricky, and sometimes it is better to discuss in terms of the time of the event.

The large distances involved in these events necessarily mean large amount of energy release – for a certain apparent brightness in the sky, the actual luminosity of an object increases as the square of the assumed distance. Astronomers deduced from this simple estimate the energy output involved in some gamma ray bursts to be as large as 10^{48} J. This is a staggering amount of energy indeed – it is even larger than what one would get if the mass of the sun were converted to energy (using $E = mc^2$). It is almost impossible to think of a scenario of converting such a large amount of mass to energy in seconds.

Astronomers soon found that gamma ray bursts do not emit equally in all directions, whereas they assumed so for their estimate of total energy involved. When they tracked the evolution of afterglow intensity, they found that after some time, the index α for time evolution (in $t^{-\alpha}$) changed markedly, the intensity falling steeply afterward. This was interpreted as the sign that the geometry of the emitting region changes with time. Initially the motion is confined to a narrow angle, so the material uptake from the surroundings is limited and the slowdown is gradual. After a certain time, when the forward motion of the jet slows down sufficiently, the sideways expansion becomes more dominant. The opening angle of the jet rapidly increases, enhancing the rate of material uptake and consequently that of slowing down of the jet. The slowing down causes the intensity to drop. Also, because of the gradual slowing down of the jet, the radiation is not beamed in a narrow angle any more. These two effects combine to make the intensity fade steeply after a certain time. This sudden drop of intensity occurs at all wavelengths, and therefore can be easily determined.

From this, one can estimate the angle of the initial cone of radiation – as in a lighthouse beam. This can then be used to estimate the total energy released by the source, and it was found that the new estimates of energy are lower by factors as large as 100–1000 than the previous ones. The total energy output is typically in the range of 10^{44-45} J, which is not much larger than that of a normal supernova, and therefore is not absurdly large.

5. Supernovae and Gamma Ray Bursts

As a matter of fact, the comparison with supernova may not be a coincidence. Supernovas happen to be stars more massive than eight times our sun, when they run out of nuclear fuel to produce energy (from thermonuclear reactions, courtesy $E = mc^2$) and cannot support the gravity of their huge mass any longer. The core then collapses under gravity to form a neutron star as mentioned earlier (or a black hole, if it turns out to be very massive). The energy released due to this drives the rest of the star outwards, shredding it to pieces and producing a bright explosion. The speed of expansion is not large for most supernovas: typically it is $\sim 10^7$ m/s, and so $\sim 0.03c$, much smaller than that needed in a gamma ray burst fireball. But astronomers wondered if there was a class of supernova, which they tentatively called a hypernova, in which most of the energy is deposited in a narrow jet which could produce gamma ray burst fireballs.

In April 1998, astronomers detected an energetic supernova, officially named SN1998bw, and it was seen at a location where there was a gamma ray burst a few days earlier. The probability of this being mere coincidence (considering the small portion of the sky within which the gamma ray burst was located) was estimated to be less than 0.01%. But this was not a proof that gamma ray bursts are associated with supernovas – this one could be an unusual supernova, and many astronomers argued that the gamma ray burst was unusually less energetic than the typical bursts.

Then, in March 2003, a satellite named HETE-2 (High-Energy Transient Explorer) with X-ray detector aboard, found a bright gamma ray burst. It turned out to be a nearby one, judged from the absorption lines in its spectrum – just about 2 billion light years away. And a supernova was seen to go off almost simultaneously! The afterglow of the burst was tracked in different wavelengths, and after a few days, some emission lines were seen in its spectrum that were similar to those seen in the supernova in 1998. The lines were wide because of Doppler shift and the speed involved was estimated to be $\sim 0.12c$. Extrapolating back with this estimate of speed, astronomers found that the supernova and the gamma ray burst occurred at the same instant.

Although one such event cannot constitute a proof that all gamma ray bursts are associated with some class of supernova, but this observation suggested a deep link between these two phenomena. The most popular model of connecting these phenomena now appears to be the 'collapsar' model.

Very massive stars, in their initial years, shed their surface layers owing to the pressure of the radiation from the star. The remaining star then burns in its core (through thermonuclear reactions) to shine and quickly depletes its supply of nuclear fuel. A core collapse ensues, just like in normal supernova, but here the core is very massive and it forms a black hole. Part of the stellar material near the collapsed core begins to orbit this black hole and forms a disk, the matter inside which slowly loses its angular momentum and sinks inward. At the same time, the rest of the star slowly responds to the events in the centre. The difference in the motion of matter – which is charged (ionized) because of the high temperature – near the core and away from the core, acts like a generator and produces high electric and magnetic fields. The effect of these strong fields is to eject matter along the rotational axis of the star. The strong jet ploughs through the surface layers of the star, taking a few seconds to emerge out of it. The star is ripped apart in this process in an explosion, which is observed as a supernova. When the jet has travelled outside the star, after a while, different parts of the jet moving with different speeds collide and release energy in powerful gamma rays – this causes the gamma ray burst.

Now, one needs to be almost in the line of sight of the jet to detect the gamma ray burst. It is however possible that there are many such explosions of 'collapsars' in which jets point in some other direction and not towards the earth. In that case we only see a supernova and not the gamma ray burst.

However, it turns out that another effect of a gamma ray burst is also detected sometimes. When the jet advances, its slowly moving parts emit radiation that is not beamed in the forward direction, and since this radiation comes from slowly moving matter, it is not shifted to very high energies, and therefore it shows up at a lower energy, in X-rays. Astronomers therefore thought that there should be bright X-ray flashes for gamma ray bursts which are missed on account of misalignment of the jet axis with our line of sight. Since the jets are usually narrow, one expects many more missed bursts than detected bursts, or in other words, more X-ray flashes than gamma ray bursts.

Astronomers have indeed detected these X-ray flashes with detectors aboard BeppoSAX and HETE-2. They expected that, firstly, the sources of X-ray flashes should be nearby – since these are expected to be not as bright as a typical gamma ray burst and cannot be detected from a large distance. Secondly, the X-ray flashes should come together with a supernova. And thirdly, since the associated afterglow should point in a different direction, it should be dim initially and then brighten, followed by a decay like all other afterglows. These expectations have been met by the X-ray flashes that have been detected, beginning with one in 2003.

The collapsar model is now being developed in detail by scientists, although astronomers have not completely abandoned other hypotheses, like mergers of neutron stars or energetic winds from newly formed, highly magnetic neutron stars. One class of gamma ray bursts – which last shorter than the more powerful and longer ones – appear to originate in a different set of objects. Astronomers think they originate in neutron stars that have extremely high magnetic fields (called 'magnetars') and most of them are nearby, as they are not powerful as the other, 'collapsar' related gamma ray bursts. Future observations will tell astronomers if there are other surprises and twists in the story of gamma ray bursts, or if they have uncovered the mystery behind the biggest explosions in the universe.

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