

Gamma-Ray Bursts, the Strongest Explosions in the Universe.

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Gamma-ray bursts, GRBs, short and intense burst of low energy γ -rays that arrive from random directions in the sky are possibly the most fascinating astronomical objects known today. GRBs are fascinating because they are the brightest objects in the sky corresponding to the strongest explosions that take place in the Universe. Not surprisingly a GRB at a record redshift of 8.1 is the most distant object seen so far. GRBs are fascinating because each one signals the birth somewhere of a new black hole. GRBs are also fascinating because of their serendipitous discovery and the roundabout way in which scientists have learnt what is their nature. Finally, GRBs are fascinating as they may play the role of a doom star that destroys life on Earth.

An unexpected discovery

The outer space treaty was signed between the USA and the USSR in 1962. This was the first nuclear non-proliferation agreement and it treaty forbade nuclear explosions in the outer space. To monitor it the USA launched a set of military satellites*,

* The Vela satellites were disguised as scientific ones and to justify this Sterling Colgate¹ from the Los Alamos National Laboratory was asked to make an invited prediction of astronomical bursts of soft γ -rays.

the Vela satellites, designed to look for flashes of soft γ -rays (radiation that is harder than X-rays) which would have been the characteristic signature of a nuclear explosion in space.



Figure 1: One of the Vela satellites with Earth in the background.

The Vela satellites were launched in 1967. They did not detect any forbidden man made explosion. Instead, they discovered unexpected γ -ray flashes coming from outer space[†]. It took several years to confirm that the bursts are real and then to declassify them and allow publication. In the spring of 1973, Ray Kelbesadal, Ian Strong and Roy Olson² from the Los Alamos National laboratories reported on the detection of the cosmic γ -ray bursts. A confirmation by a Russian spacecraft soon followed.

[†] The small dereferences in arrival times of the flashes to the four satellites reflected an extra-terrestrial origin and prevented a major cold war crisis.

The bursts are short flashes of soft γ -rays. They last from a few milliseconds (the record holder is a 0.6 msec long) to a few thousand seconds. Following the work of Chryssa Kouveliotou³ and coworkers from Huntsville, we classify today bursts as long or short according to their duration (longer or shorter than 2 seconds). The bursts arrive from random directions in the sky and disappear. Present dedicated satellites searching for GRBs detect bursts at a rate of one per day. This can be translated to one burst per Galaxy per 10 million years.

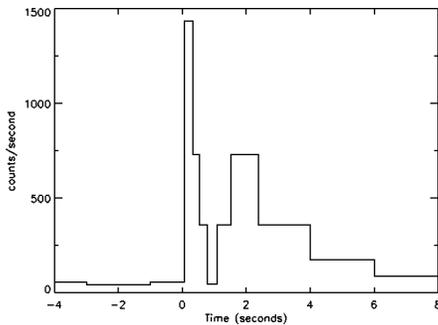


Figure 2: *The light curve (count rate as a function of time) of the first GRB detected by the Vela Satellites on July 2nd 1967.*

GRBs puzzled theoreticians ever since their serendipitous discovery and their strange nature lead to numerous speculations concerning their origin. Mel Ruderman⁴, from Columbia University discussed the phenomenon in a conference in the fall of 1974 and noted “there are more theories than bursts”. I also had my own theory at the time. As a part of my PhD thesis at the Hebrew University with Jacob Shaham, I⁵ examined the possibility that GRBs arise from instabilities in accretion disks around galactic black holes. As it turned out the real answer

was very far, and yet very close at the same time.

A wrong theory

A consensus formed at the early eighties that GRBs originate from violent processes taking place on neutron stars in our own Galaxy, the Milky Way. Several either misleading or totally wrong observations led to the general acceptance of this idea that even made it way to classroom textbooks. The BATSE (Bursts And Transient Source Experiment) detector on board of NASA’s Compton-GRO satellite was designed to prove this theory.

Another possibility

A small but vocal minority did not accept the standard paradigm. Already in 1975 Vladimir Usov (now at the Weizmann Institute) and Gregory Chibisov⁶ suggested that GRBs could be extra galactic, making them much more powerful than if they were produced by relatively “local” Galactic objects. Note that a source at distant galaxy is million times further than a source in our own Galaxy. This would make an extragalactic bursts 10^{12} times more powerful than a Galactic one.

In the mid eighties the extragalactic option gained some credibility when Jeremy Goodman⁷ from Princeton have suggested the first version of what is known today as the Cosmic Fireball model and explaining how extra-galactic GRBs might work. At the same time Bohdan Paczynski⁸, also from Princeton, have shown that the statistics of the observed GRBs favor extra-galactic rather than Galactic

sources. Together with David Eichler from Ben Gurion University, Mario Livio (then at the Technion) and Dave Schramm from the University of Chicago⁹ have suggested in 1989 that extra-galactic merging neutron stars binaries could produce GRBs. This was the first credible extra-galactic GRB model.

BATSE's Surprise and the Great Debate

BATSE was launched on April 5th 1991 on board of NASA's Compton-GRO satellite. It was the largest GRB detector ever flown detecting GRBs at rate of one per day. BATSE could locate the position of a burst within an accuracy of a few degrees. With this capability the BATSE team¹⁰ led by Gerry Fishman and Chip Meegan from Huntsville revealed that the bursts are distributed uniformly over the sky and revolutionized our understanding of GRBs.



Figure 3: *Compton-GRO with the BATSE detectors at the eight corners.*

The uniform distribution of GRBs was inconsistent with the expectations of the Galactic model, that the bursts should have been concentrated in the Galactic plane. The bursts could be

either local or extremely distant. I¹¹, and independently Shude Mao and Bohdan Paczynski¹² have immediately shown that the bursts' peak flux distribution is incompatible with a local origin, leaving the extra-galactic possibility as the only viable option. We were able to set a limit on the distances, showing that a typical GRB is at a distance of ten billion light years away from us.

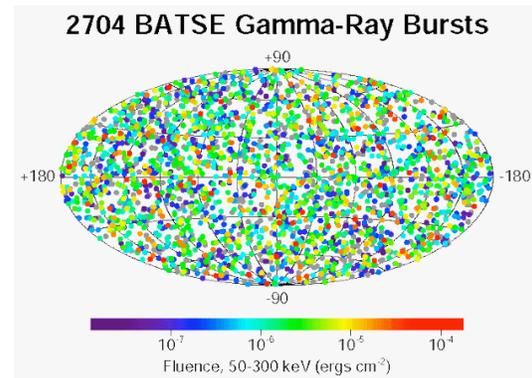


Figure 4: *The uniform distribution of 2704 GRBs observed by BATSE on the sky.*

The extra-galactic origin was not easily accepted. It required the release of a huge amount of energy in a short time. An extra-galactic GRB releases in a few seconds the energy released by a star like our Sun during its whole lifetime, several billion years. It was hard to accept that such energetic explosions exist. It was also hard to imagine how so much energy can be channeled out so quickly from a small source[‡]. The debate between the Galactic and the extra-galactic camps was particularly lively¹³⁻¹⁵. It lasted for several years with a relatively slow shift towards the extra-galactic camp.

[‡] The rapid variability implied a small size of a few km for the origin.

It did not end until 1997 when GRBs' afterglow was discovered and with it a definite proof of their extra-galactic origin.

The Fireball Model

Even before the debate ended, theorist perfected the Fireball theory that explains how so much energy can be channeled out from a very compact source in such a short time. Goodman⁷ has set in the eighties the basis for this model with his work on a radiation electron-positron fireball. However, it was clear that this simple model cannot truly explain GRBs. It led inevitably to a thermal[§] spectrum, whereas GRBs clearly show a non-thermal emission. The next step took place in 1990 when with my student Amotz Shemi¹⁶ (at that time at Tel Aviv University) we modified Goodman's model to include protons. We have shown that all the energy of the initial fireball would be converted to a kinetic energy of the protons. If the baryonic load were small enough this would result in an ultra-relativistic outflow in which the matter moves at 0.9999 of the speed of light or faster.

Martin Rees from Cambridge and Peter Meszaros¹⁷ from Penn State completed the puzzle when they suggested in 1992 that the kinetic energy of the outflow can be converted back to radiation via collisionless shocks between the outflow and the surrounding matter.

At roughly the same time with Bohdan Paczynski, Ramesh Narayan (from Harvard) I¹⁸ suggested internal shocks within the outflow as an alternative way to convert the kinetic energy to radiation. The basic idea was the collisionless shocks accelerate electrons and produce magnetic fields. The electrons moving within these magnetic fields produce the observed γ -rays via the synchrotron process.

Later on Rees and Meszaros¹⁹ have shown that the continuous interaction of the relativistic outflow with the surrounding matter produce a long lasting emission an afterglow. This afterglow is weaker and at lower wavelength (X-rays, optical and then radio) but it can last days, weeks or even months after the burst. With my student Re'em Sari, we²⁰ proceeded to show that the prompt γ -ray emission couldn't arise from external shocks between the relativistic outflow and the surrounding material. Internal shocks within the outflow remained the only viable way to produce the prompt emission. As internal shocks cannot exhaust all the energy of the outflow some is inevitably left for later external shocks, and those produce an afterglow. This concept has led to the commonly accepted internal-external shocks model according to which the prompt GRB is produced via internal shocks while external shocks produce later the afterglow.

[§] A thermal spectrum is a black body spectrum and it is described by the Planck distribution.

The Internal-External Fireball Model

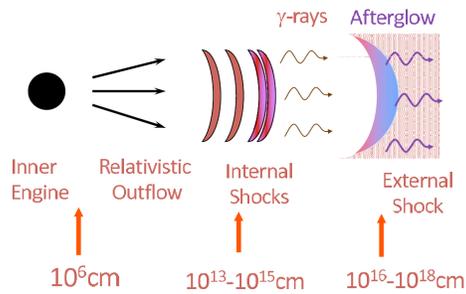


Figure 5: *The internal-external shocks model. A compact source produces a relativistic outflow. Internal shocks within the outflow produce the prompt γ -ray emission while external shocks with the surrounding matter produce the lower energy and longer lasting afterglow.*

GRB Afterglow

The Italian-Dutch satellite BeppoSAX confirmed, in the winter of 1997, the prediction of a long lasting afterglow. BeppoSAX was launched in the summer of 1996. It included, in addition to an all sky GRB detector, a wide field camera that could locate the burst and a narrow field instrument that could be pointed towards this approximate position and localize X-ray emission with a high precision. On February 28th 1997 the BeppoSAX team, led by Enrico Costa from Rome localized its first GRB and discovered²¹ X-ray afterglow. Jan van Paradijs and coworkers from Amsterdam University pointed an optical telescope to the X-ray position and detected a optical afterglow as well²².

A few months later on May 8th 1997 BeppoSAX localized a second burst. Mark Metzger²³ and coworkers from Caltech measured the optical spectrum of its afterglow and detected redshifted spectral lines indicating a source at a cosmological redshift of

0.835. The Galactic – extragalactic debate was finally over!

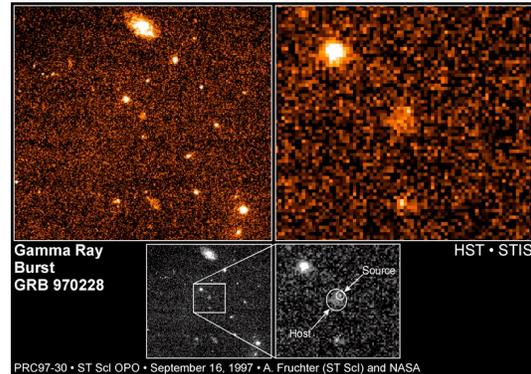


Figure 6: *The afterglow of GRB970228 as observed by the Hubble space telescope more than half a year after the burst.*

Radio observers from NRAO, headed by Dale Frail²⁴ discovered radio afterglow from the May 8th burst. Jeremy Goodman²⁵ was quick to show that the radio observations of this bursts provided the first direct confirmations to the idea that was beyond the fireball model: GRBs involve ultra-relativistic motion at a 0.99 of the speed of light or even faster. Later on in March 2003 Greg Taylor from NRAO²⁶ and coworkers gave a stronger and conclusive proof for this idea using the radio observations of the afterglow of GRB 030329.

The propagation of the blast wave into the surrounding matter was described by Roger Blandford and Chris McKee²⁷ who calculated already in the seventies the self-similar propagation of a relativistic blast wave. With Re'em Sari and Ramesh Narayan²⁸ we have combined this solution with synchrotron emission to predict the afterglow light curves. The solution describes well the late phases of the afterglow,. Ralph Wijers and Titus

Galama²⁹ were the first who compared this solution with the observed afterglow data in order to determine the physical conditions within the afterglow. This method was used commonly later.

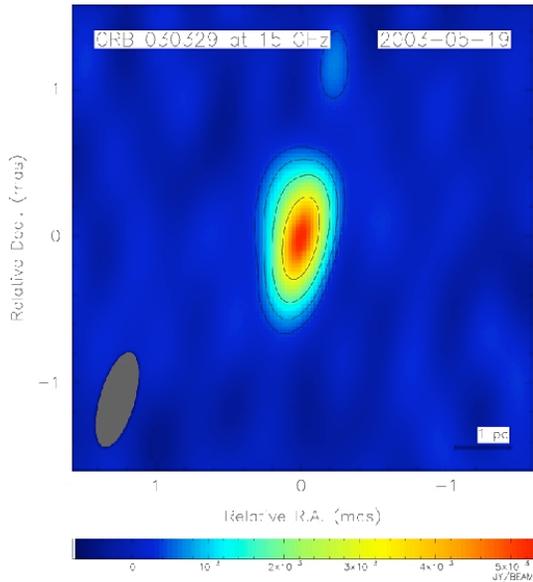


Figure 7: Radio afterglow of GRB030329 showing an extended figure and revealing relativistic motion.

As it took several hours to turn BeppoSAX towards the direction of the localized GRB the observations described only the late stages of the afterglow. Later on when NASA's satellite *Swift* observed the very early afterglow it became clear that the situation is more complicated and there are puzzles that this simple theory does not explain.

GRB Jets

The detection of the afterglow enabled redshift determinations. With those precise estimates of the distances and of the corresponding energies followed. As the energy implied in some cases was unreasonably large it became clear the emission is not

uniformed and it is beamed towards us. James Rhoads³⁰ from the Kitt Peak National Observatory and independently together with Re'em Sari, Jules Halpern (from Columbia University) we³¹ have predicted that jets would have a clear signature on the afterglow, known today as a "jet break". Such a signature was indeed observed shortly afterwards by Shri Kulkarni from Caltech and coworkers³² and enabled us to estimate the angular width of GRB jets as a few degrees. With beaming taken into account we know today that a typical GRB emits about 10^{51} erg during the few seconds that it operates.

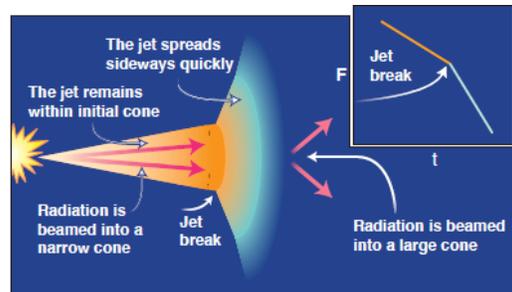


Figure 8: a schematic description of a jet break that occurs when the jet's slows down and begin expanding sideways. The insert shows the expected light curve.

GRB Progenitors

The most interesting question is what is the origin of GRBs and what are their progenitors. Timing is one argument. The rapid fluctuations seen in the prompt light curves indicate that the source must be very small – not more than several hundred kilometers wide. The enormous energy released in these explosions is another clue. It is only two orders of magnitude smaller than the binding energy of a compact object – a neutron star or a black hole. No other known

source can release so much energy so rapidly. This implies that the bursts involve the formation of one of the two. Already in 1993 I³³ have suggested that the second, a black hole, is strongly favored over the first. Each GRB signals, therefore, the birth of a new black hole.

As matter collapses to form a black hole a fraction that has too much angular momentum forms an accretion disk around the black hole. With one tenth of a solar mass the energy powering the GRB arises from the gravitational energy released when this material accretes onto the black hole**.



Figure 9: *A schematic picture of a GRB, a black hole accretion disk and a jet.*

i) Collapsar and Long GRBs

Stan Woosley³⁴ from Santa Cruz suggested in 1993 that “failed supernovae” – collapsing star that failed to explode like a regular supernova – produce GRBs. In the late nineties BeppoSAX began identifying the positions of GRBs and their host galaxies. Bohdan Paczynski³⁵ was quick to notice that GRBs arise

** As suggested in my early PhD work GRBs arise in accretion disks around black holes, but unlike this work these black holes are not Galactic but very distant ones.

preferably in star forming Galaxies. As massive stars live very short time (on astronomical scale), stellar death and supernovae are associated with star formation. Making the link Paczynski suggested that GRBs are related to powerful supernovae. At the same time Andrew MacFadyen and Stan Woosley³⁶ developed the Collapsar model, showing that a relativistic jet can punch a hole in the collapsing stellar envelope and produce a GRB. According to this idea the collapsing star forms in its center a black hole surrounded by a massive accretion disk. This “inner engine” produces the relativistic jet and powers the GRB.

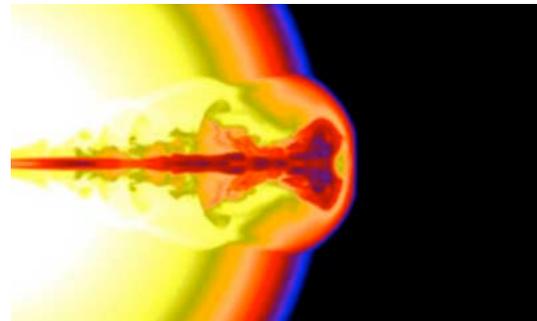


Figure 10: *A numerical simulation of a jet punching a hole in a stellar envelope. The basic ingredient of the Collapsar model.*

One did not have to wait for a long time. In April 1998 Titus Galama and co-workers from the University of Amsterdam³⁷ discovered that GRB980425 (the “phone number” of a GRB is simply its date) is associated with a distant very powerful supernova (SN98bw). Later Shri Kulkarni and his student Josh Bloom³⁸⁻³⁹, also from Caltech, found evidence for GRB-SN association in many other afterglows. This association was finally confirmed in the most spectacular way when in the spring of

2003 Kris Stanek⁴⁰ from Harvard and coworkers and Jens Hjorth⁴¹ from Copenhagen and coworkers observed the supernova SN2003dh emerged beautifully above the afterglow of GRB030329.

By now it is generally accepted that long GRBs (whose duration is longer than 2 seconds) are associated with a special type of supernovae called by the experts type Ic. However, the association is not one to one. Some type Ic supernovae don't have any GRBs and some long GRBs are not associated with supernovae (or at least very strong upper limits on its power). Clearly a few links are still missing in this puzzle.

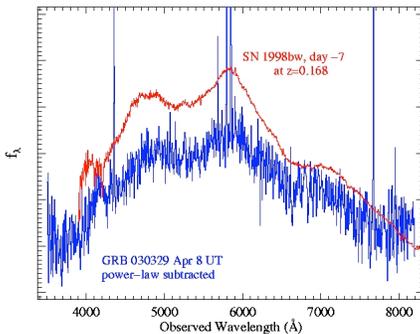


Figure 11: *The supernova spectrum of SN2003dh arising above the afterglow light curve of GRB030329 and confirming the SN-GRB connection.*

ii) Mergers and Short GRBs

Neutron star binaries are pair of neutron stars, circling around each other. Several such systems are known in our Galaxy. The most famous of those is the binary pulsar discovered in 1975 by Russel Hulse and Joseph Taylor (then at the University of Amherst).

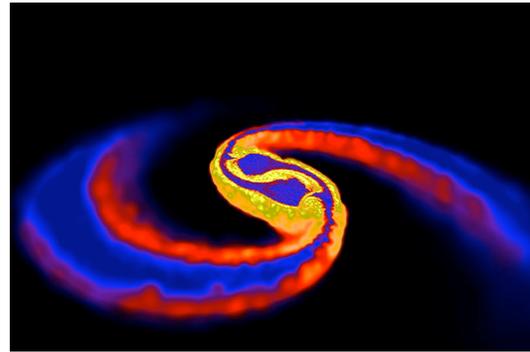


Figure 12: *A numerical simulation of the last stage of a binary neutron star merger. Shown are density contours.*

As the neutron stars circle around each other they emit gravitational radiation and their orbit shrinks. Eventually they coalesce and merge forming a black hole and an accretion disk of debris. Niel Gehrels⁴² from Goddard Space Center and coworker, Derek Fox⁴³ from Caltech and coworkers and Edo Berger⁴⁴ from Caltech and coworkers using NASA's *Swift* satellite discovered that, unlike long GRBs that arise only in star forming spiral galaxies, short GRBs (GRBs whose duration is less than 2 seconds) appear in both elliptical and spiral ones. At times they are located in the outskirts of their host galaxies. These observations are consistent with the prediction of the merger model and suggest that neutron star mergers are the progenitors of short GRBs. However a clear proof is still missing.

Neutron star mergers are the strongest sources of gravitational radiation. As such they are the prime targets for gravitational radiation detectors like LIGO and Virgo that have been constructed during the last decade both in the USA and in Europe. Already in 1993 I suggested with Chris

Kochanek⁴⁵ (from Harvard) that a combined detection of a GRB and a pulse of gravitational radiation would be the ultimate proof of this model. With the expected upgrade of LIGO we are eagerly waiting for this confirmation.



Figure 13: *The LIGO detector built to detect gravitational radiation from coalescing neutron star binaries.*

Swift and recent developments

GRBs continue to be at the focal point of the astronomical research. In the fall of 2004 NASA has launched *Swift*: a dedicated GRB satellite⁴⁶.

By localizing several short GRBs⁴²⁻⁴⁴ *Swift* has demonstrated that, as would be expected from the neutron star mergers model, those are not located within star forming regions. *Swift* has numerous discoveries concerning the early afterglow. Some of those are incompatible with the possibly over simplified fireball model. For example, some of the findings indicate that the central engines that power GRBs (the accreting black holes) are active long after the prompt emission ceases⁴⁷. Other observations suggest that the outflow may not be composed from protons and electrons, as initially

thought, but might contain a significant fraction of electromagnetic energy (the so called Poynting flux) as suggested already in 1992 by Vladimir Usov⁴⁸.

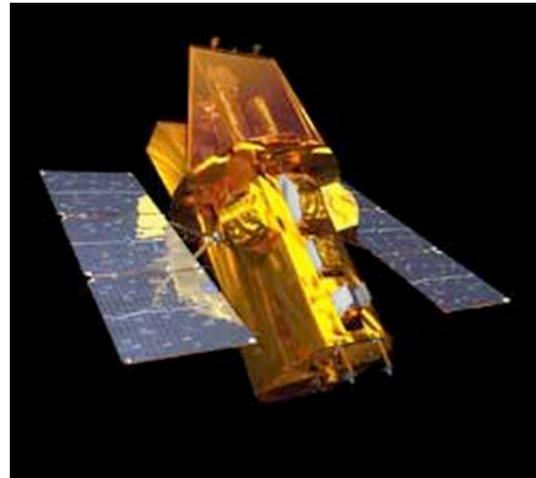


Figure 14: *NASA's Swift satellite, a dedicated GRB satellite with rapid follow up capabilities that enable it to catch the early x-ray and optical afterglow.*

Among *Swift*'s most amazing discoveries was the detection by Judith Racusin from Penn State and coworkers⁴⁹ of GRB080319b, a very powerful burst accompanied by a 5th magnitude optical flash. Optical flashes accompanying GRBs were not new. With Re'em Sari, I⁵⁰ have predicted this phenomenon in the fall of 1998. Luckily enough the first flash was detected shortly afterwards by Carl Akerlof⁵¹ and coworkers from the University of Michigan in the winter of 1999. However, the burst of GRB 080319b was the brightest flash ever. It was so powerful that it could have been seen by a naked eye even though it came from 7 billion light years away. Had the burst been in our Galaxy this optical flash would have out-shined the Sun!

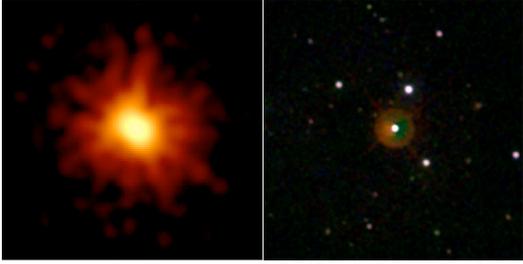


Figure 15: *The optical flash of the naked eye burst, GRB080319b. A 5th magnitude optical signal 7 billion light years away.*

Fermi

Last summer NANA has launched Fermi: a very high-energy γ -ray satellite with GRB detector on board. As far as GRBs are concerned Fermi's major goal is to search for very high-energy emission (in the range of GeV) from GRBs. Such emission would give new clues on the nature of the emission processes both during the prompt phase and during the afterglow.

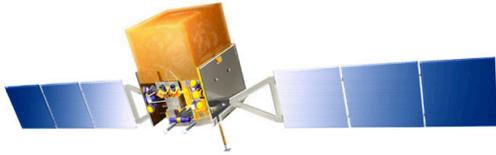


Figure 16: *Fermi, NASA's latest high energy satellite with GeV detection capabilities and a dedicated GRB detector on board.*

So far Fermi has detected GeV emission from several GRBs. This is less than what was previously expected and somewhat puzzling. Still the observations have some intriguing achievements. This April, Fermi as well as *Swift* have detected a burst, GRB 090423, at a redshift of 8.1. This

is the most distant and hence also the earliest object seen so far. The age of the Universe at the time that this burst exploded was only 570 million years old. This implies that some stars formed very early and that GRB progenitors are among the earliest objects that have formed in our Universe.

Fermi's observations of other GRBs has set strong limits on possible quantum gravity effects that would make the speed of photons energy depend. In other observations Fermi has shown that the velocity of the outflow in a particular GRB exceeded 0.999999 of the speed of light⁵².

Neutrinos and Cosmic Rays and Cosmology

GRBs involve particles moving at ultra-relativistic velocities. Collisions between these particles can produce very high-energy neutrinos. Such neutrinos are prime candidates for detection by the km³ that is being built now in Antarctica. It is amazing that this detector is so quiet and free of background that a detection of even a single neutrino in coincidence with a GRB would be significant.

Eli Waxman⁵³ and independently Mordechai Milgrom and Vladimir Usov⁵⁴ (all from the Weizmann Institute) pointed out in 1995 the exciting possibility that GRBs are the sources of ultra high energy Cosmic Rays. This is intriguing as the origin of those cosmic rays that are observed at energies above 10^{19.5}eV, that is above the GZK cutoff is still mysterious.

In 1995 I¹⁵ have suggested that as powerful beacons that can be seen

from the most distant parts of the Universe GRBs can replace supernovae as the classical tool for cosmological tests. However, in order to do so one has to find a way to estimate with high precision GRBs intrinsic luminosity so that they can become "standard candles". While numerous suggestions have been put forwards in this direction none has been successful so far.

None of these ideas was confirmed yet but they serve to indicate the vast potential of GRBs and of the extreme conditions that take place in them.

Doom Star

Even though GRBs are at cosmological distances their γ -ray flux is at times so large that it is capable of shaking the Earth ionosphere and creating noticeable disturbances. It is amazing

that, apart from the Sun and a few solar system objects - meteorites and asteroids, GRBs are the only astronomical objects that have a direct influence of any kind on Earth.

Imagine now a GRB taking place in our Galaxy. Such event will be rare as GRB take place only once every 100,000 years in our Galaxy and only once per 10 million year they will point towards us. But this could happen. If the burst is near enough its enormous radiation field could ionize and partially evaporate the Earth atmosphere. While a complete theory for the possible damage is not in place yet and the essential comparison with the effects of less powerful but thousand times more frequent supernovae should be done, it is clear that a GRB in our Galaxy can have devastating effects for life on Earth. A GRB could be our doom star.

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