The Compton Trail of Gamma-Ray Bursts: Constraints on the Galactic Frequency of GRBs

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Abstract

We investigate the observability of the indirect light of GRBs resulting from the Compton scattering of the (primary) γ-rays in the ISM. We find that the *Compton trail* of a GRB with an energy of 10^{51} erg can easily be observed from Earth, wherever the explosion occurred in our Galaxy in the past few thousand years. We also calculate the light curve and the shape of the emitting region as a function of time.

1. Introduction

The origin of the GRBs remains unclear, more than thirty years after their discovery [4]. A lot of progress has been made, however, from both theoretical and observational points of view. In particular, there is now strong evidence that GRBs have a beamed emission [3], so that we can only observe the small fraction of them which are pointing toward us. That is, we can only observe these ones *directly*. For the others, we may still be able to detect the gamma-rays from the beam which are inevitably scattered by the electrons around the explosion site, through the well-know Compton scattering process. The corresponding indirect light of GRBs, which we refer to as the *Compton trail*, could in principle allow us to observe GRBs long after their explosion, provided the scattered flux is large enough.

Quantitatively, the Compton-scattered flux from a GRB exploding at a distance D is approximately:

$$\phi = \frac{N_\gamma n_e \sigma_\mathrm{T} c}{4\pi D^2} \approx (0.15\,\mathrm{ph\,cm^{-2}\,s^{-1}}) \times E_{51} n_0 D_\mathrm{kpc}^{-2}, \quad (1)$$

where N_γ is the total number of photons in the GRB beam, n_e is the averaged electron density (free and bound) in the ISM (1 cm^{-3}), σ_T is the Thomson cross section, and a typical energy of 10^{51} erg has been assumed for the GRB, with monochromatic emission at 200 keV.

Such fluxes are enormous for Galactic GRBs, far above the detection thresholds of γ-ray satellites, so that GRB Compton trails could indeed be observed. This is due to the huge number of primary photons. On the other hand,

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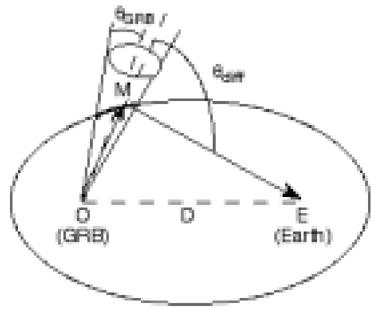

Fig. 1. Compton trail geometry. The emission region (see text) is shown as a thick line. The path of a photon scattered towards the Earth at point M is also represented.

the typical Compton depth of a galactic disk, $\tau_c = n_e \sigma_{\mathrm{C}} c$, is only $2 \times 10^{-3}\,\mathrm{kpc}^{-1}$, so that Compton scattering does not affect significantly the direct γ-ray beam of the GRBs, and double scattering can be neglected as well.

2. Compton trail geometry and γ-ray flux

Let us consider a GRB at a distance D from Earth which emits instantaneously N_γ γ-rays, uniformly distributed in a cone of opening angle θ_{GRB}. Once emitted, the photons scattered at any point M in the ISM can be observed at Earth if they have the appropriate scattering angle, θ_{Diff} (see Fig. 1). Obviously, the photons observed on Earth at time t have had the same time of flight, i.e. they have been scattered at points M such that $OM + MT = \mathrm{constant}$ (see Fig. 1). Mathematically speaking, this defines an ellipsoid with focals O (the GRB central object) and T (the Earth). But of course the emission region must lye within the GRB cone too (see Fig. 1). We can thus determine the set of points M corresponding to a time of observation t as the intersection of the above ellipsoid and the GRB emission cone (NB: in our calculation we actually take into account the duration of the burst, so that the emission region becomes the intersection of the cone and a set of ellipsoids). Note that as the GRB central object is a focal of the ellipsoid, the contour of the intersection is a planar ellipse, so that, from Earth, the emission region is always seen on the sky as an ellipse.

Once the *scattering region* is found at each observation time t, it is straightforward to calculate the Compton-scattered differential flux by integrating over the set of points $\{M\}$:

$$\frac{\partial \phi(E,t)}{\partial E} = \iiint_{\{M(t)\}} n_\gamma(t', E_0(E,\theta_{\mathrm{Diff}})) n_e(M) \frac{\mathrm{d}\sigma_{\mathrm{C}}}{\mathrm{d}\omega}(E_0(E,\theta_{\mathrm{Diff}})) \frac{c}{MT^2} \mathrm{d}V, \qquad (2)$$

where n_γ is the density of photons emitted at time $t' = t - \frac{OM+MT}{c}$, at the energy E_0 (E_0 is the energy before Compton scattering, it depends on E the observed

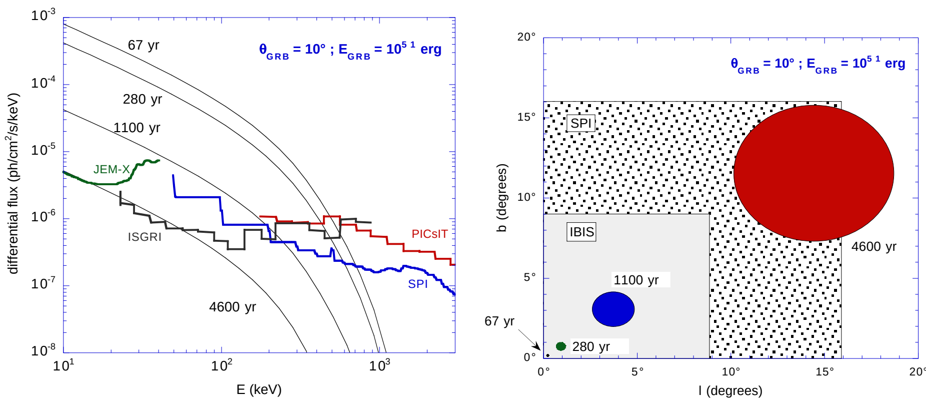

Fig. 2. a:Differential Compton-scattered flux for different times of observation compared with INTEGRAL thresholds; b: image of the scattering zone for the same times of observation, the grey squares show the fields of view of SPI and IBIS.

energy and $\theta_{\rm Diff}$ the scattering angle at M), n_e is the electron density at point M (we used a typical Galactic model, as in [2]), and $\frac{d\sigma_C}{d\omega}$ is the Compton differential cross section. For a GRB of duration τ we have $n_\gamma(E,{\rm M}) = N_\gamma(E)/[2\pi {\rm OM}^2(1-\cos\theta_{\rm GRB})c\tau]$.

3. Results

We have simulated a GRB explosion at the center of the Galaxy, with a total energy of 10^{51} erg, a beaming angle of $10°$ and an emission cone with an inclination of $60°$ with respect to the axis of the Galaxy. The assumed photon spectrum consists of two power laws with a peak at 200 keV [1]. Figure 2.a shows the differential fluxes for different times of observation (after the explosion) and compares these fluxes with the detection thresholds of INTEGRAL instruments (estimated for observation times of 10^6 s). We find that the Compton indirect light of such a GRB remains visible during thousands of years.

Figure 2.b shows the corresponding emission regions on the sky (i.e. the part of the GRB Compton trail which is visible at the same observation times) and compares their angular size with the fields of view of the SPI and IBIS instruments. Even after 4600 years, the emission region fits into both.

As we can see on Fig. 2.a the photon spectrum is only weakly modified by Compton scattering. Only the high energy part of the spectrum is in fact partially cut in the case of high scattering angles, i.e. when the scattering zone is far above the Galactic disk. Taking this into account we have estimated an integrated limit of detection for INTEGRAL of $1.1\times10^{-4}\,{\rm ph\,cm^{-2}\,s^{-1}}$ for 10^6 s of observation.

Figure 3 shows the integrated fluxes for GRBs with $E = 10^{51}$ erg, $\theta_{\rm GRB} = 10°$ and different distances and inclinations, compared to the INTEGRAL thresh-

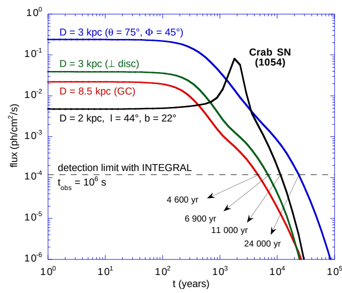

Fig. 3. Compton-scattered fluxes as a function of time for different GRBs.

olds. The maximum time of observation above the threshold is given for each case. One of the examples simulates what we could expect if the Crab supernova gave rise to a GRB. The observed peak in the scattered flux after ~ 2000 years is due to the photons crossing the denser Galactic disk (as the explosion occurred well above the plane). In all the cases shown, the fluxes remain visible during thousands of years for a GRB of energy 10^{51} erg.

4. Conclusion

We have studied the possibility of observing the indirect light of GRBs resulting from the Compton scattering of the (primary) gamma-ray photons. We found that the *Compton trail* of a GRB with an energy of 10^{51} erg can easily be observed from Earth, wherever the GRB exploded in our Galaxy in the past few thousands of years. The observability of lower (or higher) energy GRBs can be straightforwardly deduced from our calculations, by linear scaling of the fluxes. GRBs with energies as low as 10^{48} erg can be observed during 1000 years, provided they explode sufficiently close to the Earth.

The observation (or non observation) of a GRB Compton trail allows one to constrain the GRB models according to their total energy and Galactic frequency. This will be further discussed in a forthcoming paper. We merely recall here that some models predict that a large fraction of all supernovæ actually produce GRBs, so that several GRBs would have exploded in our Galaxy in the last few thousands of years. Their Compton trail should thus be emitting light just now.

Finally, we note that the geometry of the Compton trail would clearly indicate the explosion site as well as the angular distribution of the primary photons.

1. Band D., et al. 1993, ApJ 413, 281
2. Ferrière, K. 1998, ApJ 503, 700
3. Frail D. A., et al. 2001, ApJ 562, 55
4. Klebesadel R. W., Strong I. B., Olson A. O. 1973, ApJ 182, 85