

# Gamma rays from halos around stars and the Sun

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Received: 13 September 2006 / Accepted: 31 October 2006 / Published online: 20 April 2007  
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**Abstract** Inverse Compton (IC) scattering by relativistic electrons produces a major component of the diffuse emission from the Galaxy. The photon fields involved are the cosmic microwave background and the interstellar radiation field (ISRF) from stars and dust. Calculations of the inverse Compton distribution have usually assumed a smooth ISRF, but in fact a large part of the Galactic luminosity comes from the most luminous stars, which are rare. Therefore we expect the ISRF, and hence the inverse Compton emission, to be clumpy at some level, which could be detectable by instruments such as GLAST. Even individual nearby luminous stars could be detectable assuming just the normal cosmic-ray electron spectrum. We present the basic formalism required and give possible candidate stars to be detected and make predictions for GLAST. Then we apply the formalism to the OB associations and the Sun, showing that the IC emission produced is not negligible compared to the sensitivity of current or coming detectors. We estimate that the gamma-ray flux from the halo around the Sun contributes to the diffuse background emission at the few percent level.

**Keywords** Gamma rays · Cosmic rays · Stars · Sun

## 1 Introduction

In the early 90s there was already the idea to consider the IC gamma-ray emission generated by electrons accelerated

by shocks in winds around hot stars (e.g. Chen and White 1991). In the present work, for the first time, we show that even the gamma-ray emission by the ambient cosmic-ray electrons via IC scattering of the stellar radiation field could be detected by GLAST. We begin with the simplest possible rough estimate to show that the IC emission from luminous stars could be visible. The optical luminosity of the Galaxy is about  $3 \times 10^{10} L_{\odot}$ , and a typical O star has  $10^5 L_{\odot}$  i.e. about  $10^{-5}$  of the Galaxy. Consider such a star at a distance of 100 pc: compared to the entire Galaxy (distance to centre = 8.5 kpc) this inverse Compton source is on average about a factor 100 closer and hence the IC is  $10^{-5} \times 100^2$  of the Galactic IC, suggesting it is significant. The IC luminosity  $L_{IC}$  within a volume surrounding a star is proportional to the radius  $r$  around the star times the optical luminosity of the star:  $L_{IC} \propto r L_{STAR}$ . The flux depends on the star's distance  $d$ :  $\text{flux}_{IC} \propto L_{IC}/d^2$  and for an angle  $\alpha \propto r/d$ , we obtain  $\text{flux}_{IC} \propto L_{STAR}\alpha/d$ . A more precise formulation is given in the next section.

## 2 IC single stars: theory

The gamma ray intensity as a function of gamma energy of the scattered photon is:

$$I(E_{\gamma}) = \frac{1}{4\pi} \int \varepsilon(E_{\gamma}) ds \quad (1)$$

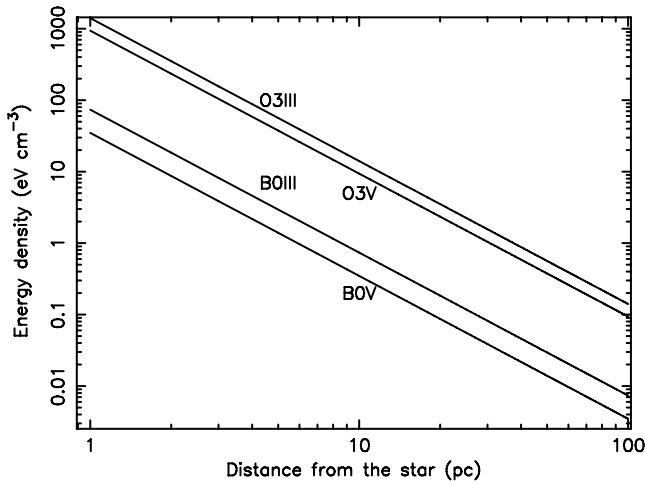
where the emissivity  $\varepsilon$  is given by:

$$\varepsilon(E_{\gamma}) = \int dE_e \int \sigma(\gamma, E_{ph}, E_{\gamma}) n_{ph}(E_{ph}) c N(E_e) dE_{ph} \quad (2)$$

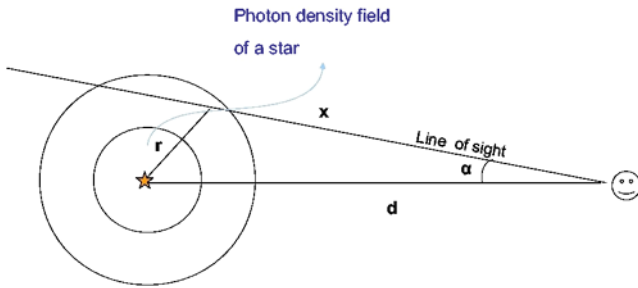
where  $N(E_e) = A E_e^{-p}$  is the electron spectrum and  $\sigma$  is the Klein–Nishina cross section for isotropic scatter-

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**Fig. 1** Photon energy density around different main sequence and giant stars from 1 pc to 100 pc



**Fig. 2** Definition of variables for equation (3)

ing.<sup>1</sup>  $E_{ph}$  is the stellar photon energy and  $n_{ph}$  the photon density. We assumed the star to be a black body where the energy density is characterized by the effective temperature following the Stefan–Boltzmann equation. The photon density at distance  $r \gg R$  from the star is:  $n_{ph}(r) = (1/4) n_{ph}(R)R^2/r^2$  since the energy density at  $r$  is  $(\sigma/c)T_{eff}^4(R^2/r^2) = (a/4) T_{eff}^4(R^2/r^2)$  where  $R$  is the radius of the star,  $n_{ph}(R)$  is the black body density at the effective temperature and  $a$  is the radiation constant. We assumed this relation for all distances. The value of the photon energy density obtained for bright stars (Fig. 1) is above the mean interstellar value of about  $1 \text{ eV cm}^{-3}$  even at 10 pc distance from the star, suggesting it contributes to clumpiness in the ISRF and hence in the IC emission. In order to obtain the inverse Compton radiation over a line-of-sight at an angle  $\alpha$  from the star, the density variation over the line has to be known. As illustrated in Fig. 2, for a given point  $x$  on the line-of-sight, the surface photon density is proportional to  $1/r^2$ , where  $r^2 = x^2 + d^2 - 2dx \cos \alpha$ , with  $d$  distance from the star. Integrating the photon density over the line of

sight from  $x = 0$  to  $x = \infty$  and over the solid angle, the total photon flux produced by inverse Compton becomes:

$$\begin{aligned}
 f(E_\gamma) &= \frac{1}{4\pi} \int_0^{2\pi} d\varphi \int_0^\alpha \sin \alpha d\alpha \int dE_{ph} \\
 &\times \int \sigma_{KN}(\gamma, E_{ph}, E_\gamma) cN(E_e) dE_e \frac{n_{ph}(R)}{4} R^2 \\
 &\times \int_0^\infty \frac{dx}{x^2 + d^2 - 2xd \cos \alpha} \\
 &= \frac{R^2}{16d} \left( \pi\alpha + \left(\frac{\pi}{2}\right)^2 - \arctan^2(\cot \alpha) \right) \\
 &\times \int dE_{ph} \int \sigma_{KN} cN(E_e) n_{ph}(R) dE_e \quad (3)
 \end{aligned}$$

which for small  $\alpha$  is proportional to  $\alpha/d$  and the intensity  $I$  (per solid angle) is proportional to  $1/(\alpha d)$ .

### 3 IC for stellar types and distances

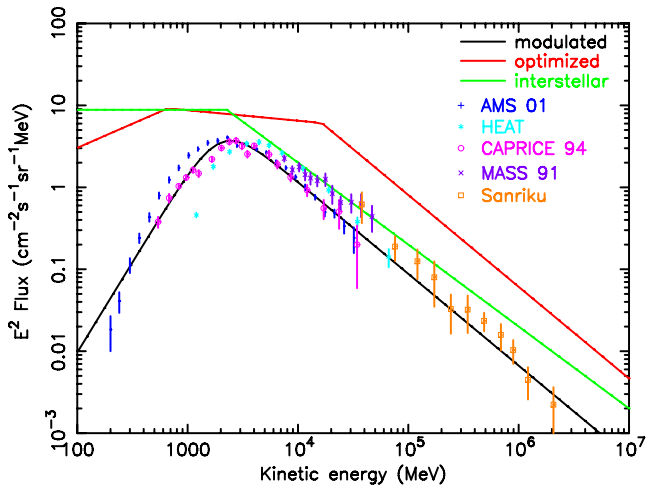
The IC emission for stars has been computed using the electron spectrum shown in Fig. 3. This approximates the local interstellar electron spectrum based on direct measurements. Explaining the diffuse Galactic emission including the ‘GeV excess’ requires about a factor 4 higher electron spectrum described by the optimized model (Strong et al. 2004a). The present estimate is therefore rather conservative. The gamma-ray flux depends on the star distance and on the angle of integration: in fact it scales as the linear inverse of the distance and to first approximation is proportional to the angular distance from the star. Figure 4 shows, as an example, the spectrum of the gamma-ray emission of stars of different spectral types and Fig. 5 the gamma-ray flux as function of the angle of integration.<sup>2</sup>

### 4 Candidates for detection and predictions for GLAST

The most luminous and nearby stars are candidates for giving a significant flux contributing to the total Galactic emission. Since the IC sources are extended, the angular radius to which the flux is taken is arbitrary, but we choose a value of  $5^\circ$  which is a compromise between angular resolution and sensitivity of gamma-ray telescopes. The value of this angle could be further optimized for specific cases.

<sup>1</sup>We have also computed the anisotropic case but the difference is less than 10%.

<sup>2</sup>Note that the main contribution to the emission comes from more than about a pc from the star and hence is mostly beyond the influence of stellar winds (Torres et al. 2004).



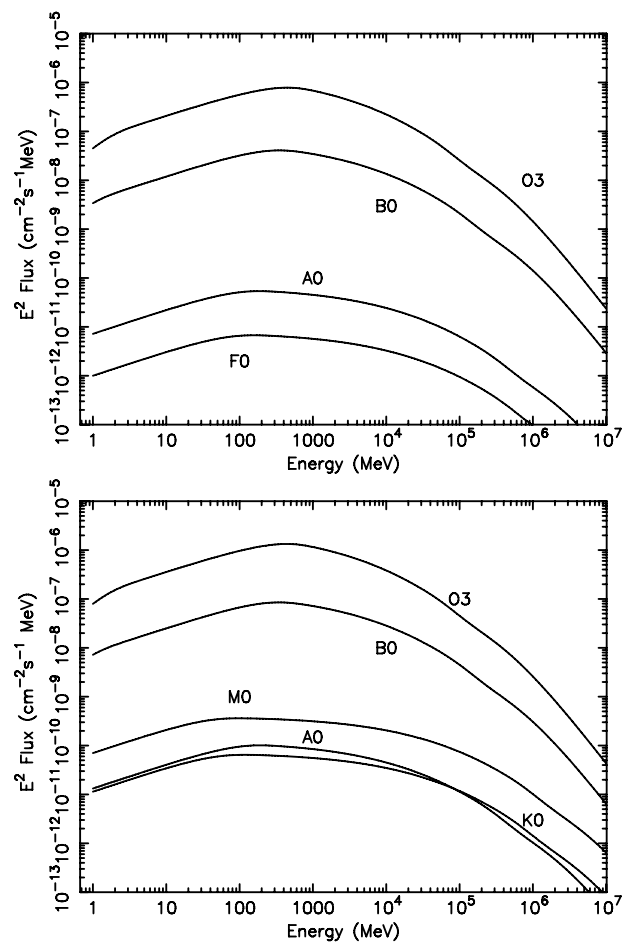
**Fig. 3** Adopted modulated electron spectrum (black line), adopted interstellar model (green line) and optimized model (red line) compared with the data. Data: AMS 01 (Alcaraz et al. 2000), HEAT 94-95 (DuVernois 2001), CAPRICE 94 (Boezio et al. 2000), MASS 91 (Grimani et al. 2002) and Sanriku (Kobayashi 1999)

#### 4.1 Possible stellar candidates

In order to simulate the gamma-ray flux from halos around stars, the possible candidates have been taken from the Hipparcos nearby star catalogue (The Hipparcos and Tycho Catalogues 1997), choosing only the first 70 most luminous stars. This list includes stars up to 600 pc distance. The results are compared in Fig. 6 with the GLAST point source sensitivity (GLAST, <http://www-glast.stanford.edu>) above 100 MeV of about  $3 \times 10^{-9} \text{ cm}^{-2} \text{ s}^{-1}$  for one year observation and about  $1.5 \times 10^{-9} \text{ cm}^{-2} \text{ s}^{-1}$  for 5 years observation. According to our prediction, the most gamma-ray bright stars are  $\kappa$  Ori (B0Iab, distance 221 pc),  $\zeta$  Pup (O5Ia, distance 429 pc, parameters from Lamers and Leitherer 1993) and  $\zeta$  Ori (O9.5Ib, distance 250 pc) with a flux respectively of 1.2, 1.1 and  $1 \times 10^{-9} \text{ cm}^{-2} \text{ s}^{-1}$  for energy  $>100$  MeV and within  $5^\circ$  angle. Further stars with a flux above  $10^{-10} \text{ cm}^{-2} \text{ s}^{-1}$  are Betelgeuse,  $\delta$  Ori,  $\beta$  Ori or Rigel,  $\zeta$  Per,  $\lambda$  Ori,  $\varepsilon$  cMa. Another important candidate is  $\eta$  Carinae with  $T_E = 30\,000$  K, 2.3 kpc distance and luminosity of  $7 \times 10^6$  solar luminosity (Davidson and Humphreys 1997). The estimated IC flux within  $5^\circ$  angle is 2.2, 0.1,  $0.005 \times 10^{-9} \text{ cm}^{-2} \text{ s}^{-1}$  respectively for energy  $>100$  MeV,  $>1$  GeV and  $>10$  GeV. However the fluxes obtained are affected by errors due to the big uncertainty of the parameters of the stars which could mean that some can be brighter  $\gamma$ -ray sources than these estimates.

#### 4.2 OB associations: Cygnus OB2

Apart from individual stars, the full stellar population will exhibit features due to their clustering e.g. in OB associations. As an example the flux from Cygnus OB2 has been

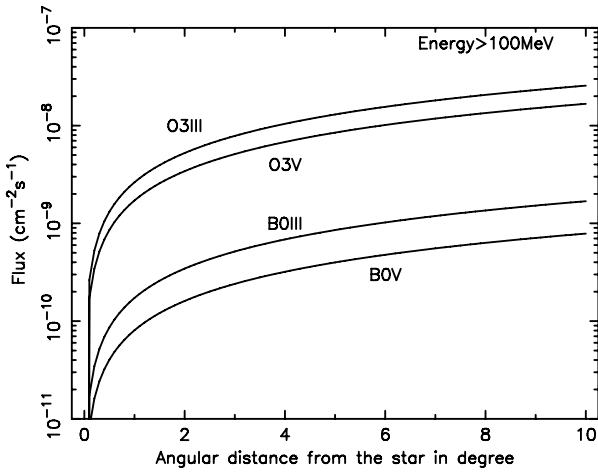


**Fig. 4** Gamma-ray spectrum generated by IC scattering on the photon field of main sequence stars (upper) and giant stars (lower) at 100 pc distance. Flux is integrated over  $5^\circ$  radius

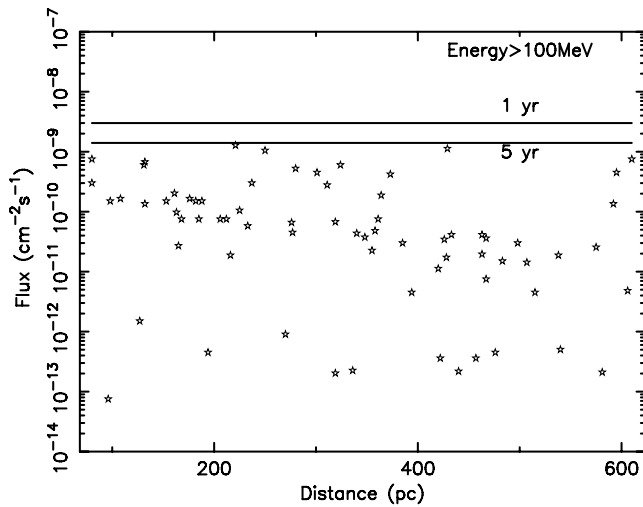
estimated for 120 O stars and 2489 B stars at 1700 pc distance. Data for the Cygnus association and stellar components are taken from Knödlseder (2000). A conservative assumption adopts only O9 and B9 main sequence stars giving a flux within  $5^\circ$  of 4.8, 0.5,  $0.02 \times 10^{-9} \text{ cm}^{-2} \text{ s}^{-1}$  respectively for energy  $>100$  MeV,  $>1$  GeV and  $>10$  GeV, while a more realistic assumption takes O6 and B5 main sequence stars, giving a flux of 18, 1.9,  $0.05 \times 10^{-9} \text{ cm}^{-2} \text{ s}^{-1}$  respectively. For  $1^\circ$  instead the estimated flux is 3.7, 0.3 and  $0.008 \times 10^{-9} \text{ cm}^{-2} \text{ s}^{-1}$  for the previous energy ranges and the more realistic assumption. This will clearly be of interest for GLAST. Furthermore we note that cosmic rays may also be accelerated in colliding winds in OB associations (e.g. Reimer 2007 and Torres 2007) which would further increase the fluxes.

## 5 The Sun

We apply the basic formalism to the Sun and find that the IC emission is not negligible. The IC emission has been com-

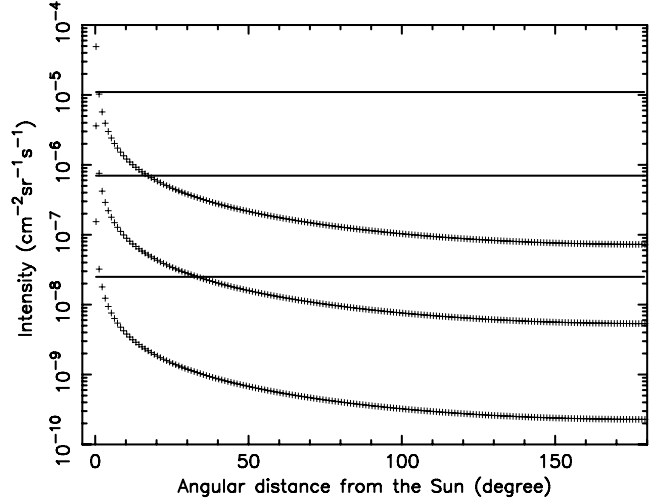


**Fig. 5** Cumulative flux integrated over solid angle from stars at 100 pc distance as a function of angle for  $E_\gamma > 100$  MeV

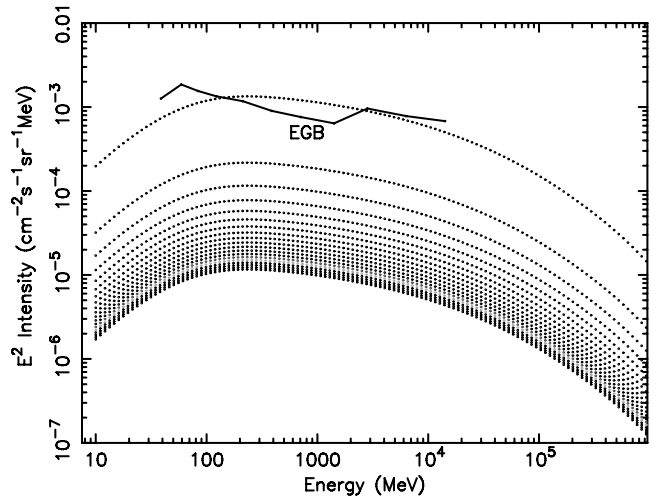


**Fig. 6** Gamma flux integrated over  $5^\circ$  angle from the 70 most luminous stars from Hipparcos catalogue for  $E_\gamma > 100$  MeV compared with the GLAST point source sensitivity for 1 year and 5 years observation (*horizontal lines*)

puted using the modulated solar electron spectrum shown in Fig. 3. Figure 7 shows the IC intensity as a function of angular distance from the Sun compared with the EGB for different energy ranges. Figure 8 shows the spectrum at different angles. We estimate that the gamma-ray intensity from the halo around the Sun contributes to the background emission at a level of a few percent of the extragalactic background (EGB) even at large angular distance from the Sun. The estimated IC flux within  $5^\circ$  angle is 100, 8.4,  $0.3 \times 10^{-9} \text{ cm}^{-2} \text{ s}^{-1}$  respectively for energy  $>100$  MeV,  $>1$  GeV and  $>10$  GeV, while within  $1^\circ$  angle it is 18, 1.3,  $0.05 \times 10^{-9} \text{ cm}^{-2} \text{ s}^{-1}$  for the same energy ranges. The gamma flux in the range 100 MeV–10 GeV for  $5^\circ$  angle is about 5% Crab. The electron spectrum is however uncertain



**Fig. 7** Estimated IC intensity (*dotted lines*) as a function of angular distance from the Sun compared with the EGB (Strong et al. 2004b) (*solid lines*) for different energy ranges: top to bottom  $>100$  MeV,  $>1$  GeV and  $>10$  GeV



**Fig. 8** Gamma-ray spectrum for different angles from the Sun. *Dotted lines* show the spectra from top to bottom at steps of  $5^\circ$  from  $1^\circ$  to  $90^\circ$ , while the *solid line* represents the EGB measured by EGRET (Strong et al. 2004b)

(Fig. 3) so that the IC flux could be larger or smaller by a factor  $\sim 2$ . In future a model of the gamma-ray flux from the Sun will be implemented, in order to take it into account for diffuse background emission studies.

### 6 Conclusion

We have estimated the gamma-ray emission by IC scattering of cosmic-ray electrons with the radiation field around stars. We find that the contribution of the most luminous stars is non-negligible and even individual luminous stars could be

detectable by GLAST. Moreover OB associations can contribute to the clumpiness of the emission. The same model applied to the Sun<sup>3</sup> shows that the IC emission produced is significant and should be accounted for in diffuse background studies.

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<sup>3</sup>When this work had already been completed we learned about work by Moskalenko et al. (2006) on the Sun.

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