Relativity at Action or Gamma-Ray Bursts

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Abstract

Gamma ray Bursts (GRBs) - short bursts of few hundred keV γ-rays - have fascinated astronomers since their accidental discovery in the sixties. GRBs were ignored by most relativists who did not expect that they are associated with any relativistic phenomenon. The recent observations of the BATSE detector on the Compton GRO satellite have revolutionized out ideas on these bursts and the picture that emerges shows that GRBs are the most relativistic objects discovered so far.

GRBs are short bursts of hundred keV range γ-rays lasting from a few milliseconds to several hundred seconds. GRBs were discovered accidentally by defense satellites - the Vela satellites - that were launched to monitor the "outer space treaty" the 1962 non-proliferation treaty that forbade nuclear explosions in space. The discovery was kept secret for a while and only in 1973 it was announced publicly [1]. During the eighties a consensus formed that GRBs originate on galactic disk neutron stars. In 1990 NASA launched Compton-GRO (Gamma-ray observatory) satellite that includes BATSE a GRB detector on board. BATSE which is more sensitive than any detector flown before detects on average one burst per day. BATSE was expected to find a concentration of GRBs towards the galactic plane and to prove the galactic neutron star model. Instead BATSE discovered that the GRB distribution has a perfect isotropy. Additionally BATSE detected a paucity of weak bursts - the number of weak bursts, N, did not increase with decreasing count rate, C, like $C^{-3/2}$, as expected in a Euclidean space [2]. The simplest explanation is that GRBs are cosmological. Isotropy of cosmological sources is obvious. As for the paucity of weak bursts here we encounter relativity for the first time. In a FRW universe the volume element does not increase like r^3 and the count rate from a given source does not decrease like r^{-2} (see e.g. [3]). If GRBs are detected to $z \approx 1$ than these relativistic effects reduce significantly the number of weak bursts in agreement with the observed $N(C)$ curve [4, 5].

Other cosmological effects should be observed as well. The spectrum of dim (and hence distant) GRBs should be red-shifted and the average duration of dim bursts should be longer then the average duration of bright ones [4, 6]. Lacking any clear spectral feature (there are no spectral lines in GRBs) it is difficult to observed the expected red-shift. However, time dilation of dim bursts relative to bright ones have been recently reported [7] confirming the theoretical predictions and the cosmological origin of GRBs.

If GRBs are located at cosmological distances they release $\approx 10^{51}$ergs. Thus, they are the most (electromagnetically) luminous objects known (only supernovae are more luminous, but their emission is mostly neutrinos). Already in the seventies Schmidt [8] pointed out that a compact source (as implied by the rapid variability) will be optically thick to pair creation ($\gamma\gamma \rightarrow e^+e^-$) and consequently it won't be able to produce such a high luminosity non-thermal radiation. This is the compactness problem.

Relativistic effects can fool us and, when ignored, lead to wrong conclusions. This happened 30 years ago when rapid variability implied "impossible" temperatures in extra-galactic radio sources. This puzzle was resolved when M. J. Rees suggested ultra-relativistic expansion which has been confirmed by VLBA measurements of super luminal jets. This also happened in the present case. It has been argued on the basis of the compactness problem that "new physics" is unavoidable if GRBs are cosmological. However, special relativity is all that is needed to resolve this paradox [9, 10, 11]. Consider a source of radiation that is moving towards an observer at rest with a relativistic velocity characterized by a Lorentz factor, $\gamma = 1/\sqrt{1 - v^2/c^2} \gg 1$. The size of the region from which the radiation is emitted should satisfy $R_i < \gamma^2 c\Delta T$ instead of the Newtonian estimate, $R_i < c\Delta T$. Additionally the photons with observed energy $h\nu_{obs}$ have been blue shifted and their energy at the source was $h\nu_{obs}/\gamma$. The fraction of photons with sufficient energy to produce pairs is smaller by a factor $\gamma^{-2\alpha}$ [where α is the spectral index] than the observed fraction. These two effects reduce the optical depth by $\gamma^{4+2\alpha}$. The system will become optically thin and the compactness problem will be resolved if the emitting regions move with an ultra-relativistic velocity with $\gamma > 100$ ($v > 0.99995c$). This is the largest observed macroscopic velocity in the Universe - how can it be reached?

We do not expect macroscopic objects to roam in the Universe with velocities approaching the speed of light. Instead the natural interpretation of this conclusion is that this is an internal motion that is produced within the sources. It is the most (energetically as well as conceptually) economical to continue and suggest that the kinetic energy of this ultra-relativistic motion is also the source of the energy of the observed GRBs - in other words that GRBs are produces during the slowing down of a bulk motion of ultra-relativistic particles. This suggests a three stage process: First, an inner compact source produces the energy. Second, this energy is transported to a large distance not as γ-rays but as the kinetic energy of an ultra-relativistic particle flow [12, 13, 14]. Third, the kinetic energy is converted to the observed radiation only after it reaches a large enough distance where the emitting region is optically thin.

One may wonder what produces the ultra-relativistic particle flow. The answer is quite simple. Suppose that a compact source with a radius R_0 emits radiation with a total energy E. This radiation is optically thick and it produces what has been called a "fireball" - an optically thick sphere of radiation and electron-position plasma. The fireball is initially radiation dominated and it expands and accelerates [15, 16]. This phase resembles the early radiation dominated Universe. The radiation cools during the expansion and its internal energy decreases until it is smaller than the rest mass energy density of baryons that are present. The fireball reaches then a matter dominated stage in which the kinetic energy of baryons equals to the initial energy of the fireball. The baryons coast at a constant velocity with a Lorentz factor $\gamma = E/Mc^2$ and their motion is described well by a Milne Universe. From the point of view of an observer at rest the baryons constitute a narrow shell with a thickness R_0 - the initial size of the fireball. The kinetic energy is transported outward where it has to be converted back to observed radiation.

It is worthwhile to consider a related well known phenomenon: supernova explosion. 10^{51}ergs are deposited in a supernova into a stellar envelope of several solar masses, M_{sn}. One percent of the total energy, $\approx 10^{49}$ergs, is observed as the spectacular optical radiation of the supernova. The rest is the kinetic energy of the ejecta that moves at a velocity $u = \sqrt{2E/M_{sn}} \approx$ 10000km/sec. When the ejecta reaches a radius $R_{snr} = 10^{18}$cm within which there is an equal mass of interstellar matter (ISM): $(4\pi/3)R^3_{snr}\rho_{ISM} = M_{sn}$ it slows down and a supernova remnant (SNR) forms. The kinetic energy of the ejecta is then converted to non-thermal radiation over a period of R_{snr}/u or tens of thousands of years.

Imagine now that the same energy is deposited into a much smaller mass ($M \approx 10^{-5}m_\odot$ or less). The ejecta will reach ultra-relativistic motion with $\gamma = E/Mc^2 > 100$. Now effective slowing down of the ejecta - that is slowing down from γ to $\gamma/2$ - takes place at $(4\pi/3)R^3_\gamma\rho_{ISM} = M/\gamma = E/\gamma^2c^2$ (note that relativistic effects add a factor of γ in this relation). Typical values of R_γ are approximately 10^{15}cm. The energy conversion takes place on a scale of R_γ/c which is several days but it is observed within R_γ/γ^2c, which is sufficiently short if $\gamma > 100$. Like in SNR two shocks appear in the interaction between the ejecta and the ISM: an outward going shock that propagates into the ISM and an inward going one that propagates into the ejecta. The shocks are ultra-relativistic and the emitted radiation is much harder than in SNRs. The emitted photons are blue shifted (since the shocked material moves relativistically relative to an observer at rest) and the observed photons are γ-rays in the hundred keV range.

So far we have seen cosmological effects and special relativistic effect - but this is only part of the story. From the generic GRB model described above it appears that the actual source that produces the energy and drives the whole process is well hidden and GRB observations do not reveal its nature. All that we know with certainty is that the sources should be capable of producing 10^{51}ergs within a short time and that the process takes place at a rate of approximately once per million years per galaxy. The latter fact is obtained from estimates of the rates of GRBs [4, 5]. At present this circumstantial evidence is all that we know!

Among all astronomical objects binary neutron star mergers can be singled out as candidates that satisfy both conditions [18]. Binary neutron stars coalesce releasing $\approx 5 \times 10^{53}$ergs - the binding energy of a neutron star. Most of this energy escapes in the form of neutrinos or gravitational radiation. Less than one percent of this amount is sufficient to power a GRB.

There are several models that suggest how such a fraction can be converted to electromagnetic radiation [18, 19]. The rate of neutron star mergers can be estimated from binary pulsar observations. Two independent estimates [17, 20] based on the three known binary pulsars find that the rate of binary neutron star mergers in our galaxy is one per million years. The agreement with the observed rate of GRBs makes binary neutron star mergers a prime candidate for sources of GRBs. In fact it is the only GRB model today that is based on an independently observed phenomenon that is known to take place at a comparable rate.

Numerous interesting relativistic effects take place in binary neutron star mergers. First, the merger is driven by gravitational radiation. The orbital decay due to gravitational radiation emission was already observed in one binary pulsar, PSR 1913+16 [21] and it manifests one of the greatest accomplishments (both in terms of precision measurements and of theoretical predictions) of general relativity so far. Second, the combined mass of two neutron stars is most likely above the maximal mass of a rapidly rotating neutron star (which is uncertain due to uncertainty in neutron stars' equation of state). Thus, the ultimate product of the merger is a rotating black hole. If this model is correct then each GRB signals to us the formation of a black hole! Other effects are still unknown or are just being explored now. Complete modeling of binary neutron star mergers requires the most general gravitational computer code: a dynamical three dimensional code that allows gravitational radiation emission as well as strong fields and black hole formation. Such codes do not exist yet but preliminary calculations with simpler three dimensional codes suggest that an intriguing instability (which resembles the instability around marginally stable orbits in black holes) exists [22]. This instability makes both neutron stars unstable when they reach a certain distance from each other even before they collide. If this is true then the whole system may collapse to a black hole before a physical collision takes place. It is intriguing question whether GRB can form if such an instability exists (note that if enough material is tidally torn from the neutron stars before this catastrophe happens its accretion on the newly formed black hole could power the GRB).

Searchers of gravitational radiation has already realized the importance of binary neutron star mergers. These are the prime targets of the next generation gravitational radiation detectors LIGO and VIRGO. If GRBs are produced in binary neutron star mergers then the accompanying GRB should increase the statistical significance of a gravitational radiation signal [23]. This would increase the sensitivity of a gravitational radiation detector by a factor of 2 and the detection rate by half an order of magnitude. Clearly such a coincident detection will resolve the enigma that surrounded GRBs for almost three decades. This would be a nice small bonus to the achievement of directly establishing the existence of gravitational radiation. It is amusing to note that such a joint detection (in which the gravitational radiation from the orbital decay is expected to precede the GRB by a fraction of a second) would immediately establish, using the time of flight argument, a direct limit on the graviton's mass. For example the arrival of a 100Hz gravitational radiation signal one second before a GRB signal will indicate that the graviton's mass is less than 10^{-21}eV!

Quite unexpectedly and practically without notice GRBs became the most relativistic objects known to us today: They demonstrate the existence of ultra-relativistic motion with velocities and Lorentz factors far larger than seen elsewhere in the Universe and they display time dilation and other cosmological effects. If GRBs are indeed produced in binary neutron star mergers (as seems most likely today) than they involve, gravitational radiation, strong dynamical gravitational fields and black hole formation. We may be seeing in GRBs the echoes of GR in full action.

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References

[1] Klebesadel, R. W., Strong, I. B., & Olson, R. A. 1973, ApJ, 182, L85.

[2] Meegan, C.A., et. al. 1992, *Nature*, **355**, 143.

[3] Weinberg, S. Gravitation and Cosmology, Wiley, 1973.

[4] Piran, T. 1992, ApJ, 389, L45.

[5] Cohen, E., & Piran, T. 1995, ApJ, 444, L25.

[6] Paczyński, B. 1992, Nature, 355, 521.

[7] Norris, J. P., et al, 1994, ApJ. **424**, 540.

[8] Schmidt, W. K. H. 1978, Nature, 271, 525.

[9] Krolik, J. H., & Pier, E. A. 1991, ApJ, 373, 277.

[10] Rees, M. J. & Mészaros, P., 1993, MNRAS, 258, 41,

[11] Piran, T. 1994, in AIP Conference Proceedings 307, Gamma-Ray Bursts, Second Workshop, Huntsville, Alabama, 1993, eds. G. J. Fishman, J. J. Brainerd & K. Hurley (New York: AIP), p. 495.

[12] Shemi, A., & Piran, T. 1990, ApJ, 365, L55.

[13] Paczyński, B. 1990, ApJ, 363, 218.

[14] Mészaros, P., & Rees, M. J. 1992, MNRAS, 258, 41p.

[15] Goodman, J. 1986, ApJ, 308, L47.

[16] Paczyński, B. 1986, ApJ, 308, L51.

[17] Narayan, R., Piran, T., & Shemi, A. 1991, ApJ, 379, L1.

[18] Eichler, D., Livio, M., Piran, T., & Schramm, D. N. 1989, Nature, 340, 126.

[19] Narayan, R., Paczyński, B., & Piran, T. 1992, ApJ, 395, L83.

[20] Phinney, E. S. 1991, ApJ, 380, L17.

[21] Taylor, J. H., & Weisberg, J. M. 1982, ApJ, 253, 908.

[22] Wilson, J. R., Matthews G. J. & Marronetti, gr-qc/9601017.

[23] Kochanek C., and Piran T., 1993 ApJ. 417, L17.