GRBs and SGRs by high energy leptons showering in blazing $\gamma$ jets: are SGRs sources of EeV CRs?

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ABSTRACT

The apparently huge energy budget of the gamma ray burst GRB 990123 led to the final collapse of the isotropic fireball model, forcing even the most skeptical to consider a beamed jet emission correlated to a supernova (SN) explosion. Similarly the surprising giant flare from the soft gamma repeater SGR 1806-20 that occurred on 2004 December 27, may induce the crisis of the magnetar model. If the apparently huge energy associated to this flare has been radiated isotropically, the magnetar should have consumed at once most of (if not all) the energy stored in the magnetic field. On the contrary we think that a thin collimated precessing jet, blazing on-axis, may be the source of such apparently huge bursts with a moderate output power. Here we discuss the possible role of the synchrotron emission and electromagnetic showering of PeV electron pairs from muon bundles. A jet made of muons may play a key role in avoiding the opacity of the SN-GRB radiation field. We propose a similar mechanism to explain the emission of SGRs. In this case we also examine the possibility of a primary hadronic jet that would produce ultra relativistic $e^\pm$ (1 - 10 PeV) from $\pi - \mu - e$ or neutron decay. Such electron pairs would emit a few hundreds keV radiation from their interaction with the galactic magnetic field, as it is observed in the intense $\gamma$-ray flare from SGR 1806-20. A thin precessing jet ($\Delta \Omega \simeq 10^{-9} - 10^{-10}$ sr) from a pulsar may naturally explain the negligible variation of the spin frequency $\nu = 1/P$ after the flare ($\Delta \nu < 10^{-5}$ Hz). A correlation between SGR 1806-20, SGR 1900 +14, Cygnus and the AGASA excess of EeV cosmic rays (CRs) has been found; we suggest that a robust EeV signal may be detected by AUGER or Milagro in the near future.

1 INTRODUCTION

1.1 GRBs fireball versus thin precessing jets

The association between gamma ray bursts (GRBs) and SNe has become more and more convincing in the last few years after the discovery of two main events. In 1998, the spectroscopical and photometrical analysis of the GRB 980425 afterglow revealed for the first time the presence of a SN related to the GRB event (Galama et al. 1998), and more recently SN2003dh has been detected in coincidence with the GRB 030329 (Hjorth et al. 2003; Stanek et al. 2003). At least other two GRB events seem to be connected to SNe explosions (GRB 011121/SN2001ke, Garnavich et al. 2003; GRB031203/SN2003lw; Malesani et al. 2004). At the time of its discovery, the GRB980425/SN1998bw association faced large resistance among the scientific community, whose attention was focused on the fireball scenario where this SN/GRB connection was unacceptable. Indeed the spherical fireball has been in the last decade the most popular model to interpret GRBs, with the basic assumption that the energy is radiated isotropically. Consequently the output power of GRBs would be billion times higher than that of a SN. According to the fireball model, GRBs are produced in shocks of highly relativistic outflows with different Lorentz factors via synchrotron radiation of electron pair. These so-called "internal shocks" are thought to produce the highest energy gamma emission. The consequent interaction of the stellar ejecta with the circum-stellar medium (external shocks) would be responsible of the multi-wavelength afterglow and its complex time structure discovered for the first time by Beppo Sax (Costa et al. 1997).

However isotropic explosions would require extremely high input energies, the larger and harder the more distant the GRBs (the so called "Amati " law, whose behaviour is opposite to the Hubble law); for example, to account for the GRB 990123 emission, about two solar masses should have been entirely converted in gamma-rays (which should be doubled if MeV neutrino pairs were taken into account; Fargion 1999). Very massive black holes (10 - 100 $M_\odot$) are needed to fuel such fireball explosions. But the inner GRB time structure, as short as a tenth of milliseconds, would require a Schwarzschild radius smaller than a few tens of km, corresponding to objects of only a few solar masses. Such a discrepancy, added to the SN/GRB connection, made clear the inconsistence of the fireball scenario. Later on new families of fireball models with a wide beamed emission have
been introduced to overcome this puzzle and reduce the energy budget (such as the Hyper-Nova, Supra-Nova, or the Collapsars models). In these "compromise" scenarios the outflow was thought to occur in a "fountain" cone with opening angles as large as $\sim 5^\circ - 10^\circ$. However we think that even this "mild" beaming is unable to solve the whole GRB puzzle.

In fact the beamed emission proposed in such models reduces the required power output by three orders of magnitude, down to $10^{30}$ erg s$^{-1}$, nonetheless this is yet $10^6 - 10^7$ times more intense than the observed SN power. There is no reason to expect such a huge unbalance between the GRB jet and the SN luminosities, $E_{\text{GRB}} \simeq 10^7 \times E_{\text{SN}}$. Moreover a few degrees jet does not solve the puzzle of the low $\gamma$ ray power detected in the GRB080425/SN1998bw event, which finds a natural understanding assuming a narrow jet blazing the observer off-axis (Wang & Wheeler 1998; Fargion 1999). Moreover a single one-shot explosion beamed in a wide jet cannot account for the presence of X-Ray precursors before the onset of a few GRB events ($\sim 6\%$).

In this context, we have been proposing for the last decade, an alternative scenario to the fireball where GRBs (as well as SGRs) are originated by highly collimated precollasing and blazing gamma jets with an aperture angle $\theta \sim 0.02^\circ - 0.006^\circ$ (Fargion & Salis 1995a, 1995b, 1995c; Fargion 1999).

The much narrower solid angle of the jet, $\Delta \Omega/\Omega \simeq 10^{-8} - 10^{-4}$, can reconcile (assuming the energy equipartition between the powers of the SN and the jet) the puzzle of the "low" observed isotropic SN luminosity with respect to the apparent "huge" GRBs power (an observed $10^{-8} - 10^{-5}$ ratio). The angular dynamics (a spinning and multi-precessing jet) may explain the wide range of properties observed in different GRB events (multiple bursts, re-brightening and bumps, X-ray precursors, dark GRBs, X-ray flashes, low luminous off-axis GRBs; Fargion 1999; Fargion 2003).

Within this framework, the Amati-Ghirlanda $E_{\text{peak}} - E_{\text{iso}}$ correlation (Amati et al. 2002, Ghirlanda et al. 2005) is just the effect of a very biased selection. At increasing distances (high $z$) and volumes, a larger sample of highly collimated GRBs becomes observable; the jets more collimated towards the observer appear as very hard and powerful GRBs, while those blazing off-axis would be mostly obscured and below the detectors' sensitivity. At extreme redshifts the number of GRBs should drop off (due to a finite age of their progenitor and the absence of SN events) or they might correspond to the mysterious short GRB events.

However assuming a thin one-shot jetted model leads to a contradiction with the observations and it does not provide the ultimate solution to the issue. In fact, such a strong collimation would imply that the rate of one-shot beamed GRBs should be $\Gamma_{\text{beamed}} \sim 10^6 - 10^7 \phi_{\text{GRB}}$, where $\Gamma_{\text{obs}} \sim 10^{-7} - 10^{-8}$ yr$^{-1}$galaxy$^{-1}$. Given that GRB are expected to be related to SN explosions, this value would be at least $10^9 - 10^{10}$ times higher than all the observed SN rate, $\Gamma_{\text{SN}} \sim 10^{-5}$ yr$^{-1}$galaxy$^{-1}$. This apparent inconsistency may be solved if one assumes that the jet structure is precessing and persistent, with a decay lifetime much longer than the typical observed GRB timescale ($t_{\text{GRB}} \sim 10$ s, $t_{\text{jet}} \gtrsim 10^4$ s, $E_{\text{jet}} \simeq E_{\text{peak}}(t_{\text{jet}}/10)^{-\alpha}$, where $\alpha \gtrsim 1$, in order to converge to the value of the total output energy). Therefore we argue that the jet continues to exist after the SN event, although it is fading with time. This reduces the number of GRBs needed to account for the observed GRB rate. The activity of the jet might be later rejuvenated by an accretion disc, possibly fed by a nearby compact companion. The torque perturbation created by the companion induces the multiprecession of the GRB jet.

This might also explain the abundance (nearly two-thirds) of the so-called "orphan" or "dark" GRBs, where the brightest event associated to the SN and its consequent afterglow may be already faded just a few weeks or months before. The delayed jet activity may blaze again and it may be source of rare optical and radio re-brightening of the GRB, while much older and weaker sources, may be observed thousands of years later as SGRs, or Anomalous X-Ray pulsars$^1$, provided that they are nearby and on-axis. This occurs mostly in our galaxy and in the Large Magellanic Cloud.

Let us remind that a few GRBs and SGRs did show comparable time structures and spectra (Fargion 1999), even if a possible connection between GRBs and SGRs has been often underestimated or even rejected (Woosley et al. 1999). Consequently the "necessary" evolution of the fireball scenario into a jetted model may be reflected on SGRs, whose blazing nature challenges the interpretation given by the magnetar model (Duncan & Thompson 1992; Thompson & Duncan 1995). In fact, similarly to the GRB 990123 fireball crisis, the very exceptional giant flare from SGR 1806-20 occurred on 2004 December 27 is suggesting that an isotropic magnetar has to be questioned as the explanation of these events for several reasons that we discuss in the following section.

1.2 SGRs and the puzzles of the magnetar model

Soft Gamma Repeaters are nearby X-ray sources localised within the Milky Way (excluding SGR 0525-66 in the Large Magellanic Cloud), emitting sporadic short bursts of soft gamma photons up to hundreds of keV. The giant flare from SGR 1806-20 on 2004 December 27 has been characterised by an energy release which largely exceeded all previous recorded events. It should be noticed that the giant flare energy exceeded the integral sum of all GRBs and SGRs ever recorded. This unique event, averaged over 100 years, would make the SGRs flux much more intense than that of GRBs ($\Phi_{\text{SGR}} \gtrsim 100$ eV cm$^{-2}$ s$^{-1}$ sr$^{-1}$). The flare, if it was blazing far from the sun in a dark night (contrary to the real case), would have shone (while showering and ionising the atmosphere) like a brief visible aurora in the sky.

At an assumed distance of 15 kpc the isotropic energy associated with the flare would be $E = 3.5 - 5 \times 10^{46} d_{15}^2$ ergs (Hurley et al. 2005; Schwartz et al. 2005) with a peak luminosity in the first 0.125 s equal to $L = 1.8 - 2.7 \times 10^{47}$ erg s$^{-1}$. Only two other giant outbursts of energy above $10^{44}$ ergs have been observed in about 30 years of previous SGR activity, but never at such a huge peak power ($E \sim 10^{47}$ erg s$^{-1}$). While the giant flare energy is a tiny fraction ($10^{-4}$) of an electromagnetic galactic Supernova, its peak power exceeds the optical SN output by nearly the inverse ratio($\approx$
Note that the energy budget could be lowered if SGR 1806-20 were closer, as it has been recently proposed that its distance may be within 6.4 - 9.8 kpc (Cameron et al. 2005). Note also that a closer distance implies an extreme relativistic propagation of the radio ejecta ($r < 0.6c$).

The most popular model to interpret the properties of SGRs is the magnetar, a neutron star with a very high magnetic field ($B \sim 10^{14} - 10^{15}$ G). This model implies an isotropic thermal energy release like a mini-fireball, and it was born in the 90's when fireball models were ruling the understanding of GRBs. Surprisingly, a flare of energy $3.5 - 5 \times 10^{46}$ d$_{15}^3$ erg radiated isotropically would need to convert at once almost all of the magnetar energy stored in the magnetic field. This would imply a remarkable decrease of the magnetic field energy density which should appear as a prompt decrease in the pulse period times the period derivative, $P\dot{P}$. As a consequence, there should be a correlation between the burst activity and the variation of the spin period, that so far has not been observed (Woods et al. 2002). Neither the recent giant flare showed evidence for a variability in its period (Mereghetti et al. 2005, Woods et al. 2005 ATEL n. 407).

Moreover the high energetics involved in this intense flare has raised the possibility that nearby extragalactic SGRs may be connected to short GRBs. In this case if SGRs are isotropic phenomena, as predicted by the magnetar model, one should observe an anisotropy in the distribution of short GRBs compared to long ones, with the first more concentrated towards local cluster of galaxies, especially towards Virgo the closest rich cluster in the local universe. Virgo contains about 128 spiral galaxies (Binggeli, Tamman & Sandage 1987), assuming that the periodicity of a giant flare in a galaxy may be 1 in 100 years, one should expect to see $128/100 \sim 1.3$ events/yr clustered in the area of Virgo. If short GRBs and SGRs are the same events, the BATSE instrument in its 10 years life time, should have detected about 13 short GRBs with a spatial distribution correlated to the Virgo cluster. Such a remarkable anisotropy, expected in the magnetar scenario, does not appear in the BATSE GRB catalogues neither from the Virgo cluster, nor from galaxies with extremely high star formation rate such as Arp 299 and NGC 3256 (Popov & Stern 2005). Moreover no similar giant flares were found in the BATSE data in nearby galaxies (within 2 and 4 Mpc) with ongoing massive star formation such as M 82, M 83, NGC 253 and NGC 4945 (Popov & Stern 2005). According to the authors, the galactic rate of giant flares with energy around $10^{46}$ erg should be less than $10^{-3}$ yr$^{-1}$.

On the other hand, a very thin, precessing $\gamma$ Jet would reduce the high energy budget required in an isotropic energy release, and it may produce at any time an exceptional bright (on-axis) event. The rarity of such an event would imply a negligible activity even from Virgo, still consistent with the absence of an anisotropy in the BATSE short bursts catalogue; the giant flare visibility may be below the threshold from clusters at larger distances ($z > 0.05$) (Popov & Stern 2005).

### 1.3 Structure of the paper

We suggest that precessing and persistent jets would better explain the observed properties of both GRBs and SGRs, even though several issues are yet to be addressed within this model. In this paper we aim to improve our scenario introduced and discussed in previous works (Fargion 1998; Fargion 1999; Fargion 2003), where we considered jets made of relativistic GeV electrons producing the gamma radiation by ICS, and we try to solve some of the problems related to this model. How can a jet of GeVs electron pair penetrate and propagate through the SN envelope? How can the collimated pairs survive the dense photon background at the baryon column depth at the SN surface? Is it possible that a jet is already present before the SN explosion, but it reaches its maximum power only after the stellar collapse?

To overcome the opacity problem due to the photon SN background, here we present a scenario for GRBs where the jet is made by muons of energy $\gtrsim 1 - 10$ PeV. We assume (but we will not thoroughly discuss this hypothesis in this paper) that in GRBs PeV muons are themselves secondaries of ultra high energy (UHE) neutrinos possibly originated in a deeper and inner jet made of EeV - ZeV nucleons accelerated in the GRB/SN explosion. We show that the PeV muons could more easily propagate through the dense SN radiation background and they could also better penetrate the outer stellar layers compared to a jet made of electrons (or baryons). When muons decay into $\sim$ PeV electrons, we compare the energy loss mechanisms that can produce the observed gamma emission: synchrotron interactions due to the stellar or galactic magnetic field, versus ICS of $e^\pm$ onto the stellar radiation background.

We discuss a similar mechanism to explain the gamma signal from SGRs, always assuming a primary jet made of muons. We find that synchrotron losses (due to the galactic magnetic field $B \sim 2.5 \times 10^{-6}$ G) of electron pairs at $E_\gamma \sim$ PeVs, from the decay of PeV muon bundles, may be the best mechanism to originate the $\gamma$ radiation from SGRs.

We consider also that PeV muons may be secondaries of EeV nucleons originated via photopion interactions, since we find a possible link between the anisotropy in the EeV CR distribution near the galactic center observed by AGASA (Hayashida et al. 1999) and SUGAR (Bellido et al. 2001), and the position of SGR 1806-20. If this correlation is not fortuitous this maybe the first evidence of a connection between EeV CRs and the SGR activity. The possibility of detecting CRs (nucleons and TeV photons) and neutrinos from this giant flare in AUGER, MILAGRO and AMANDA is also discussed.

The paper is organized as follows: in §2 we briefly summarise the main characteristics of the precessing jet model, in §3 we discuss the problem of the opacity of electrons propagating through a dense supernova gas photon, and we introduce a primary muon jet model, in §4 we discuss the possible mechanisms that can lead to the gamma emission from secondary electron pair Jets, in §5 we apply the same model to SGRs, and we discuss the correlation between EeV CRs and SGR 1806-20, and finally in §6 we present our final discussion and conclusions.

## 2 THE PRECESSING JET SIGNATURES

Precessing jets have been already introduced to explain the properties of other astrophysical objects. Well known microquasars, such as 1915-16 and SS 433, are the best candidate
to show the multi-precessing jet evolution in nearby galactic objects (see Fig. 1). Other well known sources as CH Cyg, Cyg X-3 and GRO J1655-40 show precessing jets whose properties remind, at a smaller scale, those of larger active galactic nuclei such as M87 or Cygnus A. Bipolar planetary nebulae as the Sa2-237 (Schwarz, Corradi & Montez 2002) hidden in molecular clouds or the Egg Nebulae (see Fig. 1), also show features that give evidence of a twin double cone possibly made by a precessing jet. At a lower luminosity, jets are used to explain the properties of two accreting white dwarfs (Zamanov et al. 2005) exhibiting collimated outflows with a morphology well fit by a precessing jet model. Outflows collimated in jets are also observed in Herbig Haro protostellar objects (HH 40, HH 34), and in the large protostar IRAS 16547-4247.

According to Mirabel (2004) there is an universal mechanism for the production of relativistic jets in accreting black holes that would unify AGN, GRBs, microquasars and Ultra Luminous X-ray (ULX) sources.

In our model we assume that GRBs and SGRs originate from the same process and they represent the early and the late stages of the evolution of a precessing jet. The jet is possibly fuelled by the SN event for a GRB and by an accretion disc or a companion in the case of SGRs. In SGRs the close encounter between a compact source with a fading jet and the companion star, may strip matter from the latter, that, falling into the accretion disc, leads to an increase or a revival of the jet power. The presence of a compact star (white dwarf or a neutron star) would be the best candidate to bend the jet before and after a SN in GRBs.

Therefore we propose a model of a jet that is not static, but we assume that it is spinning as the dense central object that hosts it (pre-SN star or NS), and precessing, even at random, due to the presence of a binary companion (or an asymmetric accretion disc). A nutation mode is superposed to the precession circle. The spinning motion provides a short duration of the GRB (or SGR) event, while precessing modes move the jet in and out of the line of sight leading to a re-brightening or a quasi periodic activity.

The temporal evolution of the angle between the jet direction and the rotational axis of the object, \( \theta(t) \), can be expressed as

\[
\theta(t) = \sqrt{\theta_1^2 + \theta_2^2}
\]

with

\[
\theta_1(t) = \sin(\omega_t + \phi_1) + \theta_{psr} \cdot \sin(\omega_{psr} t + \phi_{psr}) + \theta_s \cdot \sin(\omega_s t + \phi_s) + \theta_N \cdot \sin(\omega_N t + \phi_N) + \theta_0(0)
\]

\[
\theta_2(t) = \theta_0 \cdot \sin(\omega_0 t) + \cos(\omega_0 t + \phi_0) + \theta_{psr} \cdot \cos(\omega_{psr} t + \phi_{psr}) + \theta_s \cdot \cos(\omega_s t + \phi_s) + \theta_N \cdot \cos(\omega_N t + \phi_N) + \theta_0(0)
\]

\( \gamma \) is the Lorentz factor of the relativistic particles (half PeV electrons). \( \theta_{psr} \), \( \theta_s \), \( \theta_N \) are respectively the maximal opening angles due to the spinning of the star, the perturbation due to the companion, and the nutation motion of the multi-precessing jet axis. The arbitrary phases \( \phi_0 \), \( \phi_{psr} \), \( \phi_N \), for the binary, spinning pulsar and nutation, are able to fit the complicated features of the GRB light curves in most of the observed events. The additional parameters have been introduced to model the light curve of the SGR giant flare. \( \theta_n \) is the bending angle of the entire cone precessing with a frequency \( \omega_n \), corresponding to a period of nearly a dozen years (related to "intermittent" SGRs activity); \( \theta_0 \) is a possible inner pulsation of the pulsar at frequency \( \omega_0 = 25 \) rad/s; \( \theta_N \) and \( \omega_N \) refers to the nutation motion of the jet, and \( \theta_0(0) \), \( \theta_s(0) \), \( \theta_N(0) \) are fine tuned phases able to reasonably reproduce the observed light curve of the giant flare.

In Fig 2 we show the results of our models for the parameters displayed in Table 1.

We have shown already (Fargion 1999, Fargion 2003) that by varying the parameters of this simple model one can fit the profiles of the GRB events. Moreover we proved (Fargion & Salis 1995a, 1995b, 1995c, Fargion & Salis 1998, Fargion 1999) that the GRB \( \gamma \) observed spectrum may be well fit by the Inverse Compton Scattering of relativistic electrons with a power-law or a monochromatic spectrum.

\[ \text{Fig. 1. Up: The Egg Nebula, whose shape might be explained as the conical section of a twin precessing jet interacting with the surrounding cloud of ejected gas. Down: The observed structure of the outflows from the microquasar SS433. A kinematic model of the time evolution of two oppositely directed precessing jets is overlaid on the radio contours (from Blundell & Bowler 2005).} \]
GRBs and SGRs by high energy leptons showering in blazing $\gamma$ jets

3 THE NATURE OF THE GRB JETS

3.1 The opacity of the SN radiation to an electron pair jet

One important issue is whether the jet is born during the SN event or if it is already present.

If the jet is created during or immediately before the SN explosion as soon as the GRB emission is detected, it is unlikely that a jet powered for the typical duration of a long burst ~ 20 s could penetrate a giant star. It would rather dissipate its energy in the stellar envelope. Moreover it would take about 1000 s for the jet to penetrate a red supergiant and break the stellar surface (Rosswog 2003).

Recent theoretical models assume that the progenitor of a GRB is a massive star which has already lost its H envelope before core collapse, given the correlation between GRBs and supernova of type Ic (i.e. core-collapse but no hydrogen and helium lines). These type of stars are usually identified as Wolf-Rayet and are characterised by initial masses of about 25 - 40 $M_\odot$ (Maeder & Conti 1994). The heavy mass loss rate that distinguishes these objects reduces the mass of the star by losing the outer hydrogen and helium layers, leaving a carbon/oxygen core (Matheson 2004). In general they are expected to have less massive envelopes than SNe Ib. Typical masses are around 16 to 18 $M_\odot$ but the range is wide: from 5 $M_\odot$ to 48 $M_\odot$. Therefore W-R stars are the low mass descendants of previously massive O stars (Maeder 1990).

Radii are very difficult to determine for these stars, especially because of the strong mass loss that makes it difficult to define what is the stellar surface. However, few estimates exist for eclipsing binaries, where the radius is found to be 11 $R_\odot$ for the late type CQ Cephei (HD 214419, WN7+O9) and ~ 3$R_\odot$ for the earlier V444 Cygni (HD 193576, WN5+O6). There appears to be a correlation between large radii and late-type WR stars (where the Hydrogen lines are detected), while early type WR stars (no Hydrogen lines) show smaller radii.

Therefore such a smaller progenitor with a thinner stellar envelope would have more favorable conditions for the jet to emerge from the stellar surface (as for the GRB 021004, see Starling et al. 2005). GRB 031203, GRB 030329, and the most popular GRB event related to SN 1998bw, all show spectra typical of a type Ic SN.

Another possibility would be that the jet is already present before the SN event, as one can see in young stellar sources, whose jet are well observable and often in precession, such as Herbig Hero objects.

Although there is no generally accepted mechanism able to explain the making of a thin jet structure, there seems to be a link between jets and accretion discs.

3.2 Muon jets to overcome the SN-GRB opacity

In our previous models of GRB emission we assumed a jet made of electron pairs of energy around 1 - 10 GeV produc-
ing the gamma-ray emission by IC onto thermal photons (Fargion 1995a, 1995b, 1995c; Fargion 1998; Fargion 1999; Fargion 2003). However, the main difficulty for a jet of GeV primary particles of the jet may be muons which can escape from the stellar interior without significant synchrotron losses. As a consequence, a jet of GeV muons decay before losing energy via IC scattering onto the stellar radiation field is highly suppressed.

Indeed high energy electrons and positrons \( E_e > 1 \text{ GeV} \) may inverse Compton scatter the UV/optical photons emitted by the star to high energies leading to an electron-photon cascade. The interaction length of \( e^\pm \) of energy \( E_e \), in an isotropic photon gas with density \( n(\epsilon) \), is given by (Protheroe 1986)

\[
\lambda^{IC}_{\epsilon} = \frac{1}{2} \int_0^{\infty} N(\epsilon) \int_{-1}^{1} \sigma_{\epsilon\gamma}(\omega)(1 - \beta \cos \theta) d(\cos \theta) d\epsilon
\]

where \( \theta \) is the angle between the electron and photon directions in the laboratory frame and \( \omega = (\epsilon E/m_c c^2)(1 - \beta \cos \theta) \) is the photon energy in the electron rest frame.

In Fig. 4 we show the IC interaction length for electrons and muons (dashed lines) scattering a black-body radiation field at a temperature \( T = 10^6 \text{ K} \). In the Klein-Nishina limit we have used the asymptotic formula given by Gould & Raphaeli (1978). From Fig. 4 one can see that electrons at \( E_e \gtrsim 10 \text{ GeV} \) can not propagate for more than \( 10^{-3} \text{ s} \) due to the scattering with the optical/UV emission. Moreover at \( 10^{-3} \text{ s} \) (\( \sim 300 \text{ km} \)) from the stellar surface the baryon density would also be able to reduce and block the UHE electron pair propagation. This represents a strong constraint for a jet model made of \( e^\pm \).

UHE muons \( (E_\mu \gtrsim \text{PeV}) \) instead are characterised by a longer interaction length either with the circum-stellar matter and the radiation field, since the \( \mu - \gamma \) cross section scales as the inverse square of the mass of the lepton involved (in the Thomson regime). In the Klein-Nishina regime at \( E > 10^{17} \text{ eV} \) the interaction lengths for muons and electron becomes comparable (see Fig. 4).

For this reason here we discuss the possibility that the primary particles of the jet may be muons with \( E_\mu \sim 10^{15} - 10^{16} \text{ eV} \), which can more easily escape from the stellar interior. A jet of primary electrons at the same energy would have a similar IC interaction length but their escape from the stellar surface would be obstructed by both the baryon load (i.e. electromagnetic interactions inside the matter) and by the synchrotron opacity which would be dominant at those energies for a magnetic field between 1 and 100 Gauss (see dotted lines in Fig. 4). From this starting point we investigate the mechanism able to produce the observed gamma radiation in GRBs from muon jets.

We assume that the star where the GRB occurs is a WR-like object with a characteristic radius \( R_\star \sim 10R_\odot \). When the muon jet breaks through the surface of the star it may interact either with the magnetic field of the star or inverse Compton (IC) scatter its optical – UV photon field.

The importance of the synchrotron process depends on the magnetic field configuration around the jet and the star. In the case of a WR star, the magnetic field on the surface may be as high as 100 G and assuming a \( \frac{1}{r^3} \) dependence, one can estimate the field intensity at a distance \( r \).

As an example, for an initial muon at \( E_\mu \sim 10^{16} \text{ eV} \) and a magnetic field of roughly 1 Gauss, synchrotron photons would be emitted at

\[
E_{\gamma, \text{sync}} \sim 4 \times 10^5 \left( \frac{E_\mu}{10^{16} \text{ eV}} \right)^2 \left( \frac{B}{1 \text{ G}} \right) \text{ eV}
\]

and the characteristic interaction length is

\[
\lambda_{\text{sync}} = \frac{E}{\sigma_T e^\gamma \mu B} \approx 5 \times 10^7 \left( \frac{E_\mu}{10^{16} \text{ eV}} \right)^{-1} \left( \frac{B}{1 \text{ G}} \right)^{-2} \text{ s}
\]

It follows (see Fig. 4) that for \( B < 100 \text{ G} \) the synchrotron interaction distance (dashed-dotted lines) is much longer than the IC (upper dashed line) and the muon decay length (straight solid line), therefore muons can propagate outside the star without significant synchrotron losses. Only for a magnetic field around \( 10^3 \text{ G} \), muons would lose most of their energy to synchrotron emission of photons with \( E_{\gamma} \sim 400 \text{ MeV} \), but such high magnetic fields in stars are yet to be confirmed.

Nevertheless for \( E_\mu \sim 10^{16} \text{ eV} \) even the interaction length of the IC scattering onto the stellar radiation field is larger than the muon lifetime (Fig. 4), therefore such muons decay into electrons (in roughly 100 s) before their energy is dissipated via IC or synchrotron. As a consequence, a jet of muons would be able to escape from the star and propagate for about 100 light-seconds before decaying into electrons. To understand the fate of such high \( e^\pm \) one needs to compare again the IC and synchrotron interactions to establish
which is the mechanism that most affects their loss of energy as they propagate outside the stellar surface.

4 GRBS BY ELECTRONS SHOWERING IN γ JETS

The main source of the thin gamma jet is the ultra high energy electron pairs showering into thin γ jets. PeV electrons and positrons from muon decay may either inverse Compton scatter the UV/optical photons emitted by the star, leading to an electron-photon cascade, or lose energy emitting synchrotron radiation in galactic magnetic fields.

From Fig. 3 it appears that synchrotron interactions are less favored compared to ICS because their distance scale is larger. In fact, even assuming that the intensity of the magnetic field of the pre-SN star, \( B \), decreases as \( r^{-2} \) (rather than \( r^{-3} \), at 100 light seconds from the star, \( B \) is low enough (\(< 10^{-2} \) G, if the field on the surface of the star is \( \sim 100 \) G) that electrons survive synchrotron losses, and IC constitutes the dominant energy loss mechanism (see in Fig. 3 the synchrotron energy loss distance for \( B = 10^{-2} \) G and the IC interaction length for electrons at energies around \( 10^{15} \) eV).

Compton interactions for PeV electrons occur in the Klein-Nishina regime, since the ambient photon energy in the rest frame of the electron is \( \omega \gg m_e c^2 \), and the \( e^\pm \) pair tend to transfer most of their energy (about \( \frac{1}{2} E_e \)) to the background photons. The propagation of the hard γ-rays is attenuated by the collisions with the stellar radiation background that leads to pair production (\( \gamma + \gamma \rightarrow e^+e^- \)). Compton scattering and pair production interactions concur to produce a complicated "electromagnetic cascade" which appears to be the favored mechanism for the PeV electrons to lose most of their energy (see also Fargion & Colaiuda 2004).

The attenuation length for a hard photon of energy \( E \), traversing a black-body photon gas of energy \( \epsilon \) and density \( n(\epsilon) \) is given by a relation similar to Eq. 2

\[
\lambda_{\text{pair}}^{-1} = \frac{1}{2} \int_0^\infty n(\epsilon) \int_{-1}^1 \sigma_{\gamma\gamma}(s)(1 - \beta \cos \theta) d(\cos \theta) d\epsilon
\]

where \( \sigma(s) \) is the pair production cross section for photons with center of mass energy \( \sqrt{s} \), and \( s = 2\epsilon E(1 - \beta \cos \theta) \). \( \lambda_{\text{pair}} \) has been derived following Brown et al. (1973) and is shown in Fig. 4 (solid curve labelled \( e^+e^- \)) as well as the interaction length of the process \( \gamma\gamma \rightarrow \mu^+\mu^- \).

To summarise, in the \( e - \gamma \) collisions (ICS), PeV electrons transfer half of their energy to the ambient photon, producing a hard \( \gamma \)-ray which then creates an \( e^+e^- \) pair due to the interactions with the photon stellar background (\( \gamma - \gamma \rightarrow e^+e^- \)). However, as the electron propagates outward, the photons encountered are progressively redshifted, and the interaction length of the \( e^\pm\gamma \) and \( \gamma\gamma \) scattering is continuously changing with distance and time as we show in Fig. 5. We are assuming that the energy of the photons is redshifted by a factor \((1 - \beta \cos \theta)\), where \( \tan \theta = R_e/(l_e + R_e) \), with \( l_e \) being the distance covered by the electron at a certain time \( t \), and \( R_e \) is the WR star radius. The multiple photon-electron cascade continues during the electron propagation. For an initial PeV electron, we consider that about 10 collisions are needed for its energy to be degraded to \( E_e \sim 500 \) GeV – 1 TeV (see also Fargion & Colaiuda 2004). The lapse time for ten bounces is approximately \( 10 \times 10^5 \) s \( \approx 100 \) s. At this energy, the photon produced at \( E_e = \frac{1}{2} E_e \) can be "escape" without interacting anymore with the stellar background (Fig. 5). This mechanism would imply a hard \( \gamma \) emission (TeV, sub-TeV) from GRBs.

Seven GRBs with emission beyond 100 MeV have been detected by EGRET on board of the Compton Gamma Ray Observer (CGRO) (Schneid et al. 1992), including the long-duration burst (\( \sim 5000 \) s) GRB 940217 whose peak emission has been measured at \( \sim 18 \) GeV (Hurley et al. 1994). In principle one cannot exclude that GRBs may emit at TeV energies, even though the propagation of these photons would be suppressed by the presence of the infrared (IR) extragalactic background, \((\gamma\nu_{\nu} + \gamma\gamma \rightarrow e^+e^-)\), so that only photons from relatively nearby sources (<100 – 300 Mpc) could be detected. A few claims of GRB detections in the TeV and sub TeV range have appeared in the literature in the last few years. Such high energy signals have been claimed to be observed by Milagrito in one out of 54 GRBs from the BATSE catalogue (Atkins et al. 2000). Another claim of possible sub-TeV emission from GRB 971110 has come from the GRAND project (Fragile et al. 2004). However one has to keep in mind that all these results are not considered as firm detections. It follows that even if we may expect a very high energy (\( \sim \) TeV) "precursor", it would be very difficult to observe it because of the IR cut-off.

Going back to the keV - MeV emission, in this scenario it would result from the continuous IC scattering of the same electrons, when they have reached lower energies. In fact, af-
the collisions lead to the creation of photons of energy given by
\[ E_{\gamma}^{IC} = \frac{4}{3} \gamma^2 \epsilon (1 - \beta \cos \theta) \]

where \( \theta \) is the scattering angle between the photon and the electron. For \( \cos \theta = R_s/(l_s + R_s) \ll 1 \), \((1 - \beta \cos \theta) \sim \theta^2\) and the equation reduces to
\[ E_{\gamma}^{IC} \approx 4.5 \cdot 10^7 \left( \frac{E_s}{100 \text{GeV}} \right)^2 \left( \frac{\epsilon}{8.6 \text{GeV}} \right) \left( \frac{\theta}{10^{-2} \text{rad}} \right)^2 \text{eV} \]

where the \( \theta^2 \) factor accounts for the apparent redshift in the electron frame. The energy loss rate in this case has the form
\[ \frac{dE}{dt} = -\left( \frac{4 \sigma_T a T^4}{3 m_e c^3} \right) E^2 = -bE^2 \]

and the energy decrease as a function of time is given by
\[ E(t) = (E(t_0)^{-1} + bt)^{-1}. \]

Thus the collisions with the ambient photons rapidly lower the energy of the electrons. When their energy is reduced to \( E_s = 10 \text{GeV} \), from Eq. 6 one obtains approximate photon energies of 450 KeV \( \left( \frac{E_s}{10 \text{GeV}} \right)^2 \left( \frac{2}{8.6 \text{GeV}} \right) \left( \frac{6}{10^{-2} \text{rad}} \right)^2 \).

5  THE SGR 1806-20 GIANT FLARE BY A BLAZING GAMMA JET

An isotropic release of energy, as predicted by the magnetar model, shows some inconsistencies when applied to the properties of the giant flare from SGR 1806-20, as we have pointed out in §1.3. There are two more issues related to the magnetar interpretation that we want to discuss in this section.

First, how can a spherically symmetric explosion justify the peculiar features observed in its light curve? A precursor burst occurred 143 s before the initial onset, lasting slightly longer than 1 s, and it was followed by a very intense spike with a very short timescale (0.7 sec), the blazing giant flare that saturated most GRB detectors. After \( t = 61 \) until 170 ms the signal “decreased gradually with oscillatory modulation, which suggests repeated energy injections at ~ 60 ms intervals” (Terasawa et al. 2005). Soon after the peak of the emission, between 400 and 500 ms, several humps were detected in the decay profile from both Swift (Palmer et al. 2005) and GEOTAIL (Terasawa et al. 2005). Then the profile declines again until \( t \sim 300 \) s, with the light curve showing signs of pulsations with a 7.56 s period. An increase in the emission seem to occur again around \( t \sim 400 \) s, with a long bump peaking at \( t \sim 600 - 800 \) s (Mereghetti et al. 2005). An even longer tail seems to appear from the data, which lasted until 1000 - 2000 sec after the first trigger (Mereghetti et al. 2005).

Secondly, does the relation between \( \dot{P} \) and \( B^2 \), predicted by the magnetar model, find a confirmation from the observations? The magnetar scenario assumes a neutron star with a huge magnetic field that is estimated by observing the rotational energy loss (mainly due to the dipole moment radiation) and the rate of rotation variability.

Let us calculate these quantities for SGR 1806-20 assuming a simple dipole model. The rotational energy and its derivative (for a nominal period of \( P_{\text{SGR}} = 7.56 \) s) are:

\[ E_{\text{rot}} = \frac{1}{2} I_{\text{NS} \omega^2} \simeq 3.6 \cdot 10^{44} \frac{P^{-2}}{(10^{45} \text{g cm}^2)} \text{erg} \]

\[ \dot{E}_{\text{rot}} = I_{\text{NS} \omega \dot{\omega}} = 4 \cdot 10^{46} \dot{P} P^{-3} \left( \frac{I_{\text{NS}}}{10^{45} \text{g cm}^2} \right) \text{erg s}^{-1} \]

However from the dipole radiation formula one finds:

\[ E_{\text{rot}} = - \frac{(2\pi)^4 B_{\text{NS}}^2 R_{\text{NS}}^6}{6c^5 P^4} \cdot \sin^2(\theta) \]

From the last two equations one derives that the magnetic field is related to the period \( P \) and its derivative \( \dot{P} \) as follows:

\[ B = 3.2 \cdot 10^{19} (\dot{P}P^{-\frac{1}{2}}) \]

Mereghetti et al. (2005) have shown the long term \( \dot{P} \) variation of SGR 1806-20 between 1993 and October 2004, using data from ASCA, RXTE, Beppo Sax and XMM. The period derivative increased from \( 8 \times 10^{-11} \text{ s s}^{-1} \) (before 1998; Kouveliotou et al. 1998) to \( (5.49 \pm 0.09) \times 10^{-10} \text{ s s}^{-1} \) (between 1999 and 2004), while the period \( P \) changed from 7.47 s, to 7.56 s. This implies that the magnetic field has changed from

\[ B_{\text{in}} = 7.8 \cdot 10^{14} \left( \frac{P}{7.47 \text{ s}} \right)^{\frac{1}{2}} \left( \frac{\dot{P}}{8 \cdot 10^{-11} \text{ s s}^{-1}} \right)^{\frac{1}{2}} \text{G} \]

\[ B_{\text{fin}} = 2.06 \cdot 10^{15} \left( \frac{P}{7.56 \text{ s}} \right)^{\frac{1}{2}} \left( \frac{\dot{P}}{5.49 \cdot 10^{-10} \text{ s s}^{-1}} \right)^{\frac{1}{2}} \text{G} \]

it follows that \( \dot{P} P \) has increased roughly of a factor 7, as the square of the magnetic field, \( B^2 \). According to these values, the corresponding total energy \( E \simeq \frac{1}{2} B^2 R_{\text{NS}}^6 \) must have changed from

\[ E_{\text{in}} = 1.0 \cdot 10^{37} \left( \frac{P}{7.47 \text{ s}} \right)^{\frac{5}{2}} \left( \frac{\dot{P}}{8 \cdot 10^{-11} \text{ s s}^{-1}} \right)^{\frac{3}{2}} \left( \frac{R_{\text{NS}}}{10^6 \text{ cm}} \right)^3 \text{erg} \]

\[ E_{\text{fin}} = 7.1 \cdot 10^{37} \left( \frac{P}{7.56 \text{ s}} \right)^{\frac{5}{2}} \left( \frac{\dot{P}}{5.5 \cdot 10^{-10} \text{ s s}^{-1}} \right)^{\frac{3}{2}} \left( \frac{R_{\text{NS}}}{10^6 \text{ cm}} \right)^3 \text{erg} \]

Where does such an increase (7 times higher) in the energy density come from, given that the rotational energy is at least three orders of magnitude lower (see Eq. 19)?

Let us go back to the intense flare activity of 2004 December 27. No sudden change in the spin frequency (\( \nu = 1/P \)) was found after the flare and an upper limit of \( \Delta \nu < 2 \times 10^{-5} \) Hz has been set on the frequency variation (Woods et al. 2005). On the other hand a decrease of a factor 2.7 in the spin-down rate has been recently observed roughly one month after the giant flare, compared to the average value of the past 4 years (Woods et al. 2005). If \( \dot{P} P \) is proportional to \( B^2 \), the decrease in \( \dot{P} \) should imply from Eq. 19 that the energy released in the flare should have been
GRBs and SGRs by high energy leptons showering in blazing γ jets

∼ 5 × 10^{47} \text{ erg}, while only a tenth of this value (∼ 5 × 10^{46} \text{ erg}) has been recorded by RHESSI (Hurley et al. 2005) and GEOTAIL (Terasawa et al. 2005). Where has the remaining energy gone?

It follows that the evidence for a correlation between $P\dot{P}$ and $B^2$ is not at all clear thus far, especially within the magnetar scenario.

Again, we suggest that a thin collimated jet is able to solve these puzzles better than the magnetar model.

In Fig. 6 and 7, we show the results of our model (see Eq. 1) with the set of parameters displayed in Table 5. First, a thin jet would be able to lower the total energy budget of the process ($E_{\text{SGR}} \approx \frac{P}{\gamma} \approx 10^9 \times 10^{46} \text{ erg s}^{-1}$). Secondly, a jet in precession would provide a natural interpretation of the features observed in the light curve of SGR 1806-20 as one can see from Fig. 6.

The structure of the γ jet (originated either via ICS or synchrotron radiation) consists, because of the relativistic kinematic, in concentric cones where the inner and more collimated ones correspond to the more energetic gamma radiation. A section of this cone perpendicular to the axis would show different concentric rings. If the motion of the jet is slow, the profile of the light curve would appear symmetric to an observer, whereas if the jet is fast, the inner structures (at higher energy) move quicker than the outer ones (at lower energy). This determines a "compression" of the high energy cones along the direction of the precessing motion, the faster the motion of the jet the stronger this effect. Fast moving jets though should appear with a fast-rising hard signal, followed by a lower energy tail. Consequently, a fast thin jet that suddenly blazes the observer along its precessing motion may explain the short e-fold time of the initial rise ($\Delta t \sim 1.3 \text{ ms}$; Terasawa et al. 2005). The sudden oscillatory modulation detected along the decay profile at 61 ms < $t$ < 170 ms and 397 ms < $t$ < 500 ms (Terasawa et al. 2005; Palmer et al. 2005) finds explanation if we assume $\Delta t \sim P/\gamma \approx 1.3 \times 10^{-3} \text{ s}$ for $P = 7.5 \text{ s}$ and $\gamma \sim 10^4$.

We imagine that the rotational energy losses of the pulsar are mainly related to the braking torques of an accretion disk which determine the change of the period derivative. This implies that $P\dot{P}$ is not correlated to the magnetic energy density (contrary to the magnetar model) before and after the flare.

The recent increase of the hardening might be due to the motion of the cone described by the precessing jet: the more it bends towards the observer the longer is $\dot{P}$, the more frequent may be the SGR activity and the harder is the spectrum (Mereghetti et al. 2005).

Moreover the observations of the radio afterglow of the SGR 1806-20 flare (Taylor et al. 2005) give evidence for a polarization variability, for a rebrightening in the radio light curve (Gelfand et al. 2005) and they show a variation in the position of the centroid of the afterglow, that appears as asymmetric and elongated: all these properties are in favour

\[ \text{Fast and slow jets are defined by the ratio } v_\perp/c > 1 \text{ respectively where } v_\perp = \omega_{\text{psr}} R_\perp \sin \theta_{\text{psr}} \text{ and } R_\perp \sim c/P \]
of the jet interpretation. In this case a wider and less collimated cone of GeV electrons may produce the radio emission of the afterglow.

In our model, highly energetic particles are ejected from the poles of a spinning neutron star. Here we propose three possible scenarios that can account for the gamma emission from SGRs, particularly for what has been observed in the \( \gamma \)-ray giant flare from SGR 1806-20. (1) In the simplest case the jet is made of GeV electrons that emit \( \gamma \) rays via ICS onto thermal photons, as we have already discussed in previous works. Then we examine the possibility that the soft gamma flare results from synchrotron radiation (due to the galactic magnetic field) of PeV electrons possibly originated by either (2) a primary jet made of muons, or (3) by EeV nucleons \((p + \gamma \rightarrow \pi + n; \pi \rightarrow \mu \rightarrow e; n \rightarrow p + e + \bar{\nu}_e)\). At this stage we cannot decide which model is able to best interpret the giant flare emission. PeV muons have the advantage of escaping for about 100 seconds before they decay. On the other hand the introduction of an hadronic component of the jet might be necessary, given the evidence for a spatial correlation between an excess of EeV CRs and the location of SGR 1806-20.

5.1 Gamma jets by IC of GeV electrons

As we proposed in previous works, the simplest approach is to assume that the gamma emission arises from Inverse Compton Scattering of GeVs electron pairs \( (\gamma_e \geq 2 \times 10^6) \) onto thermal photons (Fargion 1995, 1996, 1998, 1999). Their ICS will induce an inner jet whose angle is \( \Delta \theta < 1/\gamma \sim 5 \times 10^{-4} \text{rad} \sim 0.0285^\circ \) and a wider, less collimated X, optical cone. Indeed the electron pair Jet may generate a secondary beamed synchrotron radiation component at radio energies, in analogy to the behaviour of BL Lac blazars whose hardest TeV component is made by ICS, while its correlated X emission is due to the synchrotron component. Anyway the inner jet is dominated by harder photons while the external emission is due to the synchrotron component. The electron pair Jet might be necessary, given the evidence for a spatial correlation between an excess of EeV CRs and the location of SGR 1806-20.

5.2 PeV Muon jets in SGRs?

Similarly to the GRB case, we assume a primary jet made of muons with \( E_\mu \sim 1 - 10 \text{ PeV} \), that can travel for about 100 s before they decay into electrons (see Fig. 4). The presence of a UV/optical photon background that can prevent the propagation of high energy electrons is negligible around a pulsar.

We are also assuming that the jet is aligned with the magnetic lines, thus muons would not emit synchrotron photons as they move through the very intense magnetic field of the pulsar generally expected near its surface (possibly as high as \( 10^{15} \text{ G} \)). The advantage of a primary beam of muons is that it guarantees that the electrons are produced away from the surface of the neutron star, where the magnetic field would be much lower.

When electrons of energy \( E_{e} \sim 1 \text{ PeV} \) arise from the decay of muons after about 100 s, the pulsar magnetic field at this distance has decreased by a factor \( B_{15}(R_{psr}/\gamma)^{-3} \)

\( G \approx 3 \times 10^{-3} B_{15}(R_{psr}/10 \text{ km})^{-3} \text{ G} \), with \( B_{15} \approx (B/10^{15} \text{ G}) \). In practice \( B \) at 100 s is comparable to the galactic magnetic field. Given that the synchrotron losses for \( B \sim 10^{-5} - 10^{-6} \text{ G} \) acts on a fairly long time scale, it is more likely that PeV electrons lose most of their energy while they propagate through the galaxy and they interact with the galactic magnetic field. This would lead to a radiation of energy

\[
E_{\gamma}^{\text{sync}} \approx 1.7 \times 10^5 \left( \frac{E_e}{10^{15} \text{ eV}} \right)^2 \left( \frac{B}{2.5 \times 10^{-6} \text{ G}} \right) \text{ eV}
\]

with an energy loss distance scale of

\[
\xi_{\text{sync}} \approx 6.3 \times 10^{10} \left( \frac{E_e}{10^{15} \text{ eV}} \right)^{-1} \left( \frac{B}{2.5 \times 10^{-6} \text{ G}} \right)^{-2} \text{ s}
\]

The Larmor radius for the galactic magnetic field is

\[
R_L \approx 8.2 \times 10^7 \left( \frac{E_e}{10^{15} \text{ eV}} \right)^{-1} \left( \frac{B}{2.5 \times 10^{-6} \text{ G}} \right)^{-1} s
\]

and it is about three orders of magnitude lower than the synchrotron energy loss distance \( (R_L/c \approx \xi_{\text{sync}} \approx 1.3 \times 10^{-5}) \). This may cause a widening of the opening angle of the jet, that would have a final "fan"-like (see also Fargion 2002, Fargion et al. 2004) or a double disc where the e\( ^{\pm} \) are bounded by the magnetic field. The jet would open along a two dimensional plane, given that the galactic magnetic field is homogeneous on a scale of 55 pc (Protheroe 1990). We are assuming a Lorentz factor which is \( \gamma_e \sim 2 \times 10^4 \), but in this case the solid angle of the jet is not \( \propto 1/\gamma^2 \sim 2.5 \times 10^{-10} \), but \( 1/\gamma \times \theta_{\text{L}} \), where \( \theta_{\text{L}} \) is the aperture angle due to the Larmor precession around the galactic field. For \( \theta_{\text{L}} \approx 10^5 \), \( \Delta \Omega \sim 10^{-6} \), and this aperture angle guarantees that the number of events is not suppressed by a too narrow beaming.

5.3 EeV nucleons as progenitors of SGR \( \gamma \) jet?

Finally we consider the possibility that SGRs may be sources of UHECRs, and that the PeV muons may be originated by jets made of higher energy hadrons. Similar ideas on UHECRs have been recently suggested also by other authors (Asano, Yamazaki, & Sugiyama 2005), but here we assume that the energy of the hadrons from SGRs does not exceed \( 10^{18} \text{ eV} \) instead of being around \( 10^{20} \text{ eV} \) as proposed by Asano and collaborators. Indeed there is strong evidence in CR spectra that the origin of EeV particles may be both galactic and extragalactic. Excluding very rare SN/GRBs, in our galaxy there are no active sources at this range of energies, thus we cannot ignore the role of SGRs as possibly related to EeV CRs.

In 1999 AGASA reported the measure of a significant anisotropy (4%) in the arrival direction of CRs in the small energy range \( 10^{17.9} - 10^{18.3} \text{ eV} \) as due to the excess of events in two regions of about 20° near the SGR 1806-20 and Cygnus, and it has been argued that this anisotropy
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...was due to EeV neutrons (Hayashida et al. 1999). Interestingly enough we have also found a correlation between the BATSE data of SGR 1806-20 and the AGASA excess, as one can see from Fig. 5 where we have overlaid the BATSE detections (between 1997 and 2000) to the AGASA map. This would suggest that the neutron signal and the soft-gamma detection from BATSE are related to the same mechanism.

To explain such an interesting correlation, we will start with the assumption that protons can be accelerated by the large magnetic field of the pulsar up to EeV energy. The protons could emit directly soft gamma rays via synchrotron radiation with the galactic magnetic field \((\text{EeV})\) protons from the galactic centre, photopion production with ambient galactic IR photons \((p + \gamma_{IR} \rightarrow \Delta^{+} \rightarrow n + \pi^{+})\) is favoured compared to proton proton collisions \((p + p \rightarrow n + p + N\pi)\) in order to produce charged pions, and they obtain a mean free path of 37 pc for the interaction with an IR galactic photon background \((T_{IR} \sim 100 \text{ K})\). Thus, even if there is not an IR source localised with the SGR, the interaction with the galactic IR background may be efficient in converting the protons into pions and neutrons (see also Grasso & Maccione 2005).

Pions then decay into muons that decay into high energy electrons \((E_e \lesssim 10 \text{ PeV})\) that, interacting with the local galactic magnetic field, lose energy via synchrotron radiation:

\[
E_{\gamma}^{\text{syn}} \simeq 4.2 \times 10^6 \left( \frac{E_e}{5 \times 10^{15} \text{ eV}} \right)^2 \left( \frac{B}{2.5 \times 10^{-6} \text{ G}} \right) \text{ eV (21)}
\]

with an interaction length given by

\[
\lambda_{\gamma}^{\text{syn}} \simeq 1.3 \times 10^{10} \left( \frac{E_e}{5 \times 10^{15} \text{ eV}} \right)^{-1} \left( \frac{B}{2.5 \times 10^{-6} \text{ G}} \right)^{-2} \text{ s (22)}
\]

The Larmor radius is about two orders of magnitude smaller than the synchrotron interaction length and this may imply that the aperture of the jet is spread by the magnetic field.

\[
R_L \simeq 4.1 \times 10^8 \left( \frac{E_e}{5 \times 10^{15} \text{ eV}} \right) \left( \frac{B}{2.5 \times 10^{-6} \text{ G}} \right)^{-1} \text{ s (23)}
\]

In this "hadronic" scenario we are assuming a Lorentz factor which is \(\gamma_e \sim 10^{10}\), and, as mentioned in the previous section, the solid angle of the jet is not \(\sim 1/\gamma^2 \sim 10^{-20}\), but \(1/\gamma \times \theta_L\), where \(\theta_L\) is the aperture angle due to the Larmor precession around the galactic field. For \(\theta_L \approx 10^6\), \(\Delta \Omega \sim 10^{-11}\), and this aperture angle again guarantees that the number of events is not suppressed by a too narrow beaming.

The photopion interactions produce neutrons at \(\sim 10^{18} \text{ eV (EeV)}\), which have a decay length of \(\lesssim 10 \text{ kpc (E/10^{18} eV)}\), and they can easily propagate along these distances without being bent by the galactic magnetic field. Neutron beta decay produces a proton, electron and an electronic antineutrino. Given its long decay length, the production of the electron would occur well far away from the original pulsar. The electron is produced with an energy spectrum that ranges between \(10^{15} \text{ eV} < E_e < 10^{17.5} \text{ eV}\) and peaks at \(E_e \sim 10^{15} \text{ eV}\). Again PeV electrons interact with the local galactic magnetic field producing via synchrotron radiation photons of few hundreds keV as given by Eq. 15.

For higher electron energies, around \(E_e \gtrsim 10^{16.5} \text{ eV}\) the Larmor radius becomes comparable and even larger than the synchrotron interaction length, therefore the opening angle of the jet would remain collimated. However such an angle would be too small and would make SGR events extremely unlikely. Again for the higher energy electrons the peak energy of synchrotron photons would be

\[
E_{\gamma}^{\text{syn}} \simeq 1.7 \times 10^9 \left( \frac{E_e}{10^{17} \text{ eV}} \right)^2 \left( \frac{B}{2.5 \times 10^{-6} \text{ G}} \right) \text{ eV (24)}
\]

and to explain the hundreds keV emission we have to assume that the jet is not pointing exactly towards the Earth,
but it is slightly off-axis so that only the softer range of frequencies could have been observed during the flare.

6 CONCLUSIONS

The most popular models to date to interpret GRBs and SGRs, the fireball collimated in a few degrees jet for GRBs, and the spherically symmetric magnetars for SGR, cannot completely explain all the issues that these events do present.

We have proposed an alternative scenario by introducing a model with highly collimated jets of high energy particles in precession. We are assuming the energy equipartition between the power of the jet and that of the SN (for GRB) or the X-ray pulsar (for SGRs). The gamma rays emerge in a small opening angle, and the narrow beaming allows to dramatically reduce the total output power (from $\sim 10^{50}$ erg s$^{-1}$ for the fireball/jet model of GRBs to $10^{43}$ - $10^{44}$ erg s$^{-1}$ in our GRB case as the typical SN power, and from $10^{47}$ erg s$^{-1}$ for the magnetar to $10^{38}$ erg s$^{-1}$ in our SGR scenario, comparable the the observed power of X-ray pulsars), which is the most radical assumption in such isotropic models.

Compared to our previous versions here we have considered that high energy electrons are the decay product of a primary particle that in the case of the GRB is a muon. For SGRs we have considered a jet of either prompt muons or of protons that produce, through photopion production, secondary muons and electrons. This proposal arises from the fact that the propagation of a jet of prompt electron pairs would be severely suppressed by the extreme opacity conditions in the proximity of the surface of a pre-SN star or a highly magnetised pulsar.

If GRBs are originated in a core collapse of very massive stars, a jet of muons would have a higher chance to escape from the stellar surface. Secondary electrons produced after the decay of the muons at about 100 s from the surface, may produce the gamma emission after a long chain of interactions with the stellar background radiation (ICS), which gradually reduce their initial energy, from $\sim 10^{15}$ eV to a tens of GeV. A narrow jet would blaze the observer at high energy when viewed on-axis (at viewing angle $\sim 1/\gamma$), while it would appear "softer" if observed off-axis. This could give an explanation to the wide range of properties and emission from different GRB events. A larger viewing angle would be associated to the softer emission of the X-ray afterglow, and it may also be linked to the properties of objects such as the XRFs.

A similar interpretation has been introduced for SGRs, with a particular attention to the giant flare from SGR 1806-20 on 2004 December 27. We have discussed different scenarios at the origin of this event. We have shown how a primary jet of muons (with $E_\mu \sim 10^{15} - 10^{16}$ eV) decaying into high energy electrons, may be a source of a collimated gamma radiation. A larger viewing angle would be associated to the softer emission of the X-ray afterglow, and it may also be linked to the properties of objects such as the XRFs.

To conclude, we imagine that if the precessing jet model gives a correct interpretation of the properties of SGRs, SGR 1806-20 will still be active in the next months and years.

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