Ultra-relativistic motion and efficient conversion of kinetic energy to radiation are required by gamma-ray burst (GRB) observations, yet they are difficult to simultaneously achieve. Three leading mechanisms have been proposed to explain the observed emission emanating from GRB outflows: radiation from either relativistic internal or external shocks, or thermal emission from a photosphere. Previous works were dedicated to independently treating these three mechanisms and arguing for a sole, unique origin of the prompt emission of GRBs. In contrast, herein, we first explain why all three models are valid mechanisms and that a contribution from each of them is expected in the prompt phase. Additionally, we show that a single parameter, the dimensionless entropy of the GRB outflow, determines which mechanism contributes the most to the emission. More specifically, internal shocks dominate for low values of the dimensionless entropy, external shocks for intermediate values, and finally, photospheric emission for large values. We present a unified framework for the emission mechanisms of GRBs with easily testable predictions for each process.

Key words: gamma-ray burst: general – radiation mechanisms: general – radiation mechanisms: non-thermal
of the burst, $M$ is the total baryonic mass of the outflow, and $c$ the speed of light.

First, we review all three models in their unembellished version and their main characteristics. Second, we come to the point of the paper and we show how the value of the dimensionless entropy strongly constrains all three emission mechanisms. Then, we analyze the implications and predictions of our classification on the afterglow and other GRB properties. Finally, we demonstrate how our classification can be tested against observations.

2. EMISSION MODELS

The “classical” fireball model (Paczyński 1990; Piran et al. 1993) assumes that a large quantity of energy $E_{\text{tot}} \sim 10^{53}$ erg is released by an unspecified cataclysmic event such as the death of a hyper-massive star. From the millisecond variability observed in a few GRBs (but not all, see Golkhou & Butler 2014), the origin of the outflow is constrained to within a few $10^9$ cm from the center of the progenitor. Such a large amount of energy in such a small region leads to the creation of an optically thick plasma. Due to its high thermal pressure, the outflow expands and is accelerated to relativistic speeds. The expansion can be described by two phases (Piran et al. 1993). During the initial accelerating phase, the Lorentz factor of the outflow increases proportionally to the radius, while after (eventually) reaching its limiting Lorentz factor $\Gamma \lesssim \eta$, the outflow coasts at constant velocity.

Other acceleration models based on magnetic fields are currently strongly debated in the literature (Drenkhahn & Spruit 2002; Narayan et al. 2007). However, our results can be re-parametrized to the magnetization of the outflow, which plays a comparable role to $\eta$ for the expansion dynamics. Therefore, the results are expected to be qualitatively similar.

2.1. Photospheric Model

In a photospheric model, the thermal energy is released when the outflow becomes transparent at typical radii $R_{\text{ph}} \sim 10^{10}-10^{12}$ cm; for a recent review on photospheric emission, see Vereshchagin (2014). The efficiency of the photospheric emission, assuming no dissipation, can be evaluated as the ratio of the thermal energy emitted at the photosphere $E_{\text{ph}}$ to the total energy $E_{\text{tot}}$

$$\epsilon_{\text{ph}} = \frac{E_{\text{ph}}}{E_{\text{tot}}} \sim 1 - \frac{\Gamma_{\text{ph}}}{\eta},$$

where $\Gamma_{\text{ph}}$ is the Lorentz factor at the photosphere. Therefore, a bright photosphere requires $\Gamma_{\text{ph}} \ll \eta$, implying transparency of the outflow in the initial accelerating phase or in the transition phase between accelerating and coasting phases. The limiting $\eta$ value separating photospheric emission in the acceleration phase from transparency in the coasting phase is (Rees & Mészáros 1994; Thompson 1994)

$$\eta^* = \left( \frac{\sigma_T E_{\text{tot}}}{4\pi m_p c^3 \Delta t R} \right) \frac{1}{\frac{1}{2} \frac{1}{2}} \sim 7 \times 10^2 E_{53} R_8 \frac{1}{\Delta t_5} \frac{1}{s},$$

where $R$ is the radius at which the outflow starts to accelerate, $\Delta t$ is the time the central engine remains active, $\sigma_T$ is the Thompson cross-section, and $m_p$ is the proton mass. For all parameters but $\Delta t$, which is normalized to 5 s (see below), we adopt the convention $X = 10^x X_0$, where all quantities $X$ are in cgs units. When $\eta > \eta^*$, more than half of the energy of the burst is emitted at the photosphere. Therefore, in this case, we consider that the emission from the photosphere dominates the emission of the prompt phase, regardless of which mechanism is responsible for any remaining emission. We further restrain the study to $\eta < \eta^*$ and consider the emission be dominated by photospheric emission for $\eta > \eta^*$.

In the first approximation, as soon as the outflow becomes transparent, the radiative pressure decreases abruptly, stopping the acceleration of the outflow. This implies that the kinetic energy of the blast wave above the photosphere is set by $\Gamma_{\text{ph}}$. Neglecting high-latitude effects, the duration of the photospheric emission is roughly given by the light crossing time of the outflow $\Delta t_{\text{ph}} \sim \Delta t \sim 1/c \sim$ few seconds, independent of the value of the Lorentz factor. Here $\Delta t \sim c \Delta t$ is the laboratory width of the outflow. The luminosity at the photosphere is then approximated by:

$$L_{\text{ph}} = \epsilon_{\text{ph}} \frac{E_{\text{tot}}}{\Delta t}.$$ (3)

An important assumption in this derivation is that, if dissipation occurs below the photosphere, it only amounts to a few percent of the total energy $E_{\text{tot}}$. This is in agreement with the analysis of spectra in the guise of a photospheric model; see, e.g., Ahlgren et al. (2015). In addition, it was demonstrated in Bégue & Iyani (2014) that if dissipation amounts to a large fraction of the total energy, the resulting observed photospheric peak energy would be too low (around 1 keV) to correspond to the peak energy of GRBs or to the additional blackbody component identified in some bursts (Ghirlanda et al. 2003; Ryde 2004).

2.2. Internal Shock Model

As the expanding outflow is unlikely to be steady due to small variations in the wind parameters, sections with different speeds will necessarily collide with one another. These collisions (internal shocks) convert a fraction of the kinetic energy to internal energy, which can subsequently be radiated away by accelerated electrons. The colliding sections will then form a single merged system. These collisions take place at typical radii $R_{\text{IS}} \sim 10^{14}$ cm. In this section, we follow the derivation of Daigne & Mochkovitch (1998) to obtain qualitative estimates. Assuming a steady injection mass rate and a Lorentz factor variation $\Delta \Gamma$, the Lorentz factor of the merged system after an internal shock $\Gamma_{\text{IS}}$ is (Daigne & Mészáros 2004).

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4 Here, we assume that the Compton drag is negligible, as implied by $\eta < \eta^*$; see Equations (10) and (11) of Mészáros & Rees (2000). However, if $\eta \gg \eta^*$, then the flow is still accelerated above the photosphere. See a complete discussion in Grismrud & Wasserman (1998) and Mészáros & Rees (2000). In the following we do not consider this effect, as we consider $\eta < \eta^*$.

5 This is true if high-latitude effects are neglected. They might be identified as the flux and temperature of the blackbody decreases as $F_{\text{BB}} \propto \Gamma^{-2}$; see Pe’er (2008).

6 One can imagine collisions at smaller radii even below the photosphere; see (Rees & Mészáros 2005). However, here we consider pure internal shocks as in their original definition.
\[ \eta_{\text{ES}} = \frac{E_{\text{ES}}}{E_{\text{tot}}} = \left( \frac{3}{4\pi m_p c^5 n} \right)^{\frac{1}{2}} \left( \frac{E_{\text{tot}}}{\epsilon_{\text{ES}}} \right)^{\frac{1}{3}} \]  

(8)

which is strongly dependent on \( \eta \). This timescale also corresponds to the time delay between the beginning of the photosphere-IS emissions and the peak of the ES emission.\(^7\)

In addition, the luminosity of the forward shock before \( t_{\text{ES}} \) can be expressed as (Sari 1997)

\[ L_{\text{ES}} = \xi_{\text{rad,ES}}^3 32\pi e^5 n m_p \Gamma_{\text{ES}}^3 r^2, \]  

(9)

where \( t \) is the observed time after trigger and \( \xi_{\text{rad,ES}} \) is the radiative efficiency of the external shock.

### 2.4. Thin or Thick Outflow?

The typical prompt phase duration of a long GRBs \( T_{\text{dur}} \) is on average a few tens of seconds. In the IS and PE framework, this duration is tightly associated with the light-crossing time of the outflow (Daigne & Mochkovitch 1998; Pe’er 2015)

\[ T_{\text{dur}} = \alpha \frac{1}{c} = \alpha \Delta t. \]  

(10)

Because of redshift dilution, we normalize our computation to \( \Delta t = 5 \) s,\(^8\) keeping in mind that it might be much larger.

By requiring \( f_{\text{ES}} \) to be smaller than \( \Delta t/2 \) such that photons from the prompt phase originate from all three mechanisms combined (PE, IS and ES), it follows that:

\[ \eta > \eta^1 = \left( \frac{6E_{\text{tot}}}{\pi n m_p c^2 / \Delta t} \right)^{\frac{1}{2}} \sim 6.6 \times 10^2 c^{-3/2} n_0^{-1} \Delta t_5^{-\frac{3}{2}}. \]  

(11)

Comparing \( \eta^1 \) to \( \eta^* \) gives a minimum energy for the burst such that the photosphere does not take place in the accelerating phase and the external shock peaks in the prompt phase:

\[ E_{\text{tot}} > E_a = 6.9 \times 10^{52} R_8^2 \Delta t_5^{-2} c^{-7} \text{ (erg)} \]  

(12)

The strong dependence on the parameters has to be noted. Therefore, we conclude that only very energetic bursts of total energy \( E_{\text{tot}} > \text{few } 10^{53} \text{ erg} \) can have a simultaneous emission from all three mechanisms.

It can be shown that requiring \( \eta > \eta^1 \) implies that the reverse shock is relativistic (Sari 1997). However, here we use \( f_{\text{ES}} \) as a proxy for the peak emission time of the ES. For instance, density gradients in the ISM below \( R_{\text{ES}} \) result in variability of the ES emission before \( t_{\text{ES}} \), which might also outshine the IS emission.

### 2.3. External Shock Model

Initially proposed by Rees & Mészáros (1992), external shocks were studied in detail by Chiang & Dermer (1999) and Panaitescu & Mészáros (1998). As the relativistic blast wave expands, it substantially slows at the deceleration radius

\[ R_{\text{ES}} = \left( \frac{3E_{\text{kin,IS}}}{4\pi m_p c^2 n \Gamma_{\text{IS}}^2} \right)^{\frac{1}{3}} \]  

(1)

\[ = 1.2 \times 10^{17} \frac{E_{\text{tot,SS}}}{T_{\text{SS,5}}} \epsilon^{-\frac{1}{2}} n_0^{-\frac{1}{2}} \Gamma_{\text{ES}}^{-\frac{2}{3}} \text{ (cm)} \]  

(7)

where \( n \) is the density of the interstellar medium. The last equality is obtained with \( \Gamma_{\text{IS}} = 3\eta \), implied by energy conservation. As the interaction between the outflow and the CBM develops, two shocks are created: the forward shock which expands into the CBM, and the reverse shock which collides back into the outflow. If the reverse shock is not relativistic, the emission peak time is (Sari 1997)

\[ \eta_{\text{ES}} = \frac{R_{\text{ES}}}{\Gamma_{\text{IS}} c} = \left( \frac{3}{4\pi m_p c^5 n} \right)^{\frac{1}{2}} \left( \frac{E_{\text{tot}}}{\epsilon_{\text{ES}}} \right)^{\frac{1}{3}} \]  

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It can be shown that requiring \( \eta > \eta^1 \) implies that the reverse shock is relativistic (Sari 1997). However, here we use \( f_{\text{ES}} \) as a proxy for the peak emission time of the ES. For instance, density gradients in the ISM below \( R_{\text{ES}} \) result in variability of the ES emission before \( t_{\text{ES}} \), which might also outshine the IS emission.

### 3. DOMINANT EMISSION MECHANISM FOR A GRB

We now qualitatively analyze the requirements for each emission mechanism to be the dominant process during the prompt phase of GRBs.
3.1. Case 1: IS Dominates the Prompt Emission

In a situation in which the main component of the prompt emission is due to internal shocks, because of the low efficiency of an internal shock, three conditions should be met:

1. The photospheric emission should be dim, that is to say, \( \Gamma_{ph} \approx \eta \). From the theory of photospheric emission (see, e.g., Vereshchagin 2014 for a review) lower \( \eta \) implies a smaller difference between the Lorentz factor at the photosphere and the dimensionless entropy, and also a lower brightness of the photosphere.

2. The onset of the ES should take place at late times and it should be dim. From Equations (8) and (9), it follows that \( \eta \) has to be small.

Therefore, combining the first and last points implies that \( \eta \) cannot be too large. If this condition is violated, the IS emission would be outshone by the photospheric and/or the ES emission. To estimate the value of \( \eta \) such that the luminosity of the internal shock is larger than that of the ES at the peak, we combine Equations (6), (8), and (9):

\[
\eta < \tilde{\eta} = \frac{1}{\varepsilon^2} \left( \frac{1}{8 + 3^2} \frac{\xi_{\text{rad,IS}}}{\xi_{\text{rad,ES}}} \epsilon_{\text{ES}} \right)^{\frac{3}{4}} \left( \frac{E_{\text{tot}}}{4\pi m_p c^5 n} \right)^{\frac{1}{8}} = 1.1 \times 10^2 \frac{E_{\text{ES}}^{\frac{1}{3}}}{\Delta t_{\text{ph}}^{\frac{3}{4}} n_0^{\frac{5}{3}}}.
\]

which is weakly dependent on the total energy of the burst or on the CBM density. For the numerical estimate, we choose \( \alpha = 1 \) and \( \varepsilon = 1 - \epsilon_{\text{ES}} = 0.8 \) (with such a small Lorentz factor, the photospheric emission is expected to be very dim \( \epsilon_{\text{ph}} \ll \epsilon_{\text{IS}}, \epsilon_{\text{ES}} \)). In addition, the radiative efficiency of the IS and ES are set equal: \( \xi_{\text{rad,ES}} = \xi_{\text{rad,IS}} \).

Therefore, an ES should easily outshine the emission from IS. However, with such a low Lorentz factor \( \langle \tilde{\eta} < \tilde{\eta} \rangle \), the ES emission takes place at later times, leading to a burst composed of two episodes: a precursor followed by one or several smooth pulses from the external shock at later time.

3.2. Case 2: ES Dominates the Prompt Emission

Let us now consider a situation in which the emission from the external shock dominates the prompt phase, which is only possible if \( E_{\text{tot}} > E_{\text{ES}} \); see Equation (12). For example, the prompt phase of GRB 141025A can be interpreted in the ES framework (Burgess et al. 2015). The requirements are:

1. the onset of the ES emission should be early. From Equation (8), one sees that it implies large \( \eta \).

2. finally, the photospheric emission should not be too bright, which implies that the transparency is reached in the coasting phase, or in the late transition phase, implying \( \Gamma_{ph} \lesssim \eta \).

Therefore, it follows that \( \eta \) should be large enough to produce the early onset of the afterglow, but small enough such that the transparency takes place in the coasting phase to avoid too bright of a photospheric emission \( \eta < \eta^* \).

Here, we only considered a CBM with constant density. If the density has some variations below \( R_{\text{ES}} \), a multi-peak light-curve with second-like variability is formed.

3.3. Case 3: PE the Prompt Emission

Finally, if the PE dominates the prompt emission as in GRB 090902B\(^9\) (Ryde et al. 2010), several constraints can also be obtained:

1. a bright photosphere requires the transparency to take place in the accelerating phase or in the transition regime, implying large \( \eta \) and \( \Gamma_{ph} \ll \eta \), that is to say \( \eta \sim \eta^* \).

2. Finally, a late onset of the ES is required and is obtained for low \( \Gamma_{ph} \), as implied by the requirement \( \eta > \eta^* \).

Therefore, a dominant photosphere requires an incomplete acceleration.

To conclude, we have shown here that for IS to be the dominant process, low \( \eta \) and transparency in the deep coasting phase are required. For ES, an intermediate value of \( \eta \) with the transparency reached in the coasting phase are required. Finally, a spectrum dominated by photospheric emission is obtained if transparency is reached in the accelerating phase, requiring large \( \eta \gtrsim \eta^* \). This is illustrated by a cartoon in Figure 1. We note that such results for PE and ES only were already obtained by Muccino et al. (2013), who considered the photospheric emission as a precursor of the main burst explained by an ES.

4. ADDITIONAL OBSERVATIONAL CONSTRAINTS

The classification scheme proposed here imposes several observational predictions and requirements, which are summarized in Table 1. Here we discuss in turn the temporal and spectral properties of GRBs dominated by one of the three mechanisms.

Both the PE and IS models can produce highly variable\(^10\) and complex (multiple peaks with no correlations between time and the amplitude/width of a peak) light-curves. However, the

\(^9\) Even if this burst is very unique, it perfectly fits in the classification scheme.

\(^10\) The IS model was initially proposed to explain sharp flux decreases on the millisecond timescale. Such variability is hardly achieved by PE models without fine tuning of the plasma emission at the central engine, and a more realistic variability timescale might be 0.1–1 s.
ES model cannot easily explain variability below the second timescale without fine tuning. In addition, the ES model can produce several peaks by adding density variations in the ISM. However, the duration of each episode should increase and the luminosity decay should become shallower. GRB 090618 is an example of such a burst (Zhang 2012): after a first episode lasting around 50 s, which might be associated with PE and/or IS, there are three episodes with increasing width and decreasing maximum luminosity, which can be interpreted in the ES framework.

The link between the prompt phase and the “afterglow” also sets tight constraints. Indeed a break in luminosity at the very end of the prompt phase observed by Swift cannot easily be explained by an ES, for which a shallow decay is expected (see however Dermer 2007 who proposed that the decay be explained by a strongly radiative phase triggered by a hadronic discharge). The steep decay might however be characteristic of an efficient PE or IS model and a low Lorentz factor for the blast wave after transparency and dissipation by IS, such that the ES emission is delayed to late times and its luminosity decreased.

The energy requirement to have the ES occurring simultaneously with PE or IS given by Equation (12) implies that a shallow decay of the afterglow, if due to an external shock, is correlated to large total energy \( E_{\text{tot}} \gg E_\ast \). This can easily be checked in the data and is currently under investigation.

Finally, the large difference between \( \eta^8 \) and \( \tilde{\eta} \) implies that numerous bursts should have (at least) two time-separated components in their light-curve: first the emission from the photosphere and the IS, followed by the emission of the ES.

Several constraints can also be obtained from the spectral shape of a burst. First the relative luminosity of the thermal component and the time evolution of its flux and temperature, as compared to that of the non-thermal emission, can give clues to identifying the emission mechanism. In particular, in an IS-PE model, the blackbody properties are likely to track the non-thermal flux evolution, while it should not be the case in a ES-PE model.

The rather low Lorentz factor implied if the emission originates from an IS suggests that a cut-off be present in the spectra at moderate energy of around hundreds of MeV (see Hascoët et al. 2012), while larger Lorentz factor as achieved for a dominant photosphere or ES increases the cut-off to larger energy. The presence or absence of this cut-off can be investigated with the Fermi-LAT instrument.

Finally, the modeling of the afterglow can help to constrain the efficiency of the prompt emission. Together with its spectral characteristics (specifically the identification of a blackbody), the emission mechanism might be constrained as low efficiency as expected from IS, medium from ES and high from PE.

Above, we only mentioned pure cases. However, hybrid bursts are expected to be numerous. As an example of a hybrid, several bursts with envelopes (Vetere et al. 2006) might be explained by two of the aforementioned emission mechanisms. A univocal determination relies on a detailed spectral analysis of each component separately.

5. DISCUSSION

The approach followed in this paper to determine the efficiency of each emission mechanism is simple, and more detailed computations can be done. As an example, the ES luminosity and peak energy are usually determined in the literature by introducing two additional parameters \( \epsilon_B \) and \( \epsilon_e \), which parametrize the microphysics (magnetic content and internal energy in random motion of electrons) of the shocked plasma. Precise values of these parameters are unknown, and limits are often obtained such that the emission of the forward shock is not detectable in the MeV band (Kumar & Barniol Duran 2009), which usually translates to low density \( n_0 \) and low \( \epsilon_B \). However, we note that the limits on the Lorentz factor do not change substantially with the introduction of \( \epsilon_B \) and \( \epsilon_e \), which justifies our simplified treatment.

Furthermore, our analysis of the photospheric emission is based on the identification of a blackbody. This might be hampered by sub-photospheric dissipation, i.e., below the
photosphere, which could result in strong distortion of the emerging spectrum. Examples of dissipation mechanisms are neutron decay (Beloborodov 2010), internal shocks (Rees & Mészáros 2005), or dissipation of magnetic energy (Giannios 2006).

Finally, we did not consider outflows where acceleration is powered by magnetic fields. On one hand, such outflows are challenged by observations (Bégué & Pe’er 2015; Bromberg et al. 2015). On the other hand, it might be possible that some GRB outflows might be powered by magnetic fields. Theoretically, the dynamics is parametrized by the magnetization \( \sigma = E_{\text{mag}}/Mc^2 \), where \( E_{\text{mag}} \) is the initial energy in magnetic fields. As for thermally powered outflows, \( \sigma \) plays the same role as \( \eta \). In particular, it scales the coasting Lorentz factor of the outflow. The determination of spectral and/or temporal criteria to distinguish between thermal and magnetic acceleration is the next step toward a more detailed classification of emission mechanisms of GRBs, but it is out of the scope of this paper. We also note that if the outflow is strongly magnetized, IS are very inefficient. However, the magnetic field can be dissipated at larger radii by magnetic reconnection, accelerating electrons which radiate synchrotron; see the ICMART model (Zhang & Yan 2011).

To conclude, we have studied the possibility that the three main emission mechanisms (PE, IS, ES) discussed in the literature are reliable mechanisms to explain the prompt phase of GRBs. We found that the dimensionless entropy and the corresponding Lorentz factors scales the relative luminosity of each mechanisms. The delay between each emission is also strongly increased with small Lorentz factors, which implies that bursts with several episodes (in the MeV energy band) exist. This work presents a simple attempt in classifying the emission mechanisms of GRBs.

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REFERENCES

Abbasi, R., Abdou, Y., Abu-Zayyad, T., et al. 2012, Natur, 484, 351

Ahlgren, B., Larsson, J., Nynmark, T., Ryde, F., & Pe’er, A. 2015, MNRAS, 454, 51

Bégué, D., & Ivyani, S. 2014, ApJ, 792, 42

Bégué, D., & Pe’er, A. 2015, ApJ, 802, 134

Beloborodov, A. M. 2010, MNRAS, 407, 1033

Bromberg, O., Granot, J., & Piran, T. 2015, MNRAS, 450, 1077

Burgess, J. M., Bégué, D., Ryde, F., et al. 2015, arXiv:1506.05131

Chiang, J., & Dermer, C. D. 1999, ApJ, 512, 699

Daigne, F., Bošnjak, V., & Dubus, G. 2011, A&A, 526, A110

Daigne, F., & Mochkovitch, R. 1998, MNRAS, 296, 275

Daigne, F., & Mochkovitch, R. 2002, MNRAS, 336, 1271

Dermer, C. D. 2007, ApJ, 664, 384

Drenkhahn, G., & Spruit, H. C. 2002, A&A, 391, 1141

Ghirlanda, G., Celotti, A., & Ghisellini, G. 2003, A&A, 406, 879

Giannios, D. 2006, A&A, 457, 763

Golkhou, V. Z., & Butler, N. R. 2014, ApJ, 787, 90

Goodman, J. 1986, ApJL, 308, L47

Grimsrud, O. M., & Wasserman, I. 1998, MNRAS, 300, 1158

Gruber, D., Greiner, J., von Kienlin, A., et al. 2011, A&A, 531, A20

Hascoët, R., Daigne, F., Mochkovitch, R., & Vennin, V. 2012, MNRAS, 421, 525

Iyyani, S., Ryde, F., Axelsson, M., et al. 2013, MNRAS, 433, 2739

Kobayashi, S., Piran, T., & Sari, R. 1997, ApJ, 490, 92

Kumar, P., & Banni Duran, R. 2009, MNRAS, 400, L75

Kumar, P., & Zhang, B. 2015, PRD, 91, 1

Lazzati, D., Morsony, B. J., Blackwell, C. H., & Begelman, M. C. 2012, ApJ, 750, 68

Mészáros, P. 2006, RRPh, 69, 2259

Mészáros, P., & Rees, M. J. 1993, ApJ, 405, 278

Mészáros, P., & Rees, M. J. 2000, ApJ, 530, 292

Muccino, M., Ruffini, R., Bianco, C. L., Izzo, L., & Penacchioni, A. V. 2013, ApJL, 763, 125

Narayan, R., McKinney, J. C., & Farmer, A. J. 2007, MNRAS, 375, 548

Pacyński, B. 1986, ApJL, 308, L43

Pacyński, B. 1990, ApJ, 363, 218

Panaiteascu, A., & Mészáros, F. 1998, ApJ, 492, 683

Pe’er, A. 2008, ApJ, 682, 463

Pe’er, A. 2015, AdAst, 2015, 907321

Piran, T., & Shemi, A. 1993, MNRAS, 263, 861

Rees, M. J., & Mészáros, P. 1992, MNRAS, 258, 41P

Rees, M. J., & Mészáros, P. 1994, ApJL, 430, L93

Rees, M. J., & Mészáros, P. 2005, ApJ, 628, 847

Ryde, F. 2004, ApJ, 614, 827

Ryde, F., Axelsson, M., Zhang, B. B., et al. 2010, ApJL, 709, L172

Rykov, E. S., Aharonian, F., Akerlof, C. W., et al. 2009, ApJ, 702, 489

Sari, R. 1997, ApJL, 489, L37

Thompson, C. 1994, MNRAS, 270, 480

Thompson, C., Mészáros, P., & Rees, M. J. 2007, ApJ, 666, 1012

Vereshchagin, G. V. 2014, JMPD, 23, 30003

Vetere, L., Massaro, E., Costa, E., Soffitta, P., & Ventura, G. 2006, A&A, 447, 499

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

Woosley, S. E., & Bloom, J. S. 2006, ARA&A, 44, 507

Zhang, B., & Yan, H. 2011, ApJ, 726, 90

Zhang, F.-W. 2012, Ap&SS, 339, 123