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Neutrino emission from gamma-ray bursts

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Abstract.

Gamma-ray bursts (GRBs) are the most violent and energetic events in the universe. Short GRBs seem to be the result of the final merger of two compact objects, whereas long GRBs are probably associated with the gravitational collapse of very massive stars (*collapsars*).

The central engine of a GRB can collimate relativistic jets, where shocks are produced and particles can be accelerated. Although the exact location of the region where the gamma rays are created is still under debate, it is widely accepted that the prompt emission has a different origin from the afterglow. The latter is emitted at a much greater distance from the central engine, when the fireball is decelerated by its interaction with the interstellar medium.

It seems reasonable to assume that if the prompt gamma-ray radiation and the afterglows are generated by relativistic electrons accelerated in shocks, then the same shocks should also accelerate baryons. These high-energy protons can produce neutrinos through pp inelastic collisions and $p\gamma$ interactions, making GRBs candidates to be sources of high-energy neutrinos.

In this review, I discuss different scenarios where high-energy neutrinos (GeV-EeV) can be generated.

1. Introduction

Gamma-ray bursts (GRBs) are the most energetic explosions known to occur in the universe since the Big Bang. The initial prompt phase can last from milliseconds to several tenths of seconds, and in this short time an energy of $\sim 10^{53}$ ergs is released (e.g., Piran, 2000; Mészáros, 2002). The peak of the spectra is in the gamma-ray band (100 keV $< E <$ MeV), hence the name of these sources.

The first event was detected in July 2, 1967, by the satellites of a military program called Vela. These satellites were built by the United States to detect gamma radiation pulses emitted by possible nuclear weapon tests in space.[1] Since the features of these bursts were unlike any known nuclear weapon, its origin was a mistery, and their existence was kept as a secret for more than 6 years. Finally, in 1973, a team at Los Alamos Scientific Laboratory, led by Ray Klebesadel, rejected the possibility of these bursts being produced within the Solar System. The observations of the new gamma ray

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[1] The *Partial Test Ban Treaty* signed in 1963, banned all nuclear testing on space, underwater and atmosphere. All testing was to be driven underground.

sources, which were called Gamma-ray bursts, were then published (Klebesadel et al., 1973).

For almost 20 years little progress was made in the understanding of the origin, until 1991, when the Compton Gamma Ray Observatory was launched. The observatory was equipped with the instrument BATSE (*Burst and Transient Source Explorer*), a sensitive gamma-ray detector, designed for detecting transient events. In the 9 years of the mission, BATSE registered more than 2700 events, an average of one gamma-ray burst event per day (Paciesas et al., 1999).

This instrument provided crucial data regarding the origin of GRBs. The bursts distribute isotropically on the sky, a fact that indicates an extragalactic origin.

The first afterglow in X-rays was found in 1997, by the Italian-Dutch X-ray astronomy satellite BeppoSAX. A few months later, the first optical spectrum was measured, rendering a determination of the host galaxy redshift. This detection finally confirmed that GRBs have an extragalactic origin. The host galaxies of several long bursts were found to have typical redshifts $z = 1 - 2$, which means that those GRBs occurred on very distant galaxies.

Once the GRB distance scale was identified, a new conundrum arised: what is the central engine of GRBs that is capable of generating more than 10^{50} ergs? The Swift observatory and the Fermi Gamma-ray Space Telescope are the missions that have helped unveiling the enigma.

Swift was launched in 2004 and is still operational. Swift is the first gamma-ray observatory designed with GRBs as the main target. It is equipped with the Burst Alert Telescope (BAT), which is a very sensitive gamma-ray detector, capable of localizing a burst with arcmin accuracy within a few seconds. It also has on board the X-ray Telescope (XRT) and the Ultraviolet/Optical Telescope (UVOT), both dedicated to study the afterglow emission.

The Fermi Gamma-ray Space Telescope was launched in 2008. One of its two main instruments is the Gamma-ray Burst Monitor (GBM); it can localize a burst with 10−degree accuracy, and has been detecting GRBs at a rate of ~ 300 per year (Gehrels et al., 2009).

These instruments have provided precise observations of hundreds of bursts, and have been crucial to understand many aspects of these sources.

The main topic of this article is the neutrino emission from GRBs; nevertheless, a basic discussion on GRB physics is presented in the first two sections. For more details and a complete discussion on phenomenology and theory of GRBs see, e.g., Zhang & Mészáros (2004), Gehrels et al. (2009) and Zhang & Kumar (2013).

2. Classification

There is a great variety of light curves of GRBs, unlike other transient sources (e.g., novas, supernovas, etc). Several categories of GRBs can be found depending on the property used as classifier. The historical classification is made considering the duration of the prompt emission, and leads to two populations of bursts: one with an average duration of ~ 0.3 s, and the other centered around ~ 30 s (see Fig. 1). Although there is a significant overlapping region where it is not clear to which category the events belong, short and long GRBs are the standard categories.

The classification in long and short relates to two different progenitors. Long GRBs make approximately 75% of the bursts. The study of long GRB afterglows shows

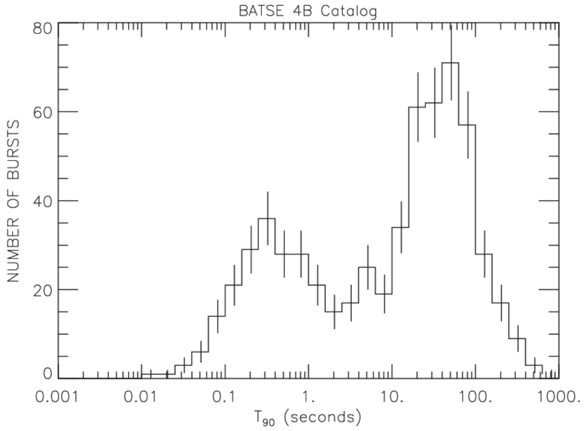

Figure 1. Duration of the bursts detected by BATSE, using a duration parameter $T90$ defined as the time over which a burst emits from 5% of its total measured counts to 95% (Paciesas et al., 1999).

that they take place in galaxies with high stellar formation rates. In addition, ~ 36 of these bursts have been associated with core-collapse supernova, which provides the best evidence that long GRBs are related to the deaths of massive stars (Hjorth & Bloom, 2012).

The first afterglow of a short GRB was detected by Swift in 2005, eight years later than the long counterpart. This is due to short GRB afterglows being fainter than long GRB afterglows, and also because short GRBs account only for about 25% of gamma-ray bursts.

Few host galaxies of short GRBs have been identified, and they are usually found to be elliptical galaxies with low stellar formation rate. There has been no association with supernovae and, consequently, these events are not linked to massive stars. The origin of short GRBs is related to the merger of two compact objects. Using numerical simulations Rezzolla et al. (2011) showed that colliding neutron stars form a rapidly spinning black hole surrounded by a hot and highly magnetized torus.

3. Theoretical models

There are at least three basic conditions that any GRB model should fulfill:

- *Energetics*: considering that GRBs occur at cosmological distances, any model should be able to account for an equivalent isotropic energy of 10^{53} ergs.

- *Size of the emitting region*: since the temporal scales of variability are very short (~ 10 ms), then the emitting region should be compact.

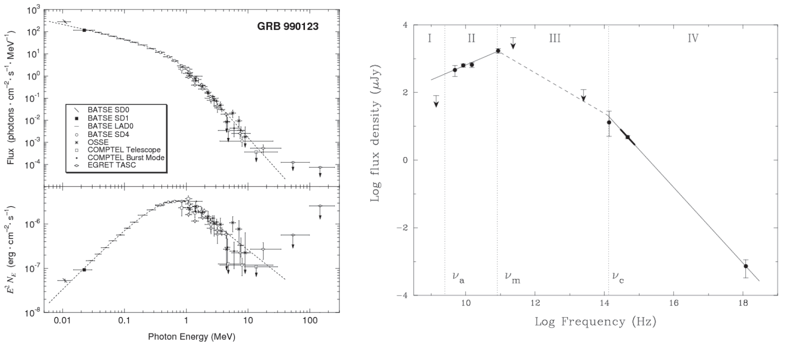

Figure 2. *Left:* Spectrum of the prompt emission of GRB 990123 detected by BATSE (Briggs et al., 1999). *Right:* Spectrum of the afterglow of GRB 970508 (Mészáros, 1999).

- *Radiation mechanism*: the prompt emission as well as the afterglow components are non-thermal (see Fig. 2), implying the presence of relativistic particles. These sources, then, should be able to accelerate particles up to relativistic energies.

These requirements can be achieved by invoking relativistic motions. If the emitting region were static, the gamma-rays should have been attenuated in the source by photo-pair production. This is known as the *compactness problem*. To ease this problem, a first ingredient of theoretical models is that the regions where the prompt and afterglow emission are produced must be moving relativistically in the direction of the observer (see Zhang & Mészáros 2004 for a detailed discussion of the compactness problem).

The typical Lorentz factor required to satisfy the observations is of the order of ~ 100. Relativistic jets in AGNs have Lorentz factors $\Gamma \lesssim 30$. GRBs present the fastest known bulk motions in the universe.

One of the most discussed models is the *standard fireball model*, which, until a few years ago, had been very successful describing many characteristic and predicting several features of GRB light curves and spectra. In this model, a central engine powered by accretion -the collapse of the nucleus of a massive star in the case of long GRBs, or the merger of two compact objects for short GRBs- launches a fireball shell. As the fireball propagates, internal shocks are produced by collisions between different shells. In these shocks, particles are accelerated up to relativistic energies in the flow co-moving frame and produce the prompt emission. The fireball shell is eventually decelerated by the interstellar medium, and external shocks are produced. Whereas the broad-band afterglow radiation is usually explained as the result of synchrotron radiation of electrons accelerated in the external shocks, there is still an open debate on what is the mechanism responsible of the non-thermal emission in the prompt phase, i.e., synchrotron or inverse Compton scattering.

With the advent of Swift and Fermi, however, many unexpected properties have been found. Some of these properties, such as afterglow light curves with plateau structure, X-ray flares found at both early and late times, optical flashes too variable or long lasting prompt emission, cannot be explained by the standard fireball model, and alternative options are being explored.

Among the new models, we can mention models where the jet is magnetically dominated; in this case, the magnetic field is dragged from the highly magnetized central engine to the surface of the progenitor star of long GRBs. Internal shocks cannot be produced in magnetically dominated environments, so, in this context, the particle acceleration may be caused by dissipation of the strong magnetic fields and fast reconnection (Woosley, 1993; Komissarov et al., 2009).

4. Neutrino emission

GRBs can also be sources of three important non-electromagnetic signals: gravitational waves, cosmic rays, and neutrinos.

High-energy neutrinos are of particular interest, since the IceCube collaboration has recently reported the observation of 28 events, including the highest energy neutrinos ever observed, with energies in excess of 1 PeV (Aartsen et al., 2013; IceCube Collaboration, 2013). GRBs are among the best candidates to be the sources of them.

GRB models involving shocks as sites to accelerate electrons which produce prompt gamma-rays and long-term afterglows, naturally suggest that baryons should be accelerated by the same shocks as well. These accelerated protons would interact with photons and other baryons to produce high-energy neutrinos that might be detected from Earth.

In a GRB event, there are multiple sites where neutrinos with different energies are generated. There is a large peak in the photo-meson production cross-section at photon energies $E_\gamma \sim 0.35$ MeV in the proton rest frame, due to the Δ-resonance (Stecker, 1973). Most of the contribution to neutrino production comes through this channel. The condition that a proton must fulfill to create pions is (Zhang & Kumar, 2013):

$$E_p E_\gamma \sim 0.147\ \mathrm{GeV}^2 \Big(\frac{\Gamma}{1+z}\Big)^2, \tag{1}$$

where z is the redshift. Neutrinos produced in $p\gamma$ interactions have energies of $E_\nu \simeq 0.05 E_p$.

Several models have been devoted to study the neutrino emission from different regions of the fireball; in what follows, some of them are briefly discussed.

4.1. Neutrinos in internal shocks

The photons produced inside the internal shocks within the fireball have typical energies around 1 MeV. For a Lorentz factor of $\Gamma = 100$, the characteristic proton energies for photomeson production are 10^6 GeV. Then, photomeson interactions in internal shocks result in the production of neutrinos with $E \sim 10^{14}$ eV.

It has been recently shown by Reynoso (2014) that interactions in internal shocks can also lead to the production of PeV neutrinos. They consider a two-zone model (see also Winter et al. 2014), with an acceleration region and a cooling zone. The relation between these regions is quantified as

$$t_{\mathrm{esc}}^{-1}(E_i) = \psi_{\mathrm{esc}} t_{\mathrm{acc}}^{-1}(E_i), \tag{2}$$

where t_{esc}^{-1} and t_{acc}^{-1} are the escape and acceleration rates, respectively. Under this assumption, the value of the parameter ψ_{esc} is related to the energy dependence of the

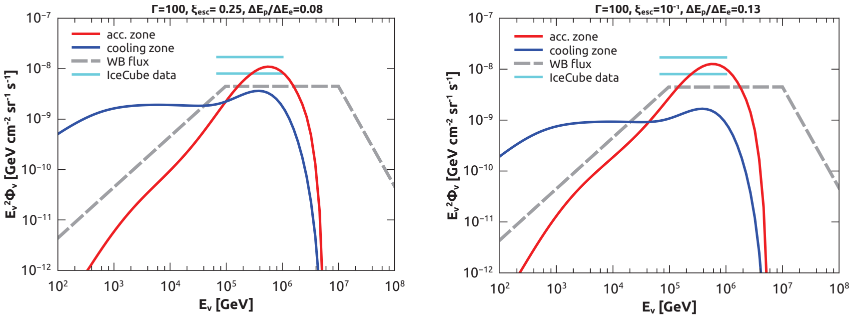

Figure 3. Diffuse flux of muon neutrinos for $\psi_{\rm esc} = 0.25$ and $\psi_{\rm esc} = 0.1$ in the left and right panels, respectively. The contribution from the acceleration zone is marked in red and the one from the cooling zone in blue. From Reynoso (2014).

particle distributions (e.g., Protheroe, 1999). The primary target for $p\gamma$ interactions are the synchrotron photons of the prompt emission. The diffuse neutrino flux is computed, and it is obtained that it can reach the level of the signal recently detected by IceCube (see Fig. 3).

For long GRBs, a different kind of internal shocks are expected in the jet interior, as a result of the propagation of the jet inside the progenitor stars. In these shocks TeV neutrinos can also be produced by photohadronic interactions. The neutrino signal is of significant relevance for the so-called *chocked* GRBs, produced when the jet is unable to break the stellar surface and produced an observable GRB (Mészáros & Waxman, 2001; Horiuchi & Ando, 2008). For these events, the neutrino emission may be the only detectable signal.

4.2. Neutrinos in external shocks

External shocks are produced when the fireball of a GRB is decelerated by the surrounding medium: a forward shock propagates over the interstellar medium, and a reverse shock propagates backward, inside the fireball. Photons produced in the GRB afterglow have energies from X-ray to the optical band. Then, photohadronic interactions in the external shocks would result in the production of TeV-PeV-EeV neutrinos (e.g., Waxman & Bahcall, 2000; Dai & Lu, 2001; Razzaque et al., 2004). In particular, in the standard afterglow model the reverse shock emission is thought to be responsible for the optical flash. Since protons can be accelerated up to $\sim 10^{20}$ eV in external shocks (Gallant & Achterberg, 1999), photohadronic interactions of these ultra-high energy protons with optical photons allows PeV-EeV neutrino production.

4.3. Neutrinos in different scenarios

Given that the standard internal shock model has been lately under discussion, different scenarios are being explored. In this regard, Gao et al. (2012) studied the neutrino emission in GRBs where the prompt emission is generated in a dissipative jet, instead of being produced in internal shocks. They explored two possibilities, baryonically or magnetically dominated dynamics.

Another example is the work by Gao & Mészáros (2012), in which they estimated the neutrino flux as a result of nuclear collisions in magnetized GRBs. They obtained a significant flux of GeV neutrinos. Murase et al. (2013), on the other hand, studied the production of GeV neutrinos in outflows loaded with neutrons, in which nuclear reactions result in subphotospheric gamma rays that can explain the prompt emission.

A different model has been proposed by Vieyro et al. (2013) in which TeV neutrinos are produced by hadronic interactions in the lateral shocks formed near the stellar surface, when the jet erupts from the star. In this work, they consider the effects of standard neutrino oscillations, and of neutrino spin-flavor precession. The latter is the result of a minimal extension of the Standard Model and was proposed by Akhmedov & Pulido (2002) as a secondary mechanism responsible for the deficit of solar electron neutrinos. The number of muon events estimated for the reverse shock region in this model is comparable with the atmospheric muon events detected by IceCube (Abbasi et al., 2011). Then, a multiyear integration might result in a detectable flux.

4.4. Constraining theoretical models

The study of GRBs as sources of high-energy neutrinos can help us to put constrains to the microphysics of GRBs (Zhang & Kumar, 2013). It is worth mentioning, as an example, the work by Gao et al. (2013), in which the implications of the non-detection of neutrinos from the burst GRB 130427A are discussed.

They first use a general model to put constrains on the dissipation radius, the bulk Lorentz factor and the composition of the jet. Figure 4 shows a density plot of the expected number of neutrino events for the burst GRB 130427A. The contours indicates the regions where one event is expected, for different values of the parameters ϵ_p, ϵ_e and ϵ_B; these quantities represent the fraction of the total energy of the jet that is dissipated and carried by protons, leptons and turbulent magnetic fields, respectively.

They also apply an internal shock model and a baryonic model to this burst, and obtained limits for the relevant parameters of each model. The most strict restrictions are found for the magnetic photospheric model, where a value of $\epsilon_p/\epsilon_e \sim 2$ is obtained, independently of Γ. The internal shock and the baryonic photosphere models are barely constrained by the absence of neutrino detection.

5. Summary and discussion

GRBs are currently regarded by many as the top potential high-energy neutrino sources. Several models of neutrino emission in GRBs predict detectable neutrino levels at different energies.

Current upper limits set by IceCube, however, have already ruled out the validity of some of these models and their predictions (Desiati et al., 2012). The upper limit obtained with the data collected with the 59-string configuration of IceCube is 3.7 times below some theoretical predictions.

This overestimation of the neutrino fluxes may be the result of several simplifications in the treatment of physical processes. On the one hand, many of these works do not consider the energy dependence of particle distribution, but instead only the energy budget is analysed. Hümmer et al. (2010) discussed the importance of considering the energy dependence, and they found that the normalization of the expected neutrino flux is reduced up to one order of magnitude, and the spectrum shifts to higher energies (see also Hümmer et al. 2012).

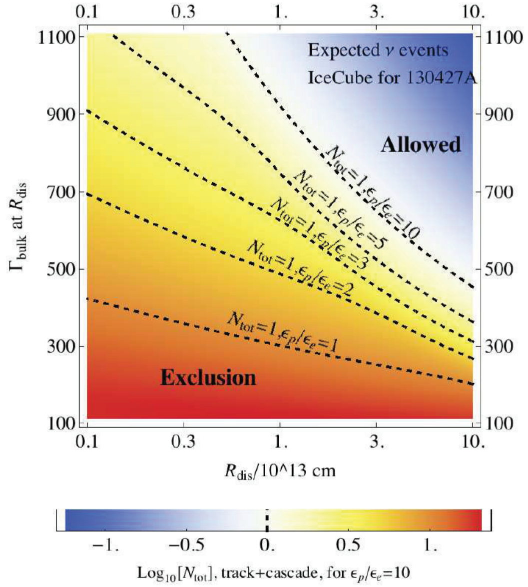

Figure 4. Map of the expected neutrino events in IceCube for GRB 130427A. Here, $\epsilon_e = 0.1$ and $\epsilon_B = 0.01$. From Gao et al. (2013).

On the other hand, the effects of magnetic field on the cooling of secondary particles cannot be neglected, since the GRB environments usually present large magnetic fields, hence synchrotron losses are significant (Li et al., 1996; Reynoso & Romero, 2009; Hümmer et al., 2012).

There are some current studies where the effects mentioned above are considered; these models predict neutrinos fluxes that might be detected by Ice Cube. With the recent completion of IceCube and the increment of the data, the study of neutrino emission might help shed light on some of the most important uncertainties in the study of GRBs, as the role of magnetic fields in the jet dynamic, and the content and composition of the fireball.

Recent works by Mészáros & Rees (2010); Gao et al. (2011); Berezinsky & Blasi (2012); Vieyro et al. (2013) have extended the calculations of neutrino emission to Population III GRBs. These stars are supposed to have been very massive, and accretion onto massive black holes (tenths of solar masses) might lead to a scaled-up collapsar gamma-ray burst (Mészáros & Rees, 2010). These events are of particular cosmological interest, since they are related to the first stars formed in the universe, and they can be used to study the universe in the re-ionization era.

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References

Aartsen, M. G., Abbasi, R., Abdou, Y., et al. 2013, Phys. Rev. Lett., 111, 021103

Abbasi, R., Abdou, Y., Abu-Zayyad, T., et al. 2011, Phys. Rev. D, 83, 012001

Akhmedov, E. K. & Pulido, J. 2002, Physics Letters B, 529, 193

Berezinsky, V. & Blasi, P. 2012, Phys. Rev. D, 85, 123003

Briggs, M. S., Band, D. L., Kippen, R. M., et al. 1999, ApJ, 524, 82

Dai, Z. G. & Lu, T. 2001, ApJ, 551, 249

Desiati, P., Abbasi, R., Abdou, Y., et al. 2012, Proceedings for the XIV Vulcano Workshop, Vulcano (ME), Italy

Gallant, Y. A. & Achterberg, A. 1999, MNRAS, 305, L6-L10

Gao, S., Asano, K., & Mészáros, P. 2012, J. of Cosm. and Astrop. Phys., 11, 58

Gao, S., Kashiyama, K., & Meszaros, P. 2013, ApJ, 772, 1, L4

Gao, S. & Mészáros, P. 2012, Phys. Rev. D, 85, 103009

Gao, S., Toma, K., & Mészáros, P. 2011, Phys. Rev. D, 83, 103004

Gehrels, N., Ramirez-Ruiz, E., & Fox, D. B. 2009, ARA&A, 47, 567

Hjorth, J. & Bloom, J. S. 2012, in Gamma-Ray Bursts, C. Kouveliotou, R. A. M. J. Wijers and S. Woosley (eds.), Cambridge Astrophysics Series 51, Cambridge University Press, Cambridge, UK

Horiuchi, S. & Ando, S. 2008, Phys. Rev. D, 77, 063007

Hümmer, S., Baerwald, P., & Winter, W. 2012, Phys. Rev. Lett., 108, 231101

Hümmer, S., Maltoni, M., Winter, W., & Yaguna, C. 2010, Astroparticle Physics, 34, 205

IceCube Collaboration, 2013, Science, 342

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

Komissarov, S. S., Vlahakis, N., Königl, A., & Barkov, M. V. 2009, MNRAS, 394, 1182

Li, H., Kusunose, M., & Liang, E. P. 1996, ApJ, 460, L29

Mészáros, P. 1999, A&AS, 138, 533

Mészáros, P. 2002, ARA&A, 40, 137

Mészáros, P. & Rees, M. J. 2010, ApJ, 715, 967

Mészáros, P. & Waxman, E. 2001, Phys. Rev. Lett., 87, 171102

Murase, K., Kashiyama, K., & Mészáros, P. 2013, Phys. Rev. Lett., 111, 131102

Paciesas, W. S., Meegan, C. A., Pendleton, G. N., et al. 1999, ApJS, 122, 465

Piran, T. 2000, Physics Reports, 333, 529

Protheroe, R. J. 1999, in Topics in Cosmic-Ray Astrophysics, M. A. Duvernois (ed.), 247

Razzaque, S., Mészáros, P., & Zhang, B. 2004, ApJ, 613, 1072

Reynoso, M. M. 2014, A&A, 564, A74

Reynoso, M. M. & Romero, G. E. 2009, A&A, 493, 1

Rezzolla, L., Giacomazzo, B., Baiotti, L., et al. 2011, ApJ, 732, L6

Stecker, F. W. 1973, Ap&SS, 20, 47

Vieyro, F. L., Romero, G. E., & Peres, O. L. G. 2013, A&A, 558, A142

von Kienlin, A. 2013, GRB Coordinates Network, 14473, 1

Waxman, E. & Bahcall, J. N. 2000, ApJ, 541, 707

Winter, W., Becker Tjus, J., & Klein, S. R. 2014, A&A, 569, A58

Woosley, S. E. 1993, ApJ, 405, 273

Zhang, B. & Kumar, P. 2013, Phys. Rev. Lett., 110, 121101

Zhang, B. & Mészáros, P. 2004, IJMP A, 19, 2385

Zhang, B. 2014, IJMP D, 1430002, 30002