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GAMMA-RAY BURSTERS AT COSMOLOGICAL DISTANCES

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ABSTRACT

We propose that some, perhaps most, gamma-ray bursters are at cosmological distances, like quasars, with a redshift $z \approx 1$ or $z \approx 2$. This proposition requires a release of supernova-like energy of about 10^{51} ergs within less than 1 s, making gamma-ray bursters the brightest objects known in the universe, many orders of magnitude brighter than any quasars. This power must drive a highly relativistic outflow of electron-positron plasma and radiation from the source. The emerging spectrum should be roughly a black body with no annihilation line, and a temperature $T \approx (\dot{E}/4\pi r_0^2 \sigma)^{1/4}$. As an example the spectrum would peak at about 8 MeV for the energy injection rate of $\dot{E} = 10^{51}$ ergs s^{-1} and for the injection radius $r_0 = 10$ km.

We propose that three gamma-ray bursts, all with identical spectra, detected from B1900+14 by Mazets, Golenetskii, and Gur'yan and reported in 1979, were all due to a single event multiply imaged by a gravitational lens. The time intervals between the successive bursts, 10 hr to 3 days, were due to differences in the light travel time for different images. The required mass of the lens is 10^{10} $M_\odot$, just right for a galaxy.

Subject headings: cosmology — gamma rays: bursts — gravitation

I. INTRODUCTION

Gamma-ray bursters are known to have a duration of about a second, their distribution on the sky is isotropic, their number density increases slowly with the decreasing burst intensity (i.e., the slope of the log N–log S curve is -1.5 for bright bursts and -0.5 for faint bursts; Jennings 1984), their spectra peak at the energy above $m_e c^2$, and they have no convincing spectral lines, according to the excellent reviews by Verter (1982) and Epstein (1985). A strong gamma-ray burst reaches an observed flux of 10^{-4} ergs s^{-1} cm^{-2} for a duration of about 1 s. The detection limit is 10^{-7} ergs s^{-1} cm^{-2}. The burst spectra have broad maxima between 0.5 MeV (e.g., 1972 May 14 event) and 5 MeV (e.g., 1982 January 25 event).

Detailed properties of various events are so different that it is possible, or even likely, that there are several different types of bursters, with entirely different origins. The most popular models utilize some energetic phenomena related to nearby neutron stars, with a typical distance of 100 pc. This distance scale is required by the observed isotropy of the burst positions. At larger distances the anisotropy due to the Galaxy should be apparent: all known Galactic objects are concentrated either on the Galactic plane or at the Galactic center. At a smaller distance there are not enough neutron stars. However, the slope of the log N–log S relation remains a mystery. Also, no specific radiation mechanism has been unambiguously identified.

Let us use strictly astronomical criteria to estimate typical distances of the unknown objects. If their distribution is isotropic then characteristic distances in the range between 1 kpc and 30 Mpc seem to be excluded. The unusual slope of the log N–log S relation implies that they are not uniformly distributed in Euclidean space. This leaves us with two possibilities: either the objects are very local indeed, associated with our solar system (e.g., with the Oort cloud of comets; Milgrom 1986), or they are at cosmological distances like quasars. No specific phenomenon was ever proposed for either of these distances. Here we shall look into the second possibility. The effect of cosmological distances of gamma-ray bursters on their log N–log S relation was discussed by Usov and Chibisov (1975). A possibility of extragalactic origin of gamma-ray bursts was discussed by van den Bergh (1983).

There are two coincidences that make the cosmological hypothesis not unreasonable: the observed energies and the observed spectra. A gamma-ray burst that brings about 10^{-6} ergs cm^{-2} at Earth, requires a total energy release of 10^{51} ergs if the source is at a Hubble distance of $c/H_0 \approx 10^{28}$ cm. This is like a supernova energy, and this is the first coincidence. It suggests that gamma-ray bursts may be related to some violent events on neutron stars which are far away. If all this energy is to be radiated away in 1 s from a surface with a radius of 10 km then the required effective temperature is about 3×10^{10} K, and it peaks around 8 MeV. With a modest cosmological redshift this falls into the range of observed peak energies, and this is the second coincidence. These two very rough coincidences encourage a more detailed analysis of the following proposition: suppose that some unknown process releases 10^{51} ergs, or even more, in a small volume of space within 1 s or so. What would be the consequences?

As an example we may take an object as big as a neutron star, just to be specific. However, our considerations do not assume or require the presence of a neutron star. A hypothesis that gamma-ray bursters are at cosmological distances was initiated because of two rather loose coincidences, which indicated that the bursts may be related to neutron stars which are far away. However, there is no direct evidence that there is such a relation, and it may well be that the origin of gamma-ray bursts is not related to neutron stars at all.

II. A SCENARIO

We consider the release of energy with a very high energy density, with the equivalent temperature $T > mc^2$ (throughout this *Letter* we shall use m for the electron mass). For simplicity we assume spherical symmetry. The release of so much energy must set up a relativistic outflow. For simplicity we assume that the flow is stationary, and we ignore the baryonic component. Flammang (1982) has written the equations of a steady state, spherical, relativistic flow in a form very easy to use. As we are interested in highly super-Eddington luminosities we may neglect gravity and the flow may be assumed to be adiabatic. We shall consider first only an optically thick medium, with the opacity due to electron scattering and pair production. After simple manipulations we may write Flammang's equations as

$$(U + P)4\pi r^2 v\gamma^2 = \dot{E} = \text{const}, \tag{1a}$$

$$T\gamma = T_0 = \text{const}, \tag{1b}$$

$$\frac{dP}{dr} = -(U + P)\frac{d\ln\gamma}{dr}, \tag{1c}$$

where $\gamma \equiv [1 - (v^2/c^2)]^{-1/2}$, and all symbols have their usual meaning. In general, pressure P, and internal energy density U, include the contribution of radiation and electron positron pairs. The flow is defined by two constants only: the total energy outflow rate $\dot{E}$, and the reference temperature T_0. Equation (1b) is a consequence of the assumed adiabaticity of the flow.

The equations (1) describe the flow between the inner radius where energy is injected, and the photosphere, beyond which radiation is streaming freely. We assume that temperature at the inner radius is high enough for pair creation, and therefore the flow is very optically thick. In the outer parts the flow accelerates, the temperature falls, and the number density of pairs becomes much less than the number density of photons, while the optical depth is still large. The equation of state is very simple there. We have

$$U = 3P = aT^4 \qquad \text{for } T \ll mc^2/k. \tag{2}$$

In the inner region $T_0 > mc^2/k$. Therefore, in the outer regions $\gamma \gg 1$ (cf. eq. [1b]), and $v \approx c$. Within this approximation we find that the equations (1) have the solution

$$\gamma = r/r_0, \tag{3a}$$

$$T = T_0 r_0/r, \tag{3b}$$

$$\dot{E} = \tfrac{16}{3}4\pi r_0^2 \sigma T_0^4, \tag{3c}$$

$$r \gg r_0. \tag{3d}$$

Notice that a sphere with a characteristic radius r_0 and with a surface temperature T_0 would radiate a blackbody radiation at a rate approximately equal to $\dot{E}$. The characteristic radius r_0 is roughly equal to the radius where energy is injected, while the "photospheric" radius turns out to be much larger than r_0.

In our scenario we neglect the baryonic component of the flow for simplicity only. However, a more realistic model with an additional free parameter, the rate of baryonic mass flow, may be easily worked out.

We are mostly interested in the outer parts of the flow, where the spectrum of the emerging radiation is formed. As long as the flow is very optically thick the radiation has a blackbody distribution in its rest frame. However, if enough pairs remained near the photosphere a characteristic annihilation line would not be thermalized, and it could be seen in the emerging spectrum. The line detectability depends on the ratio of number of pairs to the number of photons close to the photosphere, i.e., on the ratio of energy in the line to the total radiation energy.

In the low-temperature limit when $kT \ll mc^2$ the total number density of negative and positive electrons is given as

$$n_\pm \approx 8\pi(2\pi)^{1/2}\left(\frac{mc}{h}\right)^3\left(\frac{kT}{mc^2}\right)^{1.5}\exp\left(-\frac{mc^2}{kT}\right)$$
$$= 4.41 \times 10^{30}\ \text{cm}^{-3}\left(\frac{kT}{mc^2}\right)^{1.5}\exp\left(-\frac{mc^2}{kT}\right). \tag{4}$$

The ratio of energy density in pairs to the energy density in blackbody photons may be calculated as

$$E_\pm/E_{\rm rad} \approx (2\pi)^{1/2}\frac{15}{\pi^4}\left(\frac{mc^2}{kT}\right)^{2.5}\exp\left(-\frac{mc^2}{kT}\right)$$
$$= 0.386\left(\frac{mc^2}{kT}\right)^{2.5}\exp\left(-\frac{mc^2}{kT}\right). \tag{5}$$

Under the same conditions Thomson opacity due to pairs is given as

$$\kappa = \sigma_e n_\pm = 2.93 \times 10^6\left(\frac{kT}{mc^2}\right)^{1.5}\exp\left(-\frac{mc^2}{kT}\right). \tag{6}$$

As an example let us take $T = 0.05mc^2/k = 3 \times 10^8$ K. Equations (5) and (6) give us $E_\pm/E_{\rm rad} \approx 10^{-6}$ and $\kappa \approx 0.5$ cm^{-1}. It is clear that the energy in pairs is negligible while the medium is still very opaque. Therefore, we do not expect any annihilation to be visible in the emerging spectrum.

Let us consider now the photosphere of the expanding flow. It will be at a temperature at which the flow becomes transparent, i.e., at $kT \ll mc^2$. If the interior temperature $T_0 > mc^2/k$ then at the photosphere $\gamma = T_0/T \gg 1$ (cf. eq. [1b]) and $r/r_0 = \gamma \gg 1$ (cf. eq. [3a]). The observer will see the approaching part of the photosphere blueshifted by a factor γ to the apparent temperature $T_a = T\gamma = T_0$. Therefore, no matter where the photosphere is the apparent temperature will be equal to the interior temperature. As the emerging radiation will have approximately a blackbody spectrum the apparent radius of the bright part of the photosphere will always be approximately equal to r_0. To the first approximation the source would look as if there was no relativistic wind and as if we could see directly the interior where energy is injected.

A small amount of baryonic matter in the flow would not affect the shape of the emerging gamma-ray spectrum—it would remain roughly a blackbody. However, some fraction of energy would be transferred from radiation to the kinetic energy of matter, thereby reducing the apparent temperature.

III. DISCUSSION

The optically thick model we have proposed for a gamma-ray burster generates a blackbody spectrum. This is in obvious conflict with the observations of gamma-ray bursters. The flux observed in the X-ray region, F_ν, is proportional to ν^0 (cf. Epstein 1985), while a blackbody gives ν^2. There are many ways to broaden the spectrum. A cool envelope of a moderate optical depth located at some distance from the source could scatter down some of the photons. This process will not only soften the spectrum but also broaden the burst in time. It is far from obvious that there is a geometry which would satisfy all the burst requirements, but a number of various geometries is so large that this possibility cannot be dismissed. The energy injection mechanism may be rapidly variable, and therefore the apparent temperature may be rapidly variable as well. The observed spectra are averaged over large fractions of a second, and this may be responsible for the shallow slope of the low-energy part of the spectrum. This problem is discussed in some detail by Goodman (1986). Again, a rather special time variability is required.

We do not intend to speculate now about the details of the spectra as the nature of energy injection is not known. However, we would like to discuss two other aspects of the problem. Are there any phenomena on a supernova energy scale that are expected to involve bare neutron stars, so that the apparent temperatures could be in the gamma-ray region? Is there any possibility of finding convincing observational evidence that at least some gamma-ray bursters are at cosmological distances?

On various occasions very energetic phenomena that involved bare neutron stars were suggested for a variety of reasons. Haensel and Schaeffer (1982) calculated models of neutron stars with a phase transition in their structure leading to a release of 10^{48} ergs in a small fraction of a second and noticed a possibility of even more powerful events. Ostriker (1979) considered the fate of the inner cores of globular clusters where the dominant constituents may be neutron stars. From time to time neutron stars will collide, releasing up to 10^{53} ergs per event. The binary radio pulsar PSR 1913 + 16 will coalesce with its neutron star companion within about 10^8 yr as a result of gravitational radiation losses (Taylor and Weisberg 1982). The final stage is likely to be very violent, and again of the order of 10^{52} or 10^{53} ergs will be released. In all of these cases the details of a violent energy release are not known, and it is not clear at all that a significant fraction of energy will be radiated in the gamma-ray region. But it is not unreasonable to expect that some of these, or perhaps some other rare phenomena may generate enough gamma-ray energy. The frequency of events required by the available observations is very low: perhaps 1000 bursts per year per 10^{11} galaxies.

If some gamma-ray bursters are at cosmological distances, say as far away as quasars, then they should be gravitationally lensed as frequently as the quasars are. According to the recent estimates (Turner 1986) about one out of 300 quasars is lensed with two or more images separated by 2″–7″. These separations imply that the differences in the light travel time between different observed images should be between a few months and a few years. The gamma-ray burst detectors do not provide accurate enough positions of the sources to separate the images. However, it should be possible to see some bursts twice, or even a few times, depending on the structure of the lensing object. These recurrent bursts should have the same location in the sky, identical spectra, and identical gamma-ray "light curves," except for the scaling factor, as different images may have different intensity. Therefore, the cosmological scenario of gamma-ray bursters makes a prediction that some bursts should be recurrent phenomena. Unfortunately, without knowing the distances we cannot predict the frequency of gravitational lensing.

It is interesting that a few cases of recurrent bursts were observed. For example, according to Golenetskii *et al.* (1979) a very strong source FXP 0520 − 66 was discovered on 1979 March 5 (the famous event), and later a series of weak bursts was observed from the same position on 1979 March 6, April 4, and April 24. The energy spectra of all of them were found to be similar, but their "light curves" were not. A series of bursts was detected from the same source in 1981 and 1982 by Golenetskii, Il'inskii, and Mazets (1983), but their "light curves" were different again. Therefore, recurrence of FXP 0520 − 66 cannot be due to gravitational lensing. It should be remembered that March 5 event was unusual in almost every respect, and it may have a different origin than most other bursts. In particular, if it is located in a Magellanic Cloud then it would be intrinsically much fainter than the others.

A second recurrent source, B1900 + 14, was reported by Mazets, Golenetskii, and Gur'yan (1979) to burst three times: on 1979 March 24, March 25, and March 27. All three bursts had very similar time variations, and their spectra were "identical to within the errors of measurement." Therefore, B1900 + 14 is the prime candidate for a recurrence caused by gravitational lensing. The mass of the lensing object may be estimated from the observed time delays between the events. These should be roughly equal to the time it takes light to go over a distance equal to the gravitational radius of the lensing object. The required mass is about 10^{10} $M_\odot$, just right for an ordinary galaxy. The angular separation between the images is expected to be a fraction of a second of arc in this case.

If the fractions of gravitationally lensed gamma-ray bursts and quasars are roughly the same, a proposition consistent with the available data, then their typical distances are comparable, and a typical redshift of a gamma-ray burster may be about 2. The slopes of the observed log N–log S relations are very different. Therefore, the evolutionary properties and/or the intrinsic luminosity functions of bursters and quasars must be very different too.

If some gamma-ray bursts are indeed at cosmological distances, they may be used as a new unique probe of the universe. For example, if there is a significant mass density in supermassive black holes of 10^6 $M_\odot$, as recently proposed by Lacy and Ostriker (1985), then gravitational lensing by such objects will give rise to a double event, with the first burst followed a few seconds later by a weaker second burst with identical time and spectral characteristics. Dark objects with other masses would give rise to lensing with different time delays. Presence or absence of such multiple gamma-ray bursts could be used to put limits on masses of the dark objects that are otherwise undetectable.

It is interesting that some bursts have a double structure with the second subburst looking like a weaker copy of the first one. An example is the burst observed by Mazets and Golenetskii (1979) at 0859:15 UT on 1979 January 16 (cf. also Verter 1982, p. 304). This might be a candidate for a double burst resulting from gravitational lensing by a $10^6\ M_\odot$ black hole. Unfortunately, the structure of bursts is known to be very rich, and it may be very difficult to distinguish between the intrinsic structure and the effects of gravitational lensing. It would be very interesting to analyze the original data to test the hypothesis that double bursts are intrinsically single events made double through gravitational lensing by point masses. It is not clear at this time whether a reliable conclusion could be reached with the observations collected so far.

There are two issues that we consider to be the most important, one observational and one theoretical. It seems that the flattening of the log N–log S curve at low flux levels is well established. However, it is not so clear that the distribution of faint gamma-ray bursters is isotropic. The cosmological hypothesis is based on the *assumption* that faint gamma-ray bursts are distributed isotropically. Only observations may verify this assumption. The most important theoretical problem is to explain the spectra, which according to the published analysis of the available observations are believed to be much broader than those of a blackbody.

The consequences of rapid release of a large amount of energy in a small volume were recently studied by Goodman (1986). It is great pleasure to acknowledge stimulating discussions with Dr. J. Goodman, who kindly made his manuscript available prior to submitting it for publication, and who proposed a number of improvements of this paper. It is also a pleasure to acknowledge a number of helpful suggestions by Dr. J. P. Ostriker and Dr. A. Zdziarski. This project was partly supported by the NSF grant AST-8317116 and NASA grant NAGW-626.

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