Gamma-Ray Bursts and Related Phenomena

Tsvi Piran
Racah Institute for Physics, The Hebrew University,
Jerusalem, Israel 91904

Gamma-ray bursts (GRBs) have puzzled astronomers since their accidental discovery in the sixties. The BATSE detector on the COMPTON-GRO satellite has been detecting one burst per day for the last six years. Its findings have revolutionized our ideas about the nature of these objects. They have shown that GRBs are at cosmological distances. This idea was accepted with difficulties at first. However, the recent discovery of an x-ray afterglow by the Italian/Dutch satellite BeppoSAX led to a detection of high red-shift absorption lines in the optical afterglow of GRB970508 and to a confirmation of its cosmological origin. The simplest and practically inevitable interpretation of these observations is that GRBs result from the conversion of the kinetic energy of ultra-relativistic particles flux to radiation in an optically thin region. The “inner engine” that accelerates the particles or generates the Poynting flux is hidden from direct observations. Recent studies suggest the “internal-external” model: internal shocks that take place within the relativistic flow produce the GRB while the subsequent interaction of the flow with the external medium produce the afterglow. The “inner engine” that produces the flow is, however, hidden from direct observations. We review this model with a specific emphasis on its implications to underground physics.

1. Introduction

Gamma-ray bursts (GRBs), short and intense bursts of $\sim 100\text{keV-1MeV}$ photons, were discovered accidentally in the sixties by the Vela satellites[1]. The mission of the satellites was to monitor the “outer space treaty” that forbade nuclear explosions in space. A wonderful by-product of this effort was the discovery of GRBs. Had the satellites not been needed for security purposes, it is most likely that today we would still be unaware of the existence of these mysterious bursts.

The discovery of GRBs was announced in 1973 [1]. Since then, several dedicated satellites have been launched to observe the bursts and numerous theories were put forward to explain their origin. In the mid-eighties a consensus formed that GRBs originate from Galactic neutron stars. The BATSE detector on the COMPTON-GRO (Gamma-Ray Observatory) was launched in the spring of 1991. It has revolutionized GRB observations and consequently our basic ideas on their nature. It ruled out the galactic disk neutron star model. While BATSE’s observations could not rule out the possibility that GRBs originate from objects in the extended galactic halo the observations strongly suggested that the sources of GRBs are extra-galactic at cosmological distances. This idea was recently confirmed by the discovery by BeppoSAX [2] of an X-ray transient counterparts to several GRBs which was followed by the discovery of optical [3,4] and radio transients [5]. Absorption lines with $z = 0.835$ were measured in the optical spectrum of the counterpart to GRB970508, [6], providing a lower limit to the redshift of the optical transient and the associated GRB.

The cosmological origin of GRBs implies that GRB sources are much more luminous than previously thought. They release $\sim 10^{51} - 10^{52}$ergs in a few seconds putting them as the most (electromagnetically) luminous objects in the Universe. This also implies that GRBs are rare events. BATSE observes on average one burst per day and this corresponds to a rate of about one burst per million years per galaxy [7].

A generic scheme of a cosmological GRB model has emerged in the last few years [8]. The recently observed x-ray, optical and radio counterparts were predicted by this picture [9-12]. This discovery provides a confirmation of this model [13-17]. According to this scheme the observed
γ-rays are emitted when an ultra-relativistic energy flow is converted to radiation. Possible forms of the energy flow are kinetic energy of ultra-relativistic particles or electromagnetic Poynting flux. This energy is converted to radiation in an optically thin region, as the observed bursts are not thermal. The energy conversion occurs either due to the interaction with an external medium, like the ISM [18] or due to internal process, such as internal shocks and collisions within the flow [19,20]. Recent work [11,21] shows that the external shock scenario is quite unlikely, unless the energy flow is confined to an extremely narrow beam or the process is highly inefficient. The alternative is that the burst is produced by internal shocks. Not all the energy is converted to radiation in these shocks [22,23]. The remaining energy is converted to radiation in subsequent external shocks producing the afterglow [11]. We call this the **internal-external** shock model.

The “inner engine” that produces the relativistic energy flow is hidden from direct observations. However, the observed temporal structure seen in the bursts reflects directly this “inner engine’s” activity [24]. This model requires a compact inner engine that produces an irregular “wind” – a long energy flow (long compared to the size of the engine itself) – rather than an explosive engine that produces a fireball whose size is comparable to the size of the engine.

At present there is no agreement on the nature of the “engine” - even though binary neutron star mergers [24] are a promising candidate. All that can be said with some certainty is that whatever drives a GRB must satisfy the following general features: (i) It should produce an extremely relativistic energy flow containing $\approx 10^{51} - 10^{52}$ ergs. (ii) The flow is highly variable and it should last for the duration of the burst (typically a few dozen seconds). It may continue at a lower level on a time scale of a day or so. (iii) Finally, it should be a rare event occurring about once per million years in a galaxy. The rate is, of course, higher and the corresponding energy is lower if there is a significant beaming of the gamma-ray emission.

### 2. Observations

GRBs are short, non-thermal bursts of low energy γ-rays. It is quite difficult to summarize their basic features. This difficulty stems from the enormous variety displayed by the bursts. A “typical” GRB (if there is such a thing) lasts for about 10 sec. However, the observed durations vary by five orders of magnitude, from several milliseconds [23] to $10^3$ sec [27]. In one case high energy (GeV) photons were observed several hours after the main pulse [23]. The bursts have complicated and irregular time profiles which varies drastically from one burst to another. In most bursts, the typical variation takes place on a time scale, $\delta T$ significantly smaller than the total duration of the burst, $T$. We denote the ratio by $N = T/\delta T$ and typically $N \approx 100$.

GRBs are characterized by emission at the few hundred keV ranges with a non-thermal spectrum. Most bursts are accompanied by a high energy tail which contains a significant amount of energy – $E^2 N(E)$ is almost a constant. Several bursts display high energy tails up to 26 GeV [28]. In fact EGRET and COMPTEL (which are sensitive to higher energy emission but have higher thresholds and smaller fields of view) observations are consistent with the possibility that all bursts have high energy tails [29]. The high energy tails lead to a strong constraint on GRB models. The high energy photons must escape freely from the source without producing electron positron pairs! As we see in section 3 this provides the first and most important clue on the nature of GRBs.

GRB observations were revolutionized on February 28 1997 with discovery of an X-ray counterpart to GRB970228 by the Italian-Dutch satellite BeppoSAX [2]. The accurate position determined by BeppoSAX enabled the identification of an optical afterglow – a decaying point source surrounded by a red nebulae. Following observations with HST [30] revealed that the nebula is roughly circular with a diameter of 0.8. The nebula’s intensity does not vary, while the point source decays with a power law index $\approx -1.2$ [31]. X-ray observations by BeppoSAX, ROSAT and ASCA revealed a decaying x-ray flux $\propto t^{-1.33\pm0.11}$. The decaying flux can be extrapo-
lated as a power law directly to the x-ray flux of the second peak (even though this extrapolation requires some care in determining when is \( t = 0 \)).

Afterglow was also detected from GRB970508. This \( \gamma \)-ray burst lasted for \( \sim 15 \) sec, with a \( \gamma \)-ray fluence of \( \sim 3 \times 10^{-6} \) ergs/cm\(^2\). Variable emission in x-rays, optical \( [3] \) and radio \( [4] \) followed the \( \gamma \)-rays. The spectrum of the optical transient revealed a set of absorption lines associated with Fe II and Mg II with a redshift \( z = 0.835 \) \( [6] \). A second absorption line system with \( z = 0.767 \) is also seen. In addition there are O II emission lines with a redshift \( z = 0.835 \). This sets the cosmological redshift of GRB970508 to be greater or equal than 0.

The optical light curves show a clear peak at around 2 days after the burst. After that it shows a continuous power law decay \( \propto t^{-1.18} \) \( [2] \). Radio emission was observed first one week after the burst \( [3] \). This emission showed intensive oscillations which were interpreted as scintillations \( [33] \). The subsequent disappearance of these oscillations after about three weeks enables Frail and Kulkarni \( [5] \) to estimate the size of the fireball at this stage to be \( \sim 10^{17} \) cm. This was supported by the indication that the radio emission was initially optically thick \( [3] \), which yields a similar estimate to the size \( [3] \).

### 3. Compactness, Relativistic Motion and the Fireball Model.

The key to understanding GRBs lies, I believe, in understanding how GRBs bypass the compactness problem. Consider a typical burst with a total energy of \( 10^{51} \) ergs (as inferred from the observed flux and the implied distance of a cosmological source) that varies on a time scale \( \delta T \approx 10 \) msec. Standard considerations suggest that the temporal variability implies that the sources are compact with a size, \( R_c \leq c \delta T \approx 3000 \) km. The observed spectrum contains a large fraction of the high energy \( \gamma \)-ray photons. These photons could interact with lower energy photons and produce electron-positron pairs via \( \gamma \gamma \rightarrow e^+ e^- \). The average optical depth for this process is \( \sim 10^{15} (E/10^{51} \) ergs)\((\delta T/10 \) msec\))\(^{-2} \) \( [8] \). However, the observed non-thermal spectrum indicates with certainty that the source must be optically thin.

The compactness problem can be resolved if the emitting region is moving towards us with a relativistic velocity characterized by a Lorentz factor, \( \gamma \gg 1 \). We detect blue-shifted photons whose energy at the source is lower by a factor \( \gamma \). Fewer photons have sufficient energy to produce pairs. Additionally, relativistic effects allow the radius from which the radiation is emitted to be larger than the previous estimate by a factor of \( \gamma^2 \): \( R_c \leq \gamma^2 c \delta T \). The resulting optical depth is lower by a factor \( \gamma^{(4+2 \alpha)} \) (where \( \alpha \approx 2 \) is the spectral index). The compactness problem can be resolved if the sources are moving relativistically towards us with Lorentz factors \( \gamma > 10^{15/(4+2 \alpha)} \approx 10^2 \). It must be stressed that the motion is not necessarily pointed towards us. While we might be looking at a jet pointing towards us it is also possible that the motion is spherically symmetrically outwards away from some center.

The potential of relativistic motion to resolve the compactness problem was realized in the eighties by Goodman \( [34] \), Paczyński \( [35] \) and Krolik & Pier \( [36] \). While Krolik & Pier \( [36] \) considered a kinematical solution, Goodman \( [34] \) and Paczyński \( [35] \) considered a dynamical solution in which the relativistic motion results naturally when a large amount of energy is released within a small volume. They show that this would result in a relativistic explosion, which is called a fireball. Goodman \( [34] \) and Paczyński \( [35] \) considered pure radiation fireballs. Slemi & Piran \( [37] \) have shown that if the fireball contains baryonic mass it will become relativistic only if the initial rest mass energy, \( Mc^2 \), is small compared to the total energy \( E \). In these cases the initial energy of this fireball will be converted to the kinetic energy of the baryons, whose Lorentz factor is simply \( \gamma = E/Mc^2 \).

The kinetic energy is converted to “thermal” energy of relativistic particles via shocks. Both the low energy spectrum of GRBs and the high energy spectrum of the afterglow provide indirect evidence for relativistic shocks in the GRB \( [28] \) and in the afterglow \( [23] \). There are two modes of energy conversion (i) External shocks, which are
4. The Angular Spreading Problem

External shocks are practically inevitable if the fireball is surrounded by some external medium, such as the ISM. Internal shocks are more demanding. They require that the flow will be irregular and will contain faster shells that will catch up with slower ones. External shocks were considered, therefore, as the canonical model while internal shocks were considered as a more exotic variant. However, Sari & Piran [11] have recently shown that external shocks cannot produce the complicated highly variable temporal structure observed in most GRBs.

Let \( \Delta \) be the width of the shell and let the energy conversion take place between \( R_E \) and \( 2R_E \). The emitting material moves with a Lorentz factor, \( \gamma_e \). There are three generic time scales. (i) The radial time scale, \( T_R \): The difference in arrival time between two photons emitted at \( R_E \) and \( 2R_E \) - \( T_R \approx R_E/\gamma_e^2c \). (ii) The angular time scale, \( T_{\text{angular}} \): The difference in arrival time between two photons emitted along the line of sight and at an angle \( \theta \) from the line of sight. Because of relativistic beaming an observer detects radiation from an angular scale \( \gamma_e^{-1} \) around the line of sight. Thus, the angular size of the observed regions always satisfies \( \theta \leq \gamma_e^{-1} \) and \( T_{\text{angular}} \approx R_E\theta^2/c \leq R_E/\gamma_e^2c \). (iii) The shell crossing time, \( T_\Delta \): The light crossing time of the shell corresponds to the time difference between the photons emitted from the shell’s front and from its back. This equals: \( T_\Delta = \Delta/c \). Quite generally a forth time scale, the cooling time scale, is shorter than all those scales.

Comparison of \( T_R \) and \( T_{\text{angular}} \) reveals that if the system is “spherical” (\( \theta > \gamma_e^{-1} \)) then due to relativistic beaming we have effectively \( \theta \approx \gamma_e^{-1} \) and \( T_R \approx T_{\text{angular}} \). This leads to the angular spreading problem. Blending of emission from regions from an angle \( \gamma_e^{-1} \) from the line of sight leads to smoothing of the signal on a time scale: \( T_{\text{angular}} \approx T_R \). Therefore, unless \( T_\Delta > T_R \approx T_{\text{angular}} \) there will be a smooth single peak burst with \( \delta T \approx T \). It turns out that this will always be the case if the emission is due to external shocks [1].

One must break the spherical symmetry on scales smaller than \( \gamma_e^{-1} \) to produce a variable burst with \( \delta T \ll T \) via an external shock. The angular size of the emitting regions must be smaller than \( (\gamma_eN)^{-1} \leq 10^{-4} \) [1]. A sufficiently narrow jet can satisfy this condition. However, it is not clear how can such a narrow jet form. Furthermore, such narrow jets are not observed elsewhere. Emission from numerous small size regions must be highly inefficient in converting the kinetic energy to radiation [1] if we demand that the emitting regions are sparse enough to produce the observed temporal variability.

Internal shocks would take place if the “inner engine” produces an irregular wind (emission on a time scale much longer than the light crossing time of the source). These internal shocks could produce the GRB. Internal shocks take place at \( R_E \approx \delta \gamma^2 \) (where \( \delta \) is the length scale of variability of the wind - \( \delta \leq \Delta \) and \( \gamma \) is the initial Lorentz factor). For internal shocks the condition \( T_{\text{angular}} \approx T_R < T_\Delta = \Delta/c \) is always satisfied. This will produce a burst whose overall duration is \( \Delta/c \) and the observed variability scale is \( \delta T = \delta/c \approx T_{\text{angular}} \approx T_R \). The variability scale could be much shorter than the duration. The duration is determined by the activity of the inner engine and not by the emitting regions. The observed temporal structure reflects the activity of the inner engine, which must be producing a relatively long and highly irregular wind. Numerical simulations of internal shocks can actually reproduce the temporal structure observed in GRBs [2].

5. The Internal-External Model.

Internal shocks can convert only a fraction of the total energy to radiation [22,23]. A few month

---

1. This is provided, of course, that the cooling time is shorter than \( T_{\text{angular}} \).
before the discovery of the afterglow by BeppoSAX Sari & Piran \[2\] have pointed out that after the flow has produced a GRB via internal shocks it will interact via an external shock with the surrounding medium. This shock will produce the afterglow - a signal that will follow the GRB. The idea of an afterglow in other wavelengths was suggested earlier \[1\] but it was suggested as a follow up of the, then standard, external shock scenario. In this case the afterglow would have been a direct continuation of the GRB activity and its properties would have scaled directly to the properties of the GRB.

According to internal-external model (internal shocks for the GRB and external shocks for the afterglow) different mechanisms produce the GRB and the afterglow. Therefore the afterglow should not be scaled directly to the properties of the GRB. This was in fact seen in the recent afterglow observations. In all models of external shocks the observed time satisfy \( t \propto R/\gamma_e^2 \) and the typical frequency satisfy \( \nu \propto \gamma_e^4 \). Since most of the emission takes place at practically the same radius and all that we see is the variation of the Lorentz factor we expect quite generally \[10\]: \( \nu \propto t^{2+\epsilon} \).

The small parameter \( \epsilon \) reflects the variation of the radius and it depends on the specific assumptions made in the model. We would expect that \( t_e/t_\gamma \sim 50 \) and \( t_{opt}/t_\gamma \sim 300 \). The observations of GRB970508 show that \( (t_{opt}/t_\gamma)_{observed} \approx 10^4 \). This is in a clear disagreement with the single external shock model for both the GRB and the afterglow.

6. Afterglow Models

Afterglow observations agree qualitatively with the synchrotron cooling from a slowing down relativistic shell model \[3\]. In all these models the shell is expanding, collecting more external matter and slowing down. The Lorentz factor of the shell decreases and this leads to a decrease in the typical synchrotron frequency. The shock front accelerated the electrons to some power law distribution and these electrons cool via synchrotron (or Inverse Compton) emission. There are several variants to the basic model. These include adiabatic vs. radiative hydrodynamics, fast vs. slow cooling of the shock heated electrons and synchrotron vs. synchrotron-self Compton emission. Not all combinations are self consistent. For example, radiative hydrodynamics occurs if the energy extracted by the radiating electrons influences the hydrodynamics evolution of the shell. Clearly, radiative hydrodynamics is incompatible with slow cooling in which the electrons cooling time scale is longer than the hydrodynamics time scale. So far there is no single clear model that fits quantitatively all the afterglow data.

7. The “Inner Engine”

The fireball model is based on an “inner engine” that supplies the energy and accelerate the baryons. This “engine” is well hidden from direct observations and it is impossible to determine what is it from current observations. Unfortunately, the discovery of afterglow does not shed an additional light on this issue. For a long time the only direct clues that existed on the nature of the “inner engine” were the rate and the energy output. It should be active at a rate of about one per 10\(^6\) years per galaxy, as this is the observed rate of GRBs \[7\] and it should be capable of generating \( \sim 10^{52} \) ergs. Even these limits are not strict as an uncertainty in the beaming angle, \( \theta \), of the bursts leads to an uncertainty of order \( 4\pi/\theta^2 \) in the rate and in the total energy involved.

The inner engine should be also capable of accelerating \( \sim 10^{-7} m_\odot \) to relativistic energies. The need to convert the energy to a relativistic flow is rather difficult to fulfill as it requires a “clean” system with a very low baryonic load.

The recent realization that energy conversion process is most likely via internal shock rather than via external shocks provides additional information about the inner engine. According to this model the relativistic flow must be irregular (to produce the internal shocks), it must be variable on a short time scale (as this time scale is seen in the variability of the bursts), and it must be active for up to a few hundred seconds - as this duration determines the observed duration of the burst. These requirements rule out all explosive models. The engine must be compact (\( \sim 10^7 \) cm)
to produce the observed variability and it must operate for a few hundred seconds (million times larger than the light crossing time) to produce a few hundred seconds signals.

8. Neutron Star Mergers

Binary neutron star mergers (NS²Ms) 24 (or with a small variant: neutron star-black hole mergers) are, in my mind the best candidate for the “inner engine”. These mergers take place because of the decay of the binary orbits due to gravitational radiation emission. Pulsar observations suggest that NS²Ms take place at a rate of $\approx 10^{-6}$ events per year per galaxy 14,15, in amazing agreement with the GRB event rate 16. It has been suggested 13 that many neutron star binaries are born with very close orbits and hence with very short lifetimes. If this idea is correct, then the merger rate will be much higher. This will destroy, of course, the nice agreement between the rates of GRBs and NS²Ms. Consistency can be restored if we invoke beaming, which might even be advantageous for some models. The short lifetime of those systems, which is the essence of this idea, makes it impossible to confirm or rule out this speculation.

NS²Ms result, most likely, in rotating black holes 14. The process releases $\approx 5 \times 10^{51}$ ergs 14. Most of this energy escapes as neutrinos and gravitational radiation, but a small fraction of this energy suffices to power a GRB. The observed rate of NS²Ms is similar to the observed rate of GRBs. This is not a lot - but this is more than can be said, at present, about any other GRB model.

9. Implications to Underground Physics

Even though GRBs can be detected only by satellites traveling outside the atmosphere this phenomenon has several important implications to other branches of physics and in particular to underground physics. This is not surprising in view of the unique character of the fireball model that involves relativistic motion of a significant amount of particles. I will discuss some of these implications now.

It is quite likely that in addition to $\gamma$-rays other particles, denoted $x$, are emitted in these events. Let $f_{x-\gamma}$ be the ratio of energy emitted in these other particles relative to $\gamma$-rays\footnote{I assume in the following that the $\gamma$-rays from the GRB and the $x$ particles have the same angular distribution. This is a reasonable assumption if both are produced by the fireball’s shocks. It might not be the case if the $x$ particles are produced by the “inner engine”. A modification that takes care of this correction is trivial.}. These particles will appear as a burst accompanying the GRB. The total fluence of a “typical” GRB observed by BATSE, $F_{\gamma}$ is $10^{-7}$ ergs/cm², and the fluence of a “strong” burst is about hundred times larger. Therefore we should expect accompanying bursts with typical fluences of:

$$F_{x \text{ [prompt]}} = 0.001 \text{particles/cm}^2 f_{x-\gamma} \times \left(\frac{F_{\gamma}}{10^7 \text{ergs/cm}^2}\right)\left(\frac{E_x}{\text{GeV}}\right)^{-1}$$

where $E_x$ is the energy of our particles. This burst will be spread in time and delayed relative to the GRB if the particles do not move at the speed of light. Relativistic time delay will be significant (larger than 10 seconds) if the particles are not massless and their Lorentz factor is smaller than $10^8$. Similarly a deflection angle of $10^{-8}$ will cause a significant time delay.

In addition to the prompt burst we should expect a continuous background of these particles. With one $10^{51}$ ergs GRB per $10^6$ years per galaxy we expect $\sim 10^4$ events per galaxy in a Hubble time (provided of course that the event rate is constant in time). This will correspond to a background flux of

$$F_{x \text{ [background]}} = 3 \times 10^{-8} \text{particles/cm}^2\text{sec} f_{x-\gamma} \times \left(\frac{E_x}{10^{51} \text{ergs}}\right)\left(\frac{R}{10^{-8} \text{years/galaxy}}\right)\left(\frac{E_x}{\text{GeV}}\right)^{-1}.$$

For any specific particle that could be produced one should calculate the ratio $f_{x-\gamma}$ and then compare the expected fluxes with fluxes from other sources and with the capabilities of current detectors.

One should distinguish between two types of predictions: (i) Predictions of the generic fireball model which include low energy cosmic rays 15.
UCHERs \[16,15\] and high energy neutrinos \[18\].

(ii) Predictions of specific models and in particular the NS\(^2\)M model, which include bursts of low energy neutrinos \[15\] and gravitational waves.

9.1. Cosmic Rays

Already in 1990, Shemi & Piran \[37\] pointed out that fireball model is closely related to Cosmic Rays. A “standard” fireball model involved the acceleration of \(\sim 10^{-7}M_\odot\) of baryons to a typical energy of 100GeV per baryon. Protons that leak out of the fireball will become low energy cosmic rays. However, a comparison of the GRB rate (one per \(10^6\) years per galaxy) with the observed flux of low energy cosmic rays, suggests that even if \(f_{\text{CR}} - \gamma \approx 1\) this will amount only to 1% to 10% of the observed cosmic ray flux at these energies. Cosmic rays are believed to be produced by SNRs. Since supernovae are ten thousand times more frequent than GRBs, unless GRBs are much more efficient in producing Cosmic Rays in some specific energy range their contribution will be swamped by the SNR contribution.

9.2. UCHERs - Ultra High Energy Cosmic Rays

Waxman \[16\] and Vietri \[17\] have shown that the observed flux of UCHERs (above \(10^{19}\)eV) is consistent with the idea that these are produced by the fireball shocks provided that \(f_{\text{UCHERs}} - \gamma \approx 1\). SNR cannot not produce such a high energy particles, while the relativistic shocks of the fireball might be capable of doing that. Waxman \[19\] has shown that the spectrum of UCHERs is consistent with the expected from Fermi acceleration within those shocks. An advantage of this source over other sources is that it is intrinsically optically thin and the density of photons at the source that could interact with the UCHERs and slow them down is rather low.

9.3. High Energy Neutrinos

Waxman and Bahcall \[18\] suggested that collisions between protons and photons within the relativistic fireball shocks produce pions. These pions produce high energy neutrinos with \(E_\nu \sim 10^{13}\)eV and \(f_{\text{high energy} \nu - \gamma} > 0.1\). The flux of these neutrinos is comparable to the flux of atmospheric neutrinos but those will be correlated with the position of strong GRBs. This signal might be detected in future km\(^2\) size neutrino detectors.

9.4. Gravitational Waves

If GRBs are associated with NS\(^2\)Ms then they will be associated with gravitational waves and low energy neutrinos. The spiraling in phase of a NS\(^2\)M produces a clean chirping gravitational radiation signal. This signal is the prime target of LIGO and VIRGO, the two large interferometers that are build now in the USA and in Europe \[50\]. The observational scheme of these detectors is heavily dependent on digging deeply into the noise. Kochaneck & Piran \[51\] suggested that coincidence with a GRB could enhance greatly the statistical significance of detection of a gravitational radiation signal. It will also verify at the same time this model.

9.5. Low Energy Neutrinos

Most of the energy released in a NS\(^2\)M will be released as low energy (\(\sim 5 - 10\)MeV neutrinos \[45\]). The total energy is quite large \(\sim a \times 10^{53}\)ergs, leading to \(f_{\text{low energy} \nu - \gamma} \approx 100\). However, this neutrino signal will be quite similar to a supernova neutrino signal - which can be detected at present only if it is galactic. Supernovae are ten thousand times more frequent then GRBs and therefore NS\(^2\)M neutrinos constitute an insignificant contribution to the background at this energy range.

10. Concluding Remarks

After thirty years we are finally beginning to understand the nature of GRBs. The discovery of the afterglow has demonstrated that we are on the right track, at least as far as the \(\gamma\)-ray producing regions are concerned. This by itself have some fascinating implications on accompanying UCHER and high energy neutrino signals. However, we are still uncertain what are the engines that power the whole phenomenon. My personal impression is that binary neutron mergers are the best candidates. This model has one specific prediction - a correlation between GRBs and gravitational radiation signals. This would con-
firm or rule out this model next decade when the next generation of gravitational radiation detectors will begin to operate.

I thank E. Cohen, J. Katz, S. Kobayashi, R. Narayan, and R. Sari for helpful discussions. This work was supported by the US-Israel BSF grant 95-328 and by NASA grant NAG5-3516.

REFERENCES

1. Klebesadel, R. W., Strong, I. B., & Olson, R. A. 1973, Ap. J. Lett., 182, L85.
2. Costa, E., et al., 1997, Nature, 387, 783.
3. van Paradijs, J., et al., 1997, Nature, 386, 686.
4. Bond, H. E., 1997, IAU circ. 6655.
5. Frail, D., A., et al., 1997, Nature, 389, 261.
6. Metzger, M., R., et al., 1997, Nature, 387, 878.
7. Piran, T. 1992, Ap. J. Lett., 382, L45.
8. Piran, T., 1996, in Unsolved Problems in Astrophysics Eds. Bahcall, J. N., and Ostriker, J. P., Princeton University Press, 343.
9. Paczyński, B. and Rhodas, J., 1993, Ap. J., 418, L5.
10. Katz, J. I., 1994, Ap. J., 422, 248.
11. Sari, R., & Piran, T., 1997, Ap. J., 485, 270.
12. Mészáros, P., & Rees, M. J. 1997, Ap. J., 476, 232.
13. Wijers, A. M. J., Rees, M. J., & Mészáros, P., 1997, MNRAS, 288, L5.
14. Waxman, E., 1997, Ap. J. Lett. 485, L9.
15. Vietri, M., 1997, Ap. J. Lett. 478, L9.
16. Katz, J. I., & Piran, T., 1997, Ap. J., 490, 772.
17. Mészáros, P., Rees, M. J., & Wijers, A. M. J., 1997, astro-ph/9709273.
18. Mészáros, P., & Rees, M. J. 1992, Ap. J. Lett., 389, L3.
19. Narayan, R., Paczyński, B., & Piran, T. 1992, Ap. J. Lett., 395, L83.
20. Rees, M. J., & Mészáros, P. 1994, Ap. J. Lett., 430, L93.
21. Piran, T., & Sari, R., 1997, to appear in the Proc. 18th Texas Symp, in Press.
22. Mochkovitch, R., Maitia, V., & Marques, R. 1995, in Proceeding of 29th ESLAB Symposium, eds. Bennett, K. & Winkler, C., 531.
23. Kobayashi, S., Piran, T., & Sari, R., 1997, Ap. J., 490, 92.
24. Eichler, D., Livio, M., Piran, T., & Schramm, D. N. 1989, Nature, 340, 126.
25. Katz, J., I., Piran, T., & Sari, R., 1997, Phys. Rev. Lett., in press.
26. Fishman G. J., et al., 1993, A&A Supp, 97, 17.
27. Klebesadel R., Laros J. & Fenimore E. E., 1984, BAAS, 16, 1016.
28. Hurley, K., et al. 1994, Nature, 372, 652.
29. Dingus, B., et al., 1997, in The 4th Huntsville Meeting.
30. Sahu, K., et al., 1997, Nature 387, 476.
31. Galama, T., J., et al., 1997, Nature, 387, 497.
32. Sokolov, V. V., et al., 1997, in The 4th Huntsville Meeting.
33. Goodman, J., 1997, New Astronomy, 2, 449.
34. Goodman, J. 1986, Ap. J. Lett., 308, L47.
35. Paczyński, B. 1986, Ap. J. Lett., 308, L51.
36. Krolik, J. H., & Pier, E. A. 1991, Ap. J., 373, 277.
37. Shemi, A., & Piran, T. 1990, Ap. J. Lett., 365, L55.
38. Cohen, E. et al., 1997, Ap. J., 488, 330.
39. Fennimore, E. E., Madras, C., & Nayakshin, S. 1996, Ap. J. 473, 998.
40. Sari, R., & Piran, T., 1997, MNRAS, 287, 110.
41. Narayan, R., Piran, T., & Shemi, A. 1991, Ap. J. Lett., 379, L1.
42. Phinney, E. S. 1991, Ap. J. Lett., 380, L17.
43. Tutukov, A. V., & Yungelson, L. R. 1994, MNRAS, 268, 871.
44. Davies, M. B., Benz, W., Piran, T., & Thielemann, F. K. 1994, ApJ, 431, 742.
45. Clark, J. P. A., & Eardley, D. 1977, ApJ, 215, 311.
46. Waxman, E., 1995 Ap. J. Lett., 452, 1.
47. Vietri, M., 1995, Ap. J., 453, 883.
48. Waxman, E., & Bahcall, J. N., 1997, Phys. Rev. Lett., 78, 2292.
49. Waxman, E., 1995 Phys. Rev. Lett., 75, 386.
50. Abramovichi, A., et al., 1992, Science, 256, 325.
51. Kochanek C. & Piran, T., 1993, Ap. J. Lett., 417, L17.