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The Physical Conditions of the Afterglow Implied by MAGIC's Sub-TeV Observations of GRB 190114C

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Abstract

MAGIC's observations of late sub-TeV photons from GRB 190114C enable us, for the first time, to determine the details of the emission process in a GRB afterglow and to pin down the physical parameters, such as the bulk Lorentz factor and the Lorentz factor of the emitting electrons as well as some of the microphysical parameters. We find that the sub-TeV emission is synchrotron–self-Compton radiation produced at the early afterglow stage. Combining the sub-TeV and X-ray observations we narrow uncertainties in the conditions inside the emitting zone, almost eliminating them for some parameters. Seventy seconds after the trigger the external shock had a Lorentz factor $\simeq$100, and the electrons producing the observed sub-TeV radiation had a Lorentz factor $\simeq 10^4$, so that the sub-TeV radiation originates from Comptonization of X-ray photons at the border between the Thomson and Klein–Nishina regimes. The inferred conditions within the emitting zone are at odds with theoretical expectations unless one assumes moderate (with $\tau \simeq 2$) absorption of sub-TeV photons inside the source. With this correction the conditions are in good agreement with predictions of the pair-balance model, but are also acceptable for generic afterglow model as one of many possibilities. The different temporal evolution of the inverse Compton peak energy of these two models opens a way to discriminate between them once late-time detection in the TeV range become available.

Key words: acceleration of particles – gamma-ray burst: general – gamma-ray burst: individual (190114C)

1. Introduction

The bright gamma-ray burst (GRB), GRB 190114C, was detected by *Swift*-BAT (Gropp et al. 2019), *Fermi*-GBM (Hamburg et al. 2019), and Konus-*Wind* (Frederiks et al. 2019). Fifty seconds after the trigger, the MAGIC Cherenkov telescope detected a photon at an energy above 300 GeV with more than 20σ significance (Mirzoyan 2019). While GRB γ-rays of several dozen GeV have been detected in the past by EGRET (Hurley et al. 1994) and *Fermi*-LAT (Abdo et al. 2009; Ackermann et al. 2014), this was the first-ever detection of a GRB by a Cherenkov telescope at sub-TeV. With a redshift of $z = 0.4245$ (Selsing et al. 2019) the corresponding energy in the source frame of the highest-energy photon was $\simeq$0.5 TeV. Even though the information at this stage is limited to GCN circulars, we explore here the origin of the sub-TeV emission and show that it can lead to a deep insight on the conditions within the emitting regions. As we show here these observations enable us to determine the bulk Lorentz factor and the Lorentz factor of the emitting electrons as well as the details of the emission process. We can also put limits on the microphysical equipartiton parameters. This is the first time that the conditions within the emitting region of a GRB have been determined with such a confidence.

In previous bursts, the EGRET and *Fermi*-LAT GeV emission continued long after the prompt emission had faded away and have shown a gradual temporal decay. This has led to the suggestion that the GeV photons arise from the afterglow (Kumar & Barniol Duran 2009, 2010; Ghisellini et al. 2010). As the MAGIC sub-TeV radiation shows a similar behavior, i.e., it was observed after the bulk of prompt emission had faded away, we explore here the possibility that this is a part of the early afterglow.

Within the standard afterglow model (Sari et al. 1998) the emission is produced via the synchrotron mechanism in an external shock. However, emission of sub-TeV photons via the synchrotron mechanism is problematic within this model (Piran & Nakar 2010). With any reasonable bulk Lorentz factor of the emitting region, the observed photon energy violates the burn-off limit (e.g., Guilbert et al. 1983; de Jager et al. 1996; Aharonian 2000). The most natural emission mechanism is, therefore, inverse Compton (IC). We do not consider here other emission mechanisms since synchrotron–self-Compton (SSC) is the simplest option.

A synchrotron-emitting source must produce high-energy radiation through upscattering of synchrotron photons by the same electrons. Thus, GeV and TeV radiation is expected from GRBs' afterglows, both at early and late stages (e.g., Meszaros et al. 1994; Waxman 1997; Wei & Lu 1998; Chiang & Dermer 1999; Panaitescu & Kumar 2000; Sari & Esin 2001; Zhang & Mészáros 2001; Guetta & Granot 2003; Ando et al. 2008; Fan & Piran 2008). For typical early afterglow parameters at least a few percent of the total power must be transferred to TeV photons and this component may even be dominant (Derishev et al. 2001). Yet, multiple attempts to detect GRBs' TeV emission with Cherenkov telescopes resulted only in upper limits (Albert et al. 2007; Horan et al. 2007; Aharonian et al. 2009; Acciari et al. 2011; Berti 2016; Hoischen et al. 2017). The striking contrast between the theoretical predictions and the actual observations until now remained a puzzle, implying that either the physics of the emitting zone in GRB afterglows is poorly understood (and no TeV radiation produced for one or another reason) or that TeV radiation was strongly absorbed in all cases of nondetection (see also Vurm & Beloborodov 2017 for a discussion). We demonstrate that the MAGIC detection solves the puzzle: GRB afterglows are indeed routinely producing TeV emission, but it is attenuated by internal absorption that is usually strong enough to prevent detection.

Consider an IC photon with energy $E_{\rm IC}$. The emitting electron must be energetic enough to upscatter it, namely, $\Gamma\gamma_e m_e c^2 \geqslant E_{\rm IC}$, where Γ is the bulk Lorentz factor, γ_e is the Lorentz factor of the accelerated electrons, m_e the electron's rest mass, and c is the speed of light. Thus, the sub-TeV observations imply that $\Gamma\gamma_e \geqslant 10^6$. The shock dynamics with reasonable circumburst densities (see Section 4) suggests that the bulk Lorenz factor at the time of the observations can hardly be above ~100. This immediately implies that the typical electron's Lorentz factor satisfies $\gamma_e \geqslant 10^4$.

The X-ray flux observed in GRB 190114C is larger but comparable to the sub-TeV flux observed at the same time (see Section 2). Comptonization of seed photons that are more energetic than the X-rays would be much less efficient due to Klein–Nishina (KN) effect and the paucity of such photons. Lower-energy seed photons require higher electron Lorentz factors that are ruled out as we show in Section 7. This suggests that the seed photons are X-rays that we take to be $E_{\rm X} \sim 10$ keV. In this case $\gamma_e \simeq 10^4$ satisfies the Thomson IC relation $E_{\rm IC,Thomson} \simeq \gamma_e^2 E_{\rm X}$ and with $\Gamma \simeq 100$ also the KN one $E_{\rm IC,KN} \simeq \Gamma\gamma_e m_e c^2$ (see Sections 6 and 7), implying that the IC process operates on the boundary between the two regimes (Thomson and KN). A careful examination (see Section 6) shows that it is in the former and just slightly below the transition region.

When discussing the implications of our results we consider two afterglow models. Both share the same shock deceleration dynamics. The first, widely used, "generic" model (see, e.g., Sari et al. 1998; Piran 1999) assumes that the downstream electrons carry a constant fraction ϵ_e of the total downstream energy. This leads to an average Lorentz factor of the electrons γ_e that is proportional to the bulk Lorentz factor Γ.

The second is the "pair-balance" model (Derishev & Piran 2016), which makes a specific prediction about the average Lorentz factor of radiating electrons along with few other predictions. This model includes an "accelerator," which supplies energy to radiating particles, and an "emitter," which drains energy from the particles and transfers it to synchrotron and IC radiation. The interaction between the two is in the form of two-photon pair production due to internal absorption of high-energy IC photons by low-energy target photons (of synchrotron origin). The pair-balance model also specifies the energy coming from the magnetic field decay as the source of power for accelerating particles that leads to the prediction that the Compton y parameter in the emitting zone is a few. The need to balance the accelerator's power by pair loading results in the requirement that the emitting zone is not entirely transparent to its own IC radiation. It also drives the Lorentz factor of radiating electrons to a value that corresponds to the border between Thomson and KN Comptonization regimes of their own synchrotron radiation.

We begin with a brief summary of the relevant observations in Section 2. These are the preliminary results as described in GCNs. Clearly, exact numerical values may change in the final release of observational data, but this will not undermine the validity of our analysis. Some of the conclusions may change, though, if the ratio between the sub-TeV and X-ray luminosities will be revised significantly. We outline in Section 3 the basic emission zone model that we use. We recapitulate in Section 4 essential results of the blast wave dynamics. We estimate in Section 5 the opacity to two-photon absorption of the sub-TeV photons within the emitting region. We investigate in Section 6 the different IC regimes (Thomson and KN). In Section 7 we constrain the Lorentz factor of the emitting electrons. In Section 8 we derive limits on the cooling rate of the sub-TeV-producing electrons. Using these results we infer the radiative efficiency in Section 9, and we explore the limits it sets on the emission process. We discuss the temporal evolution of the IC peak in Section 10, and we conclude in Section 11.

2. Summary of Observations

GRB 190114C was a bright burst that was detected by *Fermi*-GBM (Hamburg et al. 2019), *Fermi*-LAT (Kocevski et al. 2019), *Swift* (Krimm et al. 2019), and Konus-*Wind* (Frederiks et al. 2019). The MAGIC Cherenkov telescope detected the first-ever sub-TeV GRB emission from this burst (Mirzoyan 2019). We summarize below the main GCN results that are relevant for our work. Note that as these results are preliminary our conclusions may have to be revised if some of those observational results change significantly during the refined analysis of the data.

Redshift: The associated optical transient revealed a redshift of 0.4245 (Castro-Tirado et al. 2019; Selsing et al. 2019).

Prompt emission: The prompt emission of GRB 190114C consists of initial hard-spectrum multipeaked pulse with a duration $\simeq$6 s and a weaker and softer pulse starting $\simeq$16 s after the trigger (Frederiks et al. 2019). The peak luminosity was $L_{\rm peak} \simeq 1.67 \times 10^{53}$ erg s^{-1} (Frederiks et al. 2019).

Energy release: According to *Fermi*-GBM data (Hamburg et al. 2019), the prompt energy radiated by GRB 190114C is $E_{\rm rad}^{\rm iso} = 3 \times 10^{53}$ erg (isotropic equivalent). The Konus-*Wind* team reports (Frederiks et al. 2019) a somewhat smaller value $E_{\rm rad}^{\rm iso} = 2.4 \times 10^{53}$ erg.

Duration: The reported duration of GRB 190114C is $T_{90} \simeq 116$ s in 50–300 keV energy range, according to the *Fermi*-GBM team (Hamburg et al. 2019), and $T_{90} \simeq 361$ s in the 15–350 keV energy range, according to the *Swift*-BAT team (Krimm et al. 2019). The larger number was also claimed to be a possible underestimate. The large disagreement between the two estimates of T_{90} may indicate that the burst's emission at $t \gtrsim 100$ s is dominated by a slowly decaying afterglow component and that the afterglow's contribution to the overall radiated energy is well above 10%.

The extended emission: As a reference point, we take the moment 70 s after the trigger. By this time the prompt emission of GRB 190114C has faded away and *Swift*-XRT and MAGIC observations started at around this time. Judging from the Konus-*Wind* light curve,[3] the burst's luminosity at this moment was approximately 3×10^{-3} of the peak value, which corresponds to $L_{70\,{\rm s}} \simeq 5 \times 10^{50}$ erg s^{-1}. In the available plots, the *Swift*-BAT light curve[4] appears saturated at 70 s after the trigger, but extrapolation from the 150 $\div$ 300 s time interval gives a comparable number, $L_{70\,{\rm s}}/L_{\rm peak} \sim 4 \times 10^{-3}$. The energy radiated at later time, $t > 70$ s, can be estimated as $E_{\rm afterglow} \sim L_{70\,{\rm s}} \times 70\,{\rm s} \simeq 3.5 \times 10^{52}$ erg, that is, $\simeq 0.15 E_{\rm rad}^{\rm iso}$. This is likely an underestimate, especially if the light curve's decay law is not much steeper than $\propto t^{-1}$. The average flux of GRB 190114C in the *Swift*-XRT energy range in the time

[3] http://www.ioffe.ru/LEA/GRBs/GRB190114_T75422/

[4] http://gcn.gsfc.nasa.gov/notices_s/883832/BA/

Table 1
Parameters of GRB 190114C

Quantity	Value in Progenitor's Frame (for $z = 0.4245$)
Time since explosion	$t = 50$ s
Energy of sub-TeV photons	$E_{\rm IC} = 500$ GeV
Prompt radiated energy (isotropic equivalent)	$E_{\rm rad}^{\rm iso} = 3 \times 10^{53}$ erg
Average isotropic-equivalent X-ray luminosity at $t = 50$ s	$L_{\rm X}^{\rm iso} = 9 \times 10^{49}$ erg s^{-1}
Ratio of sub-TeV to X-ray luminosities	$\eta_{\rm IC} = 0.25$

interval $70 \div 100$ s after the trigger was $F_{\rm X} \simeq 1.3 \times 10^{-7}$ erg s^{-1} cm^{-2} (corresponds to a fluence $\simeq 3.8 \times 10^{-6}$ erg cm^{-2}).[5] Comparing this flux to the fluence reported by the Konus-*Wind* team (4.83×10^{-4} erg cm^{-2}; Frederiks et al. 2019) and their estimate for $E_{\rm rad}^{\rm iso}$, we estimate the average X-ray luminosity in the time interval $70 \div 100$ s after the trigger (in the observer's frame) as $L_{\rm X}^{\rm iso} \simeq 9 \times 10^{49}$ erg s^{-1} (isotropic equivalent; in the progenitor's frame).

GeV observations: GRB 190114C was in the *Fermi*-LAT field of view for 150 s since the trigger (Kocevski et al. 2019). The estimated energy flux above 100 MeV during this period is $\simeq 2 \times 10^{-6}$ erg s^{-1} cm^{-2}, which constitutes a fair fraction of the flux at smaller photon energies (see Ravasio et al. 2019 for a discussion of GeV emission). The highest observed photon energy is 22.9 GeV. This event was observed 15 s after the trigger and most likely should be attributed to the prompt emission. In this paper we do not discuss the origin of the observed GeV emission and we focus on the two dominant afterglow components, the X-rays, and the sub-TeV emission.

TeV observations: The MAGIC Cherenkov telescope detected sub-TeV gamma-ray emission from GRB 190114C (Mirzoyan 2019). The observation started 50 s after the trigger and resulted in the detection of pointlike source with the significance $>20\sigma$ in the first 20 minutes. The source was reported to fade quickly. Due to poor observational conditions (large zenith angle $\simeq 60°$ and the presence of a partial moon) the energy threshold was $\simeq 300$ GeV. For MAGIC sensitivity, we estimate that 20σ detection in 20 minutes corresponds to the fluence $\simeq 3 \times 10^{-8}$ erg cm^{-2}. Given the redshift of GRB 190114C, it is beyond the gamma-ray horizon even at the threshold energy (about one-fourth of 300 GeV gamma-rays reach the Earth from the GRB's distance) and therefore only the fairly narrow spectral range 300–400 GeV contributed to the MAGIC fluence. The TeV component is probably 5–10 times wider (in logarithmic units). After correction for absorption and the spectrum's width we estimate that the intrinsic TeV fluence is $\sim 10^{-6}$ erg cm^{-2}.

We focus the calculations on a single epoch, the observations at 70 s after the trigger, corresponding to 50 s in the local frame. In our numerical estimates below we use values from Table 1, based on this observational summary.

In the following, unless stated otherwise all quantities are measured in the source frame. All energies and luminosities are isotropic equivalent. We express quantities denoted by ^ in terms of the observed values in GRB 190114C, e.g., $\hat{E}_{\rm IC} \equiv E_{\rm IC}/500$ GeV. With $20 \div 25\%$ radiative efficiency at the prompt phase, these numbers correspond to kinetic energy of ejecta at the afterglow phase $E_{\rm tot}^{\rm iso} \simeq 10^{54}$ erg (isotropic equivalent). The bolometric luminosity of GRB 190114C is larger than the X-ray luminosity, which we infer from the *Swift*-XRT X-ray data. It includes contributions from soft gamma-ray, MeV, GeV, and TeV spectral domains, which are comparable to that of the X-ray domain. Somewhat arbitrarily we estimate the bolometric luminosity as $L_{\rm bol}^{\rm iso} \equiv \eta_{\rm bol} L_{\rm X}^{\rm iso} \simeq 2 \times 10^{50}$ erg s^{-1}, and we will use the correction factor $\eta_{\rm bol} \simeq 2$ as a parameter.

3. The Model

The late observations of the sub-TeV component suggests that it arose from the afterglow. We consider, therefore, an external shock model. Given the scarcity of currently available data a simple one-zone model is acceptable. The shock is then characterized by its Lorentz factor, Γ, radius, R, which can be expressed in terms of Γ and the time since the explosion, t, and the surrounding matter density, ρ. For simplicity we consider a single energy electron population, characterized by the electron's Lorentz factor γ_e, but we stress that the results are valid even for more general electron distributions. As justified later in this section we focus here on IC emission as the source of the sub-TeV emission.

It is common (see, e.g., Piran 1999) to characterize the condition within the emitting region, the downstream, using the local equipartition parameters ϵ_e and ϵ_B that relate the electron's energy density and the magnetic energy density to the total downstream energy density, e. However, one can use other parameters to characterize the conditions. In particular those parameters can be interchanged with the Compton y parameter, with $t_{\rm cool}/t_{\rm dyn}$ as the ratio between the electrons' radiative cooling time $t_{\rm cool}$ and the shock's dynamical timescale $t_{\rm dyn} = R/(\Gamma c)$, and the overall radiation efficiency ϵ_r. Given that y is easy to derive from observations for 190114C, it will be illuminating to use y at times instead of one of the microphysical parameters to characterize the system.

There are only two efficient emission mechanisms for external shock: synchrotron and IC from electrons and/or positrons. Synchrotron is strongly disfavored as the source of the sub-TeV photons. In the simplest model, the radiating electrons/positrons are accelerated by the Fermi mechanism (diffusive shock acceleration, shear flow acceleration, or acceleration in turbulent electromagnetic fields), and the rate of energy gain is limited to $\sim eBc$. Equating this rate with the rate of synchrotron losses gives the largest energy a particle can achieve and, therefore, the largest energy of synchrotron photons, the so called burn-off limit (e.g., Guilbert et al. 1983; de Jager et al. 1996; Aharonian 2000): $E \sim m_e c^2/\alpha$, where α is the fine structure constant. If the sub-TeV photons were Lorentz-boosted synchrotron photons, then the bulk Lorentz factor must be larger than 5000. For the time of observations this implies an unrealistically low density of material around the GRB source.

In principle, there are several ways to surpass the burn-off limit for synchrotron photons. All use the idea of accelerating electrons in one place, with a weaker magnetic field, and then making them radiate in other regions with a stronger magnetic field (e.g., Kumar et al. 2012). One such mechanism is ultra-fast reconnection with the formation of pinch-like structures, where the local magnetic field can be much stronger than the average value (see, e.g., Kirk 2004; Uzdensky et al. 2011; Cerutti et al. 2012; Kagan et al. 2016). However, it can occur only in magnetically dominated environments, which are unlikely for external shocks. The converter acceleration

[5] http://www.swift.ac.uk/xrt_spectra/00883832/

mechanism (Derishev et al. 2003; Stern 2003) also provides the necessary nonlocal acceleration. However, in this case the highest-energy photons are less beamed than the low-energy photons (Derishev et al. 2007), and the sub-TeV synchrotron radiation generated due to converter acceleration should be time-dilated with respect to softer spectral ranges, unlike the observations of GRB 190114C.

We consider, therefore, in the following, IC in the context of SSC, as there is an observed significant flux of X-ray photons, produced presumably by the synchrotron mechanism, and those are the natural seeds for the IC process. Namely, the seed photons likely being the synchrotron radiation of the same electrons. Within the SSC scenario the TeV-emitting electrons must be in the fast-cooling regime (see Section 8), but even if the X-rays are not produced by the same electrons their large flux would force a fast-cooling solution.

4. The Blast Wave

We use the theory of an adiabatic blast wave to express the physical conditions within the emitting regions in terms of three quantities, the isotropic-equivalent bolometric luminosity $L_{\rm bol}^{\rm iso} \equiv \eta_{\rm bol} L_{\rm X}^{\rm iso}$, the time in the source frame t, and the shock's Lorentz factor Γ. These expressions are well known (e.g., Piran 1999; usually in terms of other variables) and are given here for completeness. The necessary expressions are summarized below.

We consider a uniform medium around the progenitor (interstellar medium (ISM) for short) and a stellar wind (wind for short). The density of the circumburst medium, $\rho(R)$, is

$$\rho = \begin{cases} \frac{\dot{M}}{4\pi R^2 v_w} & \text{(wind)}, \\ \rho_0 & \text{(ISM)}, \end{cases} \tag{1}$$

where ρ_0 is the local density of the circumburst medium, $\dot{M}$ and v_w are the mass-loss rate and the wind velocity, respectively.

The radius of the blast wave, R, and its Lorentz factor, Γ, are related to the observed time t as

$$R \simeq \begin{Bmatrix} 4 \\ 8 \end{Bmatrix} \Gamma^2 ct. \tag{2}$$

Here and in many expressions below, the wind and ISM cases differ only by numerical factors. We present the results as a single expression preceded by a column of two coefficients: the upper one for a wind and the lower one for an ISM. The shock's Lorentz factor Γ at a given time is expressed in terms of $E_{\rm tot}^{\rm iso}$:

$$\Gamma \simeq \begin{cases} \left(\frac{E_{\rm tot}^{\rm iso} v_w}{4\,\dot{M} c^3 t}\right)^{1/4}, & \text{(wind)} \\ \frac{1}{2}\left(\frac{3E_{\rm tot}^{\rm iso}}{8\pi\rho_0 c^5 t^3}\right)^{1/8}, & \text{(ISM)}. \end{cases} \tag{3}$$

We define the radiative efficiency ϵ_r as the ratio of outgoing radiation energy flux to the upstream energy flux: $\epsilon_r = \eta_{\rm bol} L_{\rm X}^{\rm iso}/4\pi R^2\Gamma^4\rho c^3$. The magnetic field caries a fraction ϵ_B of the comoving-frame energy density $e = 2\Gamma^2\rho c^2$, and the comoving-frame magnetic field strength is

$$B = (8\pi\epsilon_B e)^{1/2} \simeq \begin{Bmatrix} 1 \\ 1/2 \end{Bmatrix} \frac{1}{2\Gamma^3}\left(\frac{\epsilon_B \eta_{\rm bol} L_{\rm X}^{\rm iso}}{\epsilon_r c^3 t^2}\right)^{1/2}. \tag{4}$$

Finally, we write the isotropic-equivalent energy of the shock as

$$E_{\rm tot}^{\rm iso} \simeq \begin{Bmatrix} 1 \\ 2/3 \end{Bmatrix} \frac{4\eta_{\rm bol} L_{\rm X}^{\rm iso} t}{\epsilon_r}. \tag{5}$$

5. Opacity

The fact that the sub-TeV photons have not been absorbed at the source is not trivial. Thus, before turning to the radiation mechanism we consider the implications of this simple observation. The sub-TeV photons are emitted along with lower-energy X-ray photons. Regardless of the origin of the X-ray radiation—the afterglow emission, the trailing part of prompt emission, or both—it could make the source opaque for the sub-TeV photons of energy $E_{\rm IC}$ due to two-photon pair production. The main contribution to the opacity comes from photons of energy $\sim E_a = 3\Gamma^2(m_e c^2)^2/E_{\rm IC} \simeq \Gamma^2 \times 1.6$ eV (in the observer's frame this energy is $E_a^{\rm obs} = E_a/(1+z) \simeq \Gamma^2 \times 1.1$ eV). Let η_a be the fraction of the X-ray luminosity emitted at energies around E_a, then the optical depth for absorption of the sub-TeV photons is

$$\begin{aligned} \tau_{\gamma\gamma} &\simeq \frac{1}{\Gamma^2}\sigma_{\gamma\gamma} n_a R \simeq \begin{Bmatrix} 1 \\ 1/2 \end{Bmatrix} \sigma_{\gamma\gamma}\frac{\eta_a L_{\rm X}^{\rm iso} E_{\rm IC}}{48\pi\Gamma^6 tc^2 (m_e c^2)^2} \\ &\simeq \begin{Bmatrix} 1.6 \\ 0.8 \end{Bmatrix} \frac{\eta_a \hat{L}_{\rm X}^{\rm iso} \hat{E}_{\rm IC}}{\Gamma_2^6 \hat{t}}, \end{aligned} \tag{6}$$

where $\sigma_{\gamma\gamma} \simeq 0.15\ \sigma_T$ is the value of two-photon pair production cross-section near its peak, calculated assuming isotropic distribution of target photons. Recall that $\hat{X}$ denotes the value corresponding to the one observed in GRB 190114C (see Section 2) and here and elsewhere $\Gamma_2 \equiv \Gamma/100$. Note that this result was obtained here using the observed parameters. However, it is more general; see Section 8.

Using the explicit dependence of the shock's Lorentz factor on observer's time (Equation (3)), we rewrite Equation (6) as

$$\tau_{\gamma\gamma} \simeq \begin{cases} \sigma_{\gamma\gamma}\frac{\eta_a E_{\rm IC} c}{6\pi(m_e c^2)^2}\left(\frac{v_w}{c}\right)^{-3/2}\frac{(L_{\rm X}^{\rm iso} t)\dot{M}^{3/2}}{(E_{\rm tot}^{\rm iso})^{3/2} t^{1/2}}, & \text{(wind)} \\ \frac{8}{9}\left(\frac{6}{\pi}\right)^{1/4}\sigma_{\gamma\gamma}\frac{\eta_a E_{\rm IC} c^{7/4}}{(m_e c^2)^2}\frac{(L_{\rm X}^{\rm iso} t)\rho_0^{3/4}}{(E_{\rm tot}^{\rm iso})^{3/4}} t^{1/4}, & \text{(ISM)} \end{cases}. \tag{7}$$

Clearly a source capable of emitting sub-TeV radiation must have $\tau_{\gamma\gamma} \lesssim 1$. This implies that there is bias against observing sub-TeV and more energetic emission in dense circumburst environments both for the wind model, where $\tau_{\gamma\gamma} \propto \dot{M}^{3/2}$, and for the ISM model, where $\tau_{\gamma\gamma} \propto \rho_0^{3/4}$. For the wind model there is an observational bias against weak bursts, $\tau_{\gamma\gamma} \propto (E_{\rm tot}^{\rm iso})^{-1/2}$, whereas for the ISM model there is a feeble bias in favor of weak bursts, $\tau_{\gamma\gamma} \propto (E_{\rm tot}^{\rm iso})^{1/4}$. The two models differ also in the time dependence of the two-photon absorption optical depth: it slowly decreases with time for the wind model, $\tau_{\gamma\gamma} \propto t^{-1/2}$, and—even slower—increases with time for the ISM model, $\tau_{\gamma\gamma} \propto t^{1/4}$. Note that when estimating the time dependence we have approximated the shock luminosity decrease with time as $1/t$ and we have ignored the dependence of η_a on time, $E_{\rm tot}^{\rm iso}$ and $\dot{M}$ (or ρ_0). We do not expect those factors to be significant enough to change qualitatively our results.

The requirement $\tau_{\gamma\gamma} \lesssim 1$ sets a limit on the Lorentz factor:

$$\Gamma \gtrsim \begin{Bmatrix} 108 \\ 96 \end{Bmatrix} \left(\frac{\eta_a \hat{L}_{\rm X}^{\rm iso} \hat{E}_{\rm IC}}{\hat{t}} \right)^{1/6}. \quad (8)$$

Note that η_a is a function of Γ, but because of the weak dependence of Γ on all other parameters this can be ignored. For $\Gamma \simeq 100$ the energy of the absorbing photons is $E_a^{\rm obs} \simeq 11$ keV and η_a is not much below unity; therefore, the transparency condition (8) is $\Gamma \gtrsim 100$. Because of the strong dependence of the opacity on Γ, the latter conclusion will not change significantly if the source is moderately opaque ($\tau_{\gamma\gamma} \simeq 1 \div 2$), as suggested by our analysis of radiative efficiency in Section 9. Instead, this would make the estimate more certain: $\Gamma \simeq 90 \div 100$ for a moderately opaque source.

We derived Equation (6) assuming that the low-energy (X-ray) photons that absorb the high-energy (sub-TeV) photons are emitted by the same source. If the low-energy photons are prompt radiation that is emitted from smaller radii then they propagate in small angles relative to the shock normal and this accordingly reduces the interaction rate. However, given the very weak dependence in Equation (8) on the X-ray luminosity (1/6 power) this limit will be more or less valid even if only a small fraction of the X-ray photons is produced by the electrons emitting the high-energy radiation.

The lower limit on the shock's Lorentz factor, set by the transparency condition (Equation (8)), in combination with shock deceleration law (Equation (3)) yields an upper limit on the external density. This corresponds to an upper limit on the mass-loss rate for the wind case

$$\dot{M} < \dot{M}_{\rm upp} = \frac{E_{\rm tot}^{\rm iso} v_w}{c^3 t} \left(\frac{6\pi\, t c^2 (m_e c^2)^2}{\sigma_{\gamma\gamma} \eta_a L_{\rm X}^{\rm iso} E_{\rm IC}} \right)^{2/3}$$
$$\simeq 7 \times 10^{-6} \frac{E_{\rm tot,54}^{\rm iso}\, v_{w,8.5}}{\hat{t}^{1/3} (\eta_a \hat{L}_{\rm X}^{\rm iso} \hat{E}_{\rm IC})^{2/3}} M_\odot\ {\rm yr}^{-1}, \quad (9)$$

where $v_{w,8.5} = v_w/10^{8.5}$ cm s^{-1}, and to an upper limit on the density of the circumburst medium for the ISM case

$$\rho_0 < \rho_{0,\rm upp} = \frac{3E_{\rm tot}^{\rm iso}}{8\pi c^5 t^3} \left(\frac{3\pi t c^2 (m_e c^2)^2}{2\sigma_{\gamma\gamma} \eta_a L_{\rm X}^{\rm iso} E_{\rm IC}} \right)^{4/3}$$
$$\simeq 13 \frac{E_{\rm tot,54}^{\rm iso}}{\hat{t}^{5/3} (\eta_a \hat{L}_{\rm X}^{\rm iso} \hat{E}_{\rm IC})^{4/3}} m_p\ {\rm cm}^{-3}. \quad (10)$$

In both equations $E_{\rm tot,54}^{\rm iso} = E_{\rm tot}^{\rm iso}/10^{54}$ erg. Given these values, which are within the range that is typically expected in both cases, and the weak dependence of Γ on the external density (see Equation (3)), there is not much freedom in the value of Γ. Namely, Γ cannot be much larger than the opacity limit given in Equation (8).

6. Comptonization Regimes

The IC mechanism comes in two varieties: either it operates in the Thomson regime, where the energy of the electrons/positrons greatly exceeds the energy of the upscattered photons, or in the KN regime, where the energy of the upscattered photons approximately equals the energy of the electrons/positrons. The observation of GRB 190114C at sub-TeV energy allows us to discriminate between these two options. Let $E_{\rm sy}$ be the photon energy at the synchrotron peak of the SED and γ_e the (comoving-frame) Lorentz factor of electrons that emits synchrotron photons with this energy. We define $\gamma_{\rm cr}$ as the critical electron Lorentz factor that satisfies the relation

$$m_e c^2 = \gamma_{\rm cr} E_{\rm sy} = \gamma_{\rm cr}^3 \hbar\omega_B \quad \Rightarrow \quad \gamma_{\rm cr} = \left(\frac{B_{\rm cr}}{B} \right)^{1/3}, \quad (11)$$

where $B_{\rm cr} \simeq 4.5 \times 10^{13}$ G is the Schwinger field strength. Electrons with Lorentz factor $\gamma_e < \gamma_{\rm cr}$ Comptonize their own synchrotron radiation in the Thomson regime, and for $\gamma_e \gtrsim \gamma_{\rm cr}$ Comptonization proceeds in the KN regime. The largest energy of the IC photons, which can be produced in the Thomson regime, is

$$E_{\rm IC}^{\rm cr} = \Gamma \gamma_{\rm cr} m_e c^2 = \Gamma \left(\frac{B_{\rm cr}}{B} \right)^{1/3} m_e c^2. \quad (12)$$

If this energy is larger than the energy of the observed IC photons, then Comptonization is in the Thomson regime, otherwise it is in the KN regime.

Substituting the magnetic field strength expected in the external shock (Equation (4)) into Equation (12) we find that

$$E_{\rm IC}^{\rm cr} \simeq \begin{Bmatrix} 2^{1/3} \\ 4^{1/3} \end{Bmatrix} \Gamma^2 \left(B_{\rm cr}^2 \frac{\epsilon_r\, t^2 c^3}{\epsilon_B \eta_{\rm bol} L_{\rm X}^{\rm iso}} \right)^{1/6} m_e c^2$$
$$\simeq \begin{Bmatrix} 0.7 \\ 0.9 \end{Bmatrix} \Gamma_2^2 \left(\frac{\epsilon_r}{\epsilon_B \eta_{\rm bol}} \right)^{1/6} \frac{\hat{t}^{1/3}}{(\hat{L}_{\rm X}^{\rm iso})^{1/6}} \,{\rm TeV}. \quad (13)$$

Due to very weak dependence on the ratio of unknown factors ϵ_r and ϵ_B (this ratio is probably not far from unity, as suggested by the comparable luminosities in synchrotron and IC radiation), Equation (13) serves as a limit on the Lorentz factor of the external shock that separates the two Comptonization regimes, $E_{\rm IC} < E_{\rm IC}^{\rm cr}$ and $E_{\rm IC} > E_{\rm IC}^{\rm cr}$. If the shock's Lorentz factor is larger than

$$\Gamma_{\rm KN} \simeq \begin{Bmatrix} 2^{-1/6} \\ 2^{-1/3} \end{Bmatrix} \left(\frac{E_{\rm IC}}{m_e c^2} \right)^{1/2} \left(\frac{\epsilon_B \eta_{\rm bol} L_{\rm X}^{\rm iso}}{\epsilon_r B_{\rm cr}^2 t^2 c^3} \right)^{1/12}$$
$$\simeq \begin{Bmatrix} 85 \\ 76 \end{Bmatrix} \left(\frac{\epsilon_B \eta_{\rm bol}}{\epsilon_r} \right)^{1/12} \frac{\hat{E}_{\rm IC}^{1/2} (\hat{L}_{\rm X}^{\rm iso})^{1/12}}{\hat{t}^{1/6}}, \quad (14)$$

then the IC radiation is produced in the Thomson regime.

For GRB 190114C the transparency condition (8) implies that $\Gamma > \Gamma_{\rm KN}$, and hence the observed sub-TeV radiation is produced in the Thomson regime, but not very far from the KN limit. The fact that $\Gamma_{\rm KN}$ is close to the limit set by the transparency condition (8) is a mere coincidence for the generic afterglow model that employs the classical equipartition parameters (Sari et al. 1998), i.e., the peak of synchrotron spectrum is by chance close to the energy of photons, which contribute the most to the opacity. On the contrary, it is a basic prediction for the pair-balance model (Derishev & Piran 2016).

7. The Lorentz Factor of the Radiating Electrons

One may calculate the comoving-frame Lorentz factor, γ_e, of the electrons that produce the IC photons in two ways: assuming that Comptonization proceeds in the KN regime that gives

$$E_{\rm IC} \simeq \Gamma \gamma_{e,{\rm KN}} m_e c^2 \qquad \Rightarrow \qquad \gamma_{e,{\rm KN}} \simeq \frac{E_{\rm IC}}{\Gamma m_e c^2}, \tag{15}$$

or assuming that electrons are producing IC photons by upscattering of their own synchrotron photons in the Thomson regime[6] that gives

$$E_{\rm IC} \simeq \Gamma \gamma_{e,{\rm Th}}^4 \frac{B}{B_{\rm cr}} m_e c^2 \qquad \Rightarrow \qquad \gamma_{e,{\rm Th}} \simeq \left(\frac{E_{\rm IC}}{\Gamma m_e c^2} \frac{B_{\rm cr}}{B}\right)^{1/4}. \tag{16}$$

From the last equation, substituting the magnetic field strength B from Equation (4), we obtain

$$\gamma_{e,{\rm Th}} \simeq \begin{Bmatrix} 2^{1/4} \\ 2^{1/2} \end{Bmatrix} \left(\Gamma^2 B_{\rm cr} \frac{E_{\rm IC}}{m_e c^2}\right)^{1/4} \left(\frac{\epsilon_r c^3 t^2}{\epsilon_B \eta_{\rm bol} L_{\rm X}^{\rm iso}}\right)^{1/8}. \tag{17}$$

Comparison of the above equation with Equation (14) reveals a simple relation

$$\gamma_{e,{\rm Th}} \simeq \left(\frac{\Gamma}{\Gamma_{\rm KN}}\right)^{3/2} \gamma_{e,{\rm KN}}. \tag{18}$$

The actual value of the electron's Lorentz factor is

$$\gamma_e = \max\,[\gamma_{e,{\rm Th}},\, \gamma_{e,{\rm KN}}]. \tag{19}$$

By making this choice, one immediately knows the regime of Comptonization.

Substituting the lower limit (Equation (8)) on the shock's Lorentz factor Γ into Equation (18) and recalling that Γ cannot be much larger, we find that $\gamma_{e,{\rm Th}} \simeq (1.5 \div 2)\, \gamma_{e,{\rm KN}}$. This means that the observed sub-TeV radiation was produced in the Thomson regime (though rather close to the KN regime), and hence

$$\gamma_e \simeq \gamma_{e,{\rm Th}} \simeq \begin{Bmatrix} 1.2 \\ 1.5 \end{Bmatrix} \times 10^4 \left(\frac{\epsilon_r}{\epsilon_B \eta_{\rm bol}}\right)^{1/8} \Gamma_2^{1/2} \frac{(\hat{E}_{\rm IC} \hat{t})^{1/4}}{(\hat{L}_{\rm X}^{\rm iso})^{1/8}}. \tag{20}$$

Given the weak ($\gamma_{e,{\rm Th}} \propto \Gamma^{1/2}$) dependence on the shock's Lorentz factor and the fairly narrow allowed range of Γ, this expression provides a rather good estimate for γ_e.

8. The Cooling Rate

The cooling parameter is the ratio of the radiative cooling time, $t_{\rm cool}$, to the shock dynamical timescale, $t_{\rm dyn} \simeq R/(\Gamma c)$. Using the magnetic field strength (Equation (4)) and the shock radius (Equation (2)) we have

$$\frac{t_{\rm cool}}{t_{\rm dyn}} = \frac{6\pi\, m_e c}{\gamma_e \sigma_T B^2 (1 + \eta_{\rm IC})} \frac{\Gamma c}{R}$$
$$\simeq \begin{Bmatrix} 6 \\ 12 \end{Bmatrix} \frac{\pi\, \Gamma^5 m_e c}{\gamma_e \sigma_T (1 + \eta_{\rm IC})} \left(\frac{\epsilon_r c^3 t}{\epsilon_B \eta_{\rm bol} L_{\rm X}^{\rm iso}}\right). \tag{21}$$

[6] Strictly speaking, the statement that the largest contribution to the seed photons in the Thomson regime is due to self-produced synchrotron photons is true if the synchrotron SED around the frequency $\gamma_e^2 \omega_B$ has a convex shape in a log–log plot.

The slowest cooling corresponds to the smaller electron's Lorentz factor $\gamma_e = \gamma_{e,{\rm KN}}$ (see Equation (15)):

$$\left(\frac{t_{\rm cool}}{t_{\rm dyn}}\right)_{\max} \simeq \begin{Bmatrix} 6 \\ 12 \end{Bmatrix} \frac{\pi\, \Gamma^6 (m_e c^2)^2}{\sigma_T (1 + \eta_{\rm IC}) E_{\rm IC}} \left(\frac{\epsilon_r c^2 t}{\epsilon_B \eta_{\rm bol} L_{\rm X}^{\rm iso}}\right). \tag{22}$$

Using Equations (3) and (5) to substitute the shock's Lorentz factor Γ and kinetic energy $E_{\rm tot}^{\rm iso}$, we find the fast-cooling condition $(t_{\rm cool}/t_{\rm dyn})_{\max} < 1$ for a wind:

$$\dot{M} > \frac{v_w}{c} \left(\frac{6\pi (m_e c^2)^2 t}{\sigma_T c (1 + \eta_{\rm IC}) E_{\rm IC}}\right)^{2/3} \left(\frac{\eta_{\rm bol} L_{\rm X}^{\rm iso}}{\epsilon_B^2 \epsilon_r}\right)^{1/3}$$
$$\simeq 9 \times 10^{-9} v_{w,8.5} \left(\frac{\hat{t}}{(1 + \eta_{\rm IC}) \hat{E}_{\rm IC}}\right)^{2/3}$$
$$\times \left(\frac{\eta_{\rm bol} \hat{L}_{\rm X}^{\rm iso}}{\epsilon_B^2 \epsilon_r}\right)^{1/3} M_\odot\ {\rm yr}^{-1}, \tag{23}$$

and for an ISM:

$$\rho_0 > \frac{c^3}{t^{2/3}} \left(\frac{3\, m_e^2}{16 \sigma_T (1 + \eta_{\rm IC}) E_{\rm IC}}\right)^{4/3} \left(\frac{\pi\ \epsilon_r}{\epsilon_B^4 \eta_{\rm bol} L_{\rm X}^{\rm iso}}\right)^{1/3}$$
$$\simeq 7.5 \times 10^{-4} \frac{1}{\hat{t}^{2/3}} \left(\frac{1}{(1 + \eta_{\rm IC}) \hat{E}_{\rm IC}}\right)^{4/3}$$
$$\times \left(\frac{\epsilon_r}{\epsilon_B^4 \eta_{\rm bol} \hat{L}_{\rm X}^{\rm iso}}\right)^{1/3} m_p\ {\rm cm}^{-3}. \tag{24}$$

Given these small values we conclude that fast-cooling regime for GRB 190114C at time moment $t = 50$ s is assured.

The fastest cooling corresponds to the larger electron's Lorentz factor $\gamma_e = \gamma_{e,{\rm Th}}$ (see Equation (17)). We then multiply Equation (22) by $\gamma_{e,{\rm KN}}/\gamma_{e,{\rm Th}}$ to obtain $(t_{\rm cool}/t_{\rm dyn})_{\min}$ and substitute Γ from the equation for the two-photon optical depth (6) to obtain

$$\left(\frac{t_{\rm cool}}{t_{\rm dyn}}\right)_{\min} \simeq \frac{1}{8 \tau_{\gamma\gamma}} \left(\frac{\gamma_{e,{\rm KN}}}{\gamma_{e,{\rm Th}}}\right) \frac{\sigma_{\gamma\gamma}}{\sigma_T} \frac{\eta_a}{(1 + \eta_{\rm IC})} \frac{L_{\rm X}^{\rm iso}}{L_{\rm bol}^{\rm iso}} \frac{\epsilon_r}{\epsilon_B}$$
$$\simeq 0.02 \frac{1}{\tau_{\gamma\gamma}} \left(\frac{\gamma_{e,{\rm KN}}}{\gamma_{e,{\rm Th}}}\right) \frac{\eta_a \epsilon_r}{(1 + \eta_{\rm IC}) \eta_{\rm bol} \epsilon_B} \tag{25}$$

for both the wind and ISM cases. The similarity of the expression for $(t_{\rm cool}/t_{\rm dyn})_{\max}$ (Equation (22)) to expression (6) for the photon absorption optical depth, which eventually leads to the above simple relation, is not coincidental. Both describe electromagnetic interaction of energetic particles (electrons in one case and photons in the other) having the same energy with the same background low-energy photons. The only difference is in the cross-sections for electron–photon and photon–photon interactions. Thus, if Comptonization operates in the KN regime or close to it, then the IC photons arising from fast-cooling electrons should have an optical depth to pair creation with the low-energy seed photons that is larger than y (see, e.g., Moderski et al. 2005; Derishev 2009).

In the above discussion the cooling rate was considered within the SSC model. However, it is important to note that the large flux of low-energy X-rays ensures that the IC-emitting electrons would be in fast cooling regardless of the origin of the X-ray photons and a slow-cooling IC regime is ruled out.

9. The Radiation Efficiency and Its Implications

Assuming turbulent, i.e., isotropic on large scales, magnetic field in the downstream the intensity of the synchrotron radiation at the front of a plane-parallel emitting region at an angle θ to its normal is

$$I_{\rm sy}(\theta) \simeq \frac{1}{\cos(\theta)} \frac{\sigma_T \gamma_e^2 n_e e_B c l_{\rm em}}{3\pi} = \frac{I_{\rm sy}(0)}{\cos(\theta)} = y \frac{e_B c}{4\pi \cos(\theta)}.$$

Here $l_{\rm em}$ is the thickness of the emitting region measured in the shock comoving frame:

$$l_{\rm em} \simeq \begin{cases} c t_{\rm cool} < R/\Gamma & \text{for} \quad t_{\rm cool} < t_{\rm dyn} \quad \text{(fast cooling)}, \\ R/\Gamma & \text{for} \quad t_{\rm cool}/t_{\rm dyn} > 1 \quad \text{(slow cooling)}, \end{cases} \tag{26}$$

and

$$y \equiv \frac{4}{3} \sigma_T \gamma_e^2 n_e l_{\rm em} \tag{27}$$

is the Compton y parameter. The energy density of the synchrotron radiation inside the emitting region is

$$e_{\rm sy} \simeq \frac{2\pi}{c} \int_0^{\pi/2} I_{\rm sy}(\theta) \sin\theta d\theta \simeq \frac{2\pi \Lambda I_{\rm sy}(0)}{c} \simeq \frac{\Lambda}{2} y e_B. \tag{28}$$

The integral in this equation has a logarithmic divergence at $\theta \to \pi/2$ that is an artifact of the plane geometry approximation. However, the shock has a finite curvature, and hence the integral is finite. We take this into account introducing the geometrical factor

$$\Lambda \simeq 1 + \ln\left(\frac{R}{\Gamma l_{\rm em}}\right) \tag{29}$$

that reproduces both asymptotic limits, $\Lambda \simeq 1$ for $l_{\rm em} \simeq R/\Gamma$ and $\Lambda \simeq \ln(R/\Gamma l_{\rm em})$ for $l_{\rm em} \ll R/\Gamma$.

The synchrotron radiation flux at the shock front is[7]

$$F_{\rm sy} \simeq 2\pi \int_0^{\pi/2} \cos\theta I_{\rm sy}(\theta) \sin\theta d\theta \simeq 2\pi I_{\rm sy}(0) \simeq \frac{y}{2} e_B c. \tag{30}$$

Comparing it to the energy flux, associated with the downstream plasma, $F = (c/2)e = (c/2)e_B/\epsilon_B$ for a downstream velocity equal to $c/3$, we introduce the synchrotron radiative efficiency (Sari et al. 1996):

$$\epsilon_{\rm sy} \equiv \frac{F_{\rm sy}}{F} \simeq y \epsilon_B. \tag{31}$$

[7] This flux is calculated for a static emission zone. In the case of GRB afterglows, the emitting zone is associated with the downstream plasma, which recedes from the shock front, and hence fewer photons move in a forward direction in the shock plane. On the other hand, most of the photons, which appear to move backward in the shock frame, actually move in a forward direction in the progenitor's frame and overtake the shock at later time when it decelerates.

Note that the radiative efficiency can also be expressed in terms of ϵ_e:

$$\epsilon_{\rm sy} < \epsilon_r = \epsilon_e \begin{cases} 1 & \text{for} \quad t_{\rm cool} < t_{\rm dyn} \quad \text{(fast cooling)}, \\ t_{\rm dyn}/t_{\rm cool} & \text{for} \quad t_{\rm cool} > t_{\rm dyn} \quad \text{(slow cooling)}. \end{cases} \tag{32}$$

While the latter expression for the efficiency, $\epsilon_r = \epsilon_e \min(1, t_{\rm dyn}/t_{\rm cool})$, is more familiar, the expression $\epsilon_{\rm sy} = y\epsilon_B$ is also useful here as y can be directly estimated from the observable $\eta_{\rm IC}$.

Calculating the IC radiation flux at the shock front in the same way as for synchrotron radiation, where the magnetic field energy density is replaced by the energy density of synchrotron radiation with an additional factor $\kappa_{\rm KN} \leqslant 1$ that accounts for the KN effect, we obtain

$$F_{\rm IC} \simeq \kappa_{\rm KN} \frac{y}{2} e_{\rm sy} c \simeq \kappa_{\rm KN} \frac{\Lambda}{4} y^2 e_B c. \tag{33}$$

Therefore, the IC radiative efficiency is (Sari et al. 1996)[8]

$$\epsilon_{\rm IC} \equiv \frac{F_{\rm IC}}{F} \simeq \kappa_{\rm KN} \frac{\Lambda}{2} y^2 \epsilon_B; \qquad \eta_{\rm IC} \equiv \frac{F_{\rm IC}}{F_{\rm sy}} \simeq \kappa_{\rm KN} \frac{\Lambda}{2} y. \tag{34}$$

Note that within the Thomson regime y and $\eta_{\rm IC}$ are the same up to the logarithmic geometrical factor $\Lambda/2$. The overall radiative efficiency is $\epsilon_r = \epsilon_{\rm sy} + \epsilon_{\rm IC} \leqslant \epsilon_e$. The equality $\epsilon_r = \epsilon_e$ holds for the fast-cooling regime.

If $L_{\rm IC}^{\rm iso}$, inferred from the available observational data, is treated as the intrinsic IC luminosity of the external shock, then the Compton y parameter can be estimated from the ratio of sub-TeV (IC) to X-ray (synchrotron) luminosities (see Equation (34)). Assuming a geometrical factor $\Lambda \sim 2$ and keeping in mind that Comptonization proceeds in the nearly Thomson regime, we arrive at $y \sim 0.25$. To first order in y, the external shock efficiency can be estimated as $\epsilon_r \simeq y\epsilon_B \sim 0.25\epsilon_B$.

Using the above estimates for the radiative efficiency and combining it with the expression for the shock's isotropic-equivalent kinetic energy (see Equation (5)) we find that

$$\epsilon_B \simeq \begin{Bmatrix} 1 \\ 2/3 \end{Bmatrix} \frac{4\eta_{\rm bol} L_{\rm X}^{\rm iso} t}{(1 + \eta_{\rm IC}) y E_{\rm tot}^{\rm iso}} \simeq \begin{Bmatrix} 0.07 \\ 0.05 \end{Bmatrix} \frac{\eta_{\rm bol} \hat{L}_{\rm X}^{\rm iso} \hat{t}}{\hat{\eta}_{\rm IC} E_{\rm tot,54}^{\rm iso}}, \tag{35}$$

where the last approximate equality is valid for small values of $\eta_{\rm IC}$ as in the case of GRB 190114C. The above equation suggests either a large magnetization or a very large value of $E_{\rm tot}^{\rm iso}$ and, consequently, a low efficiency of the prompt phase.

Large magnetization is unexpected as the shock propagates into an unmagnetized medium. In particular, PIC simulations consistently show $\epsilon_B \sim 10^{-2}$ for a shock propagating into an unmagnetized medium (e.g., Sironi & Spitkovsky 2011; Sironi et al. 2015). This value implies $E_{\rm tot}^{\rm iso} \sim 10^{55}$ erg, the implied real energy is uncomfortably large, even after adding typical beaming corrections. This also implies a radiative efficiency of only a few percent at the prompt phase. Numerical simulations also suggest that the magnetic field's energy share is several times less than that of the accelerated electrons (e.g., Spitkovsky 2008; Kumar et al. 2015). Again this is at odds with our estimate for GRB 190114C unless the electrons

[8] Note the geometrical factor Λ that was included here relative to Sari et al. (1996).

radiate in the slow-cooling regime, which is ruled out (see Equations (23) and (24) and the discussion thereafter).

A possible resolution of this apparent problem is that the sub-TeV radiation is stronger than what we use as a canonical value and y is larger. This can happen if the sub-TeV radiation is strongly absorbed within the emitting zone or if our estimate of the sub-TeV luminosity from the available GCN data was too low, or both. A larger intrinsic sub-TeV luminosity (and hence a larger Compton y) would resolve both problems of a too large shock kinetic energy and too low ϵ_e (relative to ϵ_B). While a careful examination of the observational data could reveal a better estimate for the ratio of sub-TeV to X-ray fluxes it may be much more difficult to assess directly whether there was some level of internal self-absorption of the sub-TeV photons or not.

Yet another possibility is that at an observer time of $t = 70$ s the X-ray radiation is still dominated by the prompt emission and the external shock's contribution to the observed X-ray and sub-TeV fluxes is small. This would relax the requirements for the shock's kinetic energy. But the estimate of the Compton y parameter would remain essentially unchanged; hence, $\epsilon_B > \epsilon_e$ will still hold.

An independent way of estimating the parameters of the emitting zone is based on the relation between radiative efficiency and the total energy of the radiating particles (electrons and/or positrons). Given their Lorentz factor γ_e and their number per baryon, ξ_e (note that here ξ_e can be larger than unity if there is a significant pair loading as a result of internal absorption of IC photons), one can set an upper limit to the radiative efficiency,

$$\epsilon_r \leqslant \epsilon_e \equiv \xi_e \gamma_e m_e/(\Gamma m_p), \tag{36}$$

that becomes an equality in the fast-cooling case relevant to GRB 190114C.

Using this relation with Equations (31) and (34) we find that in the fast-cooling regime,

$$\epsilon_B \simeq \frac{\xi_e \gamma_e m_e}{y(1 + \eta_{\rm IC})\Gamma m_p} \simeq 0.22\, \frac{\xi_e \gamma_{e,4}}{\hat{\eta}_{\rm IC}\Gamma_2}. \tag{37}$$

For the parameters of GRB 190114C we get $\epsilon_B \simeq 0.2\xi_e$. If all the electrons from the circumburst medium are accelerated, then $\xi_e = 0.5$ for a Wolf–Rayet stellar wind case and $\xi_e = 0.87$ for the ISM case. This would imply a rather large $\epsilon_B \simeq 0.1 \div 0.2$. If on the other hand ϵ_B is small, as implied by the PIC simulations, then the fraction of accelerated of electrons, ξ_e, should be small as well. This is also observed in PIC simulations (Sironi & Spitkovsky 2011).

Combined with Equation (5), (37) gives a lower limit on the kinetic energy of the shock. Comparing this value with the estimated isotropic-equivalent prompt γ-ray energy (3×10^{53} erg from Section 2) the ISM scenario is consistent with a prompt radiation efficiency up to $\simeq$40%. A smaller prompt efficiency would imply that only a fraction of the available electrons is accelerated by the external shock. In the wind scenario the prompt efficiency is limited to $\lesssim$20%, unless there are additional electron–positron pairs that are produced within the external shock and are accelerated along with electrons from the wind. If one assumes that only a fraction of the observed X-ray luminosity is due to external shock (as discussed earlier in this section), then the shock's contribution to IC luminosity and hence the requirements on the shock's kinetic energy would be proportionally smaller.

The parameters, which we determined for the early afterglow phase of GRB 190114C, are consistent with the generic afterglow model, albeit with a larger than expected ϵ_B value and with $\epsilon_B > \epsilon_e$ (if one assumes that the observed ratio of IC to synchrotron luminosity is intrinsic to the source). At the same time they fit well into more specific predictions of the pair-balance model. Two key predictions of this model are: (i) the IC peak is produced at the border between the KN and Thomson regimes; (ii) $\eta_{\rm IC}$ = a few. Both are satisfied here (see Equations (14) and (18) and discussions there for the first condition). As noted earlier the unexpectedly large inferred magnetization together with the inequality $\epsilon_B > \epsilon_e$ suggest that there is moderate internal absorption of sub-TeV photons. If so, this will increase the estimate of the intrinsic Compton y parameter to $\simeq$ a few, getting it closer to the range predicted by the pair-balance model.

10. Temporal Evolution of IC Peak Position: Generic versus Pair-balance Models

Predictions of the temporal evolution of the IC peak are drastically different in these two models, making it possible to distinguish between the two if observations at later times become available. In the simplest scenario for both models, the microphysical parameters ϵ_B and ϵ_e remain constant. In the case of fast cooling and Comptonization in the Thomson regime, this implies that $\eta_{\rm IC}$ does not change with time. But the two models differ in the predicted evolution of the IC peak energy, $E_{\rm IC,p} \propto \Gamma\gamma_{e,{\rm p}}^4 B$ (in the Thomson regime).

In the generic model $\gamma_{e,{\rm p}}$ is proportional to Γ (see Equation (36)). Therefore,

$$E_{\rm IC,p} \propto \Gamma^5 B \propto \Gamma^2 t^{-3/2} \propto \begin{cases} t^{-2}, & \text{(wind)} \\ t^{-9/4}, & \text{(ISM)}, \end{cases} \tag{38}$$

where we substituted the magnetic filed strength B from Equation (4) and then the shock Lorentz factor Γ from Equation (3). Both for the wind and for the ISM cases the generic model predicts a fast decrease of the peak IC energy. For example, if a GRB starts with $E_{\rm IC,p} \simeq 1$ TeV at 100 s after the explosion, then one hour later the IC peak would be located at $\simeq$1 GeV.

In the pair-balance model the peak Lorentz factor of the radiating electrons is determined by the pair-production condition and the number of energetic electrons (positrons) is regulated in such a way that $\gamma_{e,{\rm p}} \simeq \gamma_{\rm cr} \propto B^{-1/3}$ (see Equation (11)). Therefore,

$$E_{\rm IC,p} \propto \Gamma B^{-1/3} \propto \Gamma^2 t^{1/2} \propto \begin{cases} const, & \text{(wind)} \\ t^{-1/4}, & \text{(ISM)}. \end{cases} \tag{39}$$

The pair-balance model predicts that the peak IC energy does not change with time in the wind case. In the ISM case, the model predicts weak evolution IC peak toward lower energies. For the same hypothetical GRB, which starts with $E_{\rm IC,p} \simeq 1$ TeV at 100 s after the explosion, the IC peak would be above $\simeq$200 GeV even at 10 hr after the explosion and will still be accessible for Cherenkov telescopes, provided that the flux, which decreases like t^{-1}, does not fall below the sensitivity limit.

11. Conclusions

MAGIC's observations of the sub-TeV emission from GRB 190114C opened a new window on the emission process in GRBs' afterglows. Within the SSC framework this emission has to be assigned to the IC component. It is the first time when this component was unequivocally observed. With this information at our disposal we are able to constrain the conditions within the emitting region of a GRB to a better precision than has been ever possible.

Our analysis is based on the preliminary data described in GCNs. We expect that our results will hold unless these values will be significantly revised in the refined analysis. Given the available data we use a single-zone model and we do not attempt to reproduce the whole spectrum. Instead, we focus on the two dominant components, the sub-TeV radiation and the lower-energy X-rays that turn out to be the seed photons for the IC process producing the sub-TeV photons. An external shock with a bulk Lorentz factor $\Gamma \simeq 100$ and electrons accelerated to $\gamma_e \simeq 10^4$ can explain the observations with an SSC model in which the IC process is in the Thomson regime but near the transition to the KN regime. The radiating electrons cool rapidly (fast cooling). Regardless of the details of the model the strong X-ray emission will essentially lead to fast-cooling of the IC-emitting electrons.

We find that the transparent (for sub-TeV photons) solution is possible at the expense of assuming very large shock magnetization or very large kinetic energy. However, the optical depth for internal absorption of sub-TeV photons in any case exceeds the value $(\Gamma^2\epsilon_r)^{-1}$, which means the upstream acquires enough momentum from secondary pairs to start moving at relativistic speed even before the shock comes. This forces one to use a modified shock solution, as discussed in Derishev & Piran (2016).

The detection of sub-TeV photons implies that the source's optical depth with respect to two-photon pair production is at most a few. Note that we cannot exclude absorption of sub-TeV radiation at a moderate level within the source itself. The target photons for absorption are in the X-rays. The pair annihilation opacity is alleviated by the Lorentz boost, just like in the common compactness argument (e.g., Baring & Harding 1997; Piran 1999; Lithwick & Sari 2001). It turns out that for both wind and ISM a minimal bulk Lorentz factor of the order $\Gamma \simeq 100$ at the time of observation is needed to allow the escape of sub-TeV photons. As usual in compactness arguments the dependence of this limit on the different parameters is rather low and the limit is very robust. For the same reason the limit does not vary much if we require an optical depth of a few instead. On the other hand, the shock deceleration dynamics implies, for reasonable circumburst densities, that the bulk Lorentz factor must be $\Gamma \lesssim 100$ at the time of the observations. Combined with the opacity limit we find that the bulk Lorentz factor of the afterglow is $\Gamma \simeq 100$.

The electrons must be energetic enough to produce the sub-TeV photons. With $\Gamma \simeq 100$ this implies $\gamma_e \gtrsim 10^4$. An upper limit $\gamma_e \lesssim 1.2 \div 1.5 \times 10^4$ derives from the condition that the emission process is SSC in the Thomson regime. Once more, the two limits bracket γ_e nicely from above and from below. Thus, the IC operates in the Thomson regime but very close to the Thomson/KN boundary. The seed photons are X-rays and they are, indeed, the synchrotron emission produced by $\gamma_e \simeq 10^4$ electrons. Remarkably the observed flux of the X-ray photons is compatible with this interpretation. Furthermore, our analysis indicates that the observed sub-TeV emission is near the peak of the IC component.

We obtained the values for Γ and γ_e in a way that does not use spectral information (i.e., we were not making spectral fits). Yet, we arrived at pretty certain estimates. This was possible because we could constrain the IC mechanism to the Thomson regime of operation. In this regime the electrons that are responsible for the peak of synchrotron SED Comptonize mostly their own synchrotron radiation. This alleviates the major uncertainty of SSC modeling—a possibility that the seed photons for the main (in the sense of energetics) part of electron distribution are produced by some lower-energy electrons.

If the ratio between IC and synchrotron luminosities $\eta_{\rm IC} \simeq 0.25$, as we used in our estimates, reflects the intrinsic conditions in the emitting zone, then either the GRB's kinetic energy was in excess of 10^{55} erg and its radiative efficiency was below several percent or the shock magnetization is large, with $\epsilon_B \sim 0.1$. In either case the energy share of the radiating electrons is $\simeq$4 times smaller than that of the magnetic field. These findings concerning the microphysical equipartition parameters depart from both theoretical expectations and results of PIC simulations (e.g., Sironi & Spitkovsky 2011; Sironi et al. 2015). However, they can be made consistent with those expectations assuming a moderate (with $\tau_{\gamma\gamma} \simeq 2$) intrinsic absorption of the sub-TeV radiation.

If the sub-TeV radiation from GRB 190114C was indeed partially self-absorbed, as suggested by our analysis, then we can speculate that other bursts regularly escape detection by Cherenkov telescopes just because the sources are typically self-absorbed in the TeV range. Indeed, the opacity argument sets an upper limit on the surrounding matter density. While this limit is not very stringent for an ISM, it is rather low for a wind, $\dot{M} < 6.5 \times 10^{-6} E_{\rm tot,54}^{\rm iso} v_{w,8.5}\, M_\odot\ {\rm yr}^{-1}$, and the majority of progenitors may fail to pass the self-absorption filter (see also Vurm & Beloborodov 2017).

Under the assumption of moderate intrinsic absorption of the sub-TeV radiation, the conditions in the emitting zone fit nicely into the predictions of the pair-balance model: Comptonization proceeds at the border between the Thomson and KN regimes; internal absorption of IC photons provides secondary pairs for further acceleration and emission; the Compton y parameter is of order unity. The same conditions are possible for a generic model as well, though there is no special preference for this region in the parameter space. A clear distinction between the generic and the pair-balance models can be made if late-time observations of TeV emission become available: the generic model predicts a rapid decline of peak IC energy with time, whereas the pair-balance model predicts that the peak IC energy stays approximately constant in time.

The main uncertainty in the interpretation of our results arises from the uncertainty in the IC-to-synchrotron luminosity ratio $\eta_{\rm IC}$ that we inferred from the preliminary data to be $\approx$0.25. This has lead to the conclusion that $\epsilon_B > \epsilon_e$ and to the conclusion that ϵ_B is rather large compared to expectations. However, the analysis outlined here does not depend on this value. Clearly the qualitative conclusions will have to be revised if it turns out that $\eta_{\rm IC} > 1$. However, the rest of the analysis concerning the conditions within the emitting regions still holds.

Future observations of GRBs in the sub-TeV range will provide further insight into the conditions within GRBs' emitting zones. In particular, we will be able to explore the range of microphysical parameters that arise in GRBs afterglow. Once the sub-TeV spectra become available, they may shed more light on whether there is significant internal absorption or not, which is critical to some parts of the analysis. The observations will enable us to distinguish between different acceleration mechanisms and explore the microphysics of shock accelerations. Beyond GRBs, these results will have an impact on a whole suite of other astrophysical phenomena involving relativistic shocks.

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