

# Are Galactic Gamma-Ray Bursters the Main Source of Hadronic Non-Solar Cosmic Rays at all Energies ?

R. Plaga<sup>1</sup>, O.C. de Jager<sup>2</sup>, and A.Dar<sup>3</sup>

<sup>1</sup> Max-Planck-Institut für Physik, 80805 München, Germany

<sup>2</sup> Potchefstroomse Universiteit vir CHO, Potchefstroom 2520, South Africa

<sup>3</sup> Technion, Israel Institute of Technology, Haifa 32000, Israel

## Abstract

We propose a new hypothesis for the origin of non-solar hadronic cosmic rays (CRs) at all energies: Highly relativistic, narrowly collimated jets from the birth or collapse of neutron stars (NSs) in our Galaxy accelerate ambient disk and halo matter to CR energies and disperse it in “hot spots” which they form when they stop in the Galactic halo. Such events - “Galactic Gamma-Ray Bursters” (GGRBs) - are proposed to cause cosmological gamma-ray bursts (GRBs) in other galaxies when their beamed radiation happens to point in our direction. Our hypothesis naturally explains some observations which are difficult to understand with the currently popular ideas about CR origin - e.g. the small Galacto-centric gradient of the cosmic-ray density and the absence of the Greisen-Zatsepin-Kuzmin cutoff. *Our idea stands or falls with the existence of the “hot spots” (“GGRB remnants”) in the Galactic halo.* We discuss their expected observational signatures and find that they could appear as EGRET unidentified high-latitude sources.

## 1 A fresh sheet of paper for the problem of CR origin

Neglecting solar modulation effects, the flux of the dominating hadronic component of the local non-solar cosmic rays (CR), as a function of energy, which has been measured between about a GeV and  $3 \cdot 10^{20}$  eV, can be well described by one power-law which changes its slope slightly at only two energies - at about  $4 \cdot 10^{15}$  eV (the “knee”) and  $3 \cdot 10^{18}$  eV (the “ankle”). This striking simplicity and unity of the data originally led most authors to ascribe the origin of hadronic cosmic rays to a single source class, either a Galactic one - such as supernova remnants (SNRs) - or extragalactic one, e.g. active galaxies (AGs). Later an “eclectic” scenario for CR origin became generally accepted: SNRs accelerate the CRs below the knee and AGs are the source of CRs above the ankle. This happened mainly because with a better understanding of SNRs and AGs it became clear that it is unlikely that either one can be the searched for single source class. Two consequences from this scenario were predicted long ago:

A. the analysis of  $\gamma$ -rays from the interaction of low energy CRs with the interstellar medium in the Galaxy should show that the CR density rapidly decreases with rising distance from the Galactic centre, towards which SNRs are strongly concentrated (Stecker & Jones 1977).

B. there should be an “end of the the CR spectrum” (Greisen 1966) around  $10^{20}$  eV - the Greisen-Zatsepin-Kuzmin (GZK) cutoff - because of universal, i.e. not locally produced, CRs with higher energies are severely depleted by interactions with the 3 K background radiation.

Both of these predictions have not been borne out by observations. The data from three  $\gamma$ -ray satellites have consistently favoured a much shallower Galacto-centric gradient of the hadronic cosmic-ray density than expected from SNRs. In spite of great efforts there is not a single *quantitative* description of the observed behaviour assuming the observed Galacto-centric distribution of SNRs in the literature (Moskalenko & Strong, 1998). The CR spectrum definitely extends beyond the GZK cutoff (Takeda et al., 1998). Moreover, up to now, there is no experimental indication of *hadron* acceleration in SNRs.

This is motivation to search for alternatives to the “eclectic” view. At face value A. suggests that the hadronic CR sources extend to the outskirts of our Galaxy, whereas B. means that UHE CRs are produced near our Galaxy. This points towards the Galactic halo as the *single* site of CR origin. We propose that gamma-ray bursts that occur in our Galaxy - i.e. a single source class - accelerate the observed hadronic CRs at this site.

The next section summarises our hypothesis which has been described in detail by Plaga & Dar (1999), the other sections are new material.

## 2 Plasmoid ejection in neutron star birth or collapse, GRBs and CR origin

Our two basic assumptions are:

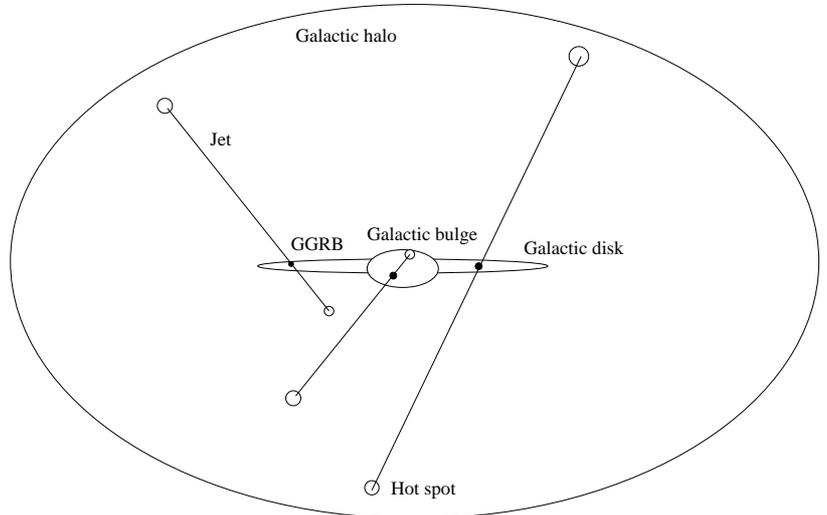
1. during *common* events in the life of neutron stars (NSs) - such as their birth in a supernova or their collapse to configuration with a different form of nuclear matter (Dar 1999) - ultrarelativistic “plasmoids” (Lorentz factor  $\Gamma \approx 1000$ ) are emitted carrying a significant fraction ( $\approx 10^{52}$  ergs) of the NS’s binding energy. After an initial expansion after the ejection they remain confined - by some as yet ill understood magnetic or inertial (ram pressure) mechanism to a radius of  $\approx 10^{-3}$  pc.
2. after ejection the plasmoid decelerates - mainly via accretion of ambient matter. Only after it slowed down considerably, it begins a final expansion to about  $R_f \approx 0.1$  pc and then dissipates its kinetic energy, partly via particle acceleration.

These assumptions seem natural because ejection of plasmoids seems to be common when mass is accreted at a high rate onto a central compact object, a situation expected in most scenarios for the formation of compact objects. The Galactic superluminal source GRS 1915+105 has properties consistent with our assumptions. The ejection of plasmoids with a strong confinement mechanism obviously at work are commonly observed in extragalactic superluminal sources (there called “plasmons”)

Synchrotron radiation from decelerating plasmoids with properties similar to the ones assumed here were shown to account for GRB afterglows by Chiang and Dermer (1997). In our scenario GRBs are expected to be relativistically beamed by a factor  $1/4\Gamma^2 \approx 2 \times 10^{-7}$  during the burst and initial afterglow phase: The observed GRB rate then leads to a GGRB rate similar to the NS birth rate of ca. one in 20 years.

It can be shown that the plasmoid escapes into the Galactic halo if its final expansion does not begin too early. Because the final dissipational phase takes place over a distance small compared to the total travelled distance, the CR acceleration happens in a small region which we call “hot spots” - in analogy to morphologically similar regions in radio galaxies (fig.1). Its

equipartition magnetic field is about 1 G. *These hot spots are expected to accelerate particles via shock-wave acceleration and magnetic reflection and are identified as the single source of hadronic CRs at all energies.* Only about 1% of the plasmoid’s kinetic energy needs to be channelled into CR energy to explain its energy input into the Galaxy inferred from spallation yields (Drury et al.,1989). The plasmoids inject turbulent energy into the halo, and in equipartition a halo magnetic field similar to the one in disk is expected. This leads to CR trapping in the halo. If the plasmoids produce a hadronic CR power-law spectrum according to  $E^{-\alpha}$  with  $\alpha = 2.2$  below and  $\alpha = 2.5$  above the knee, then - together with an energy dependence of the interhalo diffusion coefficient according to  $E^{-0.5}$  - the complete observed CR spectrum from a GeV up to  $10^{20}$  eV is naturally obtained.



**Figure 1:** A schematic sketch of our scenario. The birth or collapse of NSs in the disk of our Galaxy leads to an ejection of two opposite jets (plasmoids) that produce “hot spots” when they stop in an extended Galactic halo.

### 3 The observational properties of the halo “hot spots”

Our ignorance about the confinement mechanism of plasmoids and relativistic jets in general introduces two basic unknowns which we shall leave as parameters in all expressions:

1. *the time scale  $\tau_{\text{rad}}$  of plasmoids’ final expansion*, during which they dissipate most of their kinetic energy into the form of CRs, radiation and turbulent motion of the interhalo matter. (Because of the strong beaming in our scenario only a very small fraction (less than 0.1 %) of the initial kinetic energy is radiated away in the prompt burst and early afterglow.) With a particle density of  $10^{-3}/\text{cm}^3$  in the halo the Lorentz factor of a plasmoid with a radius of 0.1 pc is decelerated to  $\Gamma = 2.5$  in  $10^4$  years. Further expansion will take place in the final phase of slow-down. Therefore we will specify  $\tau_{\text{rad}}$  in units of 1000 years below. 2. *the distance  $d$  of a typical hot spot*. The data on the Galacto-centric distribution of CRs suggest a scale of tens of kpc.

The hot spots bear some similarity to their brethren in Fanaroff-Riley II galaxies, which have been experimentally identified as prolific CR accelerators (Rachen & Biermann, 1993). Following them, the time scale for acceleration  $\tau_+$  up to an energy  $E_a$  in a jet with a speed/ $c = \beta$  and a Kolmogorov turbulence spectrum is given as:

$$\tau_+ = 5(R_f/0.1pc)^{2/3} \beta^{-2} ((E_a/10^{20}eV)/(B/1G))^{1/3} \text{years} \quad (1)$$

If this timescale (comfortably smaller than  $\tau_{\text{rad}}$ ) is larger than the synchrotron cooling time - this is certainly valid for electrons - acceleration is limited by synchrotron losses. For protons diffusive loss could also be important. de Jager et al. (1996) showed that the maximal characteristic synchrotron energy for a particle with mass  $m$  is given -independent of the magnetic field strength - as:

$$E_{\text{max}} = 46.3(m/m_{\text{proton}})\text{GeV} \quad (2)$$

for maximal acceleration at a pitch angle of  $90^\circ$ . The hot spot has to accelerate  $E_{\text{tot}} = 10^{50}$  ergs in protons to play its role as a universal CR source.  $\epsilon$  is the fraction of this energy emitted as proton synchrotron radiation.  $\epsilon$  is smaller than one, its exact value depends on the spectral index at the highest energies and the importance of diffusive losses and could only be precisely determined in a more detailed model. We then obtain the luminosity of the hot spot due to synchrotron radiation by requiring  $\int_0^{E_m} I_{\text{syn}} E dE = (\epsilon E_{\text{tot}})/(\tau_{\text{rad}} 4\pi d^2)$ ; this leads to the following expression for the hot-spot energy flux:

$$F_{HS}(\text{protons}) = 1.4 \times 10^{-8} \epsilon (E/E_m)^{-(\alpha+3)/2} (1000\text{years}/\tau_{\text{rad}}) (d/50\text{kpc})^{-2} \text{erg cm}^{-2} \text{sec}^{-1} \quad (3)$$

The spectrum of the electron synchrotron has a spectral index smaller by 0.5 above a synchrotron break energy  $E_{\text{break}} \approx 8 \left( \frac{(B/1G)}{(\tau_{\text{rad}}/1000y)} \right)$  keV, which corresponds to a synchrotron break at 0.3 kHz. This steeper spectrum leads to a dominance of proton synchrotron radiation above about the IR region. The potential importance of proton synchrotron radiation in GRB afterglows (which are closely related to the hot spots in our scenario) was recognised by various authors (e.g. Boettcher & Dermer, 1998). With our very simplifying assumptions a proton synchrotron break could appear around  $10^{17}$  eV, but at these energies diffusive losses from the hot spot - which counteract against a break in the emitted charged particle spectrum - are important. The exact synchrotron spectrum in the  $\gamma$ -ray range then depends on the magnetic fields around the hot spot. We assume that protons and electrons are accelerated to a given *Lorentz factor* with equal efficiency by the relativistic shocks and bulk motions (Dar 1998). Taking into account the synchrotron break one then obtains for the radio intensity due to electron synchrotron radiation:

$$I_{HS}(\text{electrons}) = 6(\nu/5\text{GHz})^{-\alpha/2} (1000/\tau_{\text{rad}})^{3/2} \text{mJy} \quad (4)$$

The proton synchrotron radiation contributes only about 0.1 mJy at 5 GHz.

At energies above  $E_{\text{max}}$  (46 GeV) the decay of  $\pi_0$ s from proton interactions with ambient matter swept up by the plasmoid is expected to dominate the  $\gamma$  radiation. We estimate the integral flux above  $\approx 10$  GeV:

$$F_{\pi_0} = 2 \times 10^{-13} (\rho/50\text{cm}^{-3}) (d/50\text{kpc})^{-2} (E/\text{TeV})^{-1.1} \text{cm}^{-2} \text{sec}^{-1} \quad (5)$$

This is on the order of 10 mCrab around one TeV, just at the limit of a deep exposure with existing air-Čerenkov telescopes.

#### 4 Unidentified (UI) high-latitude $\gamma$ sources: “hot spots” in the Galactic halo?

The third EGRET catalogue lists 96 UI sources at high Galactic latitudes. Could some fraction of them be “active” hot spots? As an example we discuss the brightest of them, the UI source GRO J1835+5921 at a Galactic latitude of  $25^\circ$ ; at energies above 1 GeV it is about half as bright as the Crab nebula (Nolan et al. 1996). Its energy flux at 100 MeV is  $1.1 \times 10^{-10}$  erg cm $^{-2}$  sec $^{-1}$  which is the one predicted above for a typical hot spot for  $\epsilon \approx 0.03$ . Its spectral index above 30 MeV is  $-1.69 \pm 0.07$  in agreement with the index of  $-1.75$  which follows for  $\alpha=2.5$  (the expected source index for UHE protons in our scenario). GRO J1835+5921 could be a (perhaps exceptional) hot spot which proton synchrotron spectrum extends up to  $E_{\max}$ . In spite of the fact that its position is known with a precision of  $4.5'$  no counterpart has been found (the only object within its error box is the IRAS source F18343+5913 which is misprinted in Nolan et al.(1996) and identical to the main sequence K dwarf HD 172147; hardly a  $\gamma$ -ray source). The absence of a counterpart in the ROSAT 1 RXS RASS catalogue sets an upper limit of about  $4 \times 10^{-13}$  erg/cm $^2$ /sec on emission in the 0.1 - 2.4 keV band. This upper limit is about one order of magnitude below the prediction with  $\epsilon=0.03$  and  $\alpha=2.5$ , the predicted flux would be below this limit for a CR source spectrum with  $\alpha=2$ . We therefore expect that a search for X-ray emission near GRO J1835+5921 will detect a hard X-ray source near the sensitivity limit of the RASS. The absence of a radio source in the 87GB (TXS) catalogue sets upper limits of 25 (400) mJy at 4.85 (0.365) GHz. These values are above the expected one from eq. 4. A deeper search near GRO J1835+5921 should reveal a soft nonthermal radio source (spectral index  $-1$ ) with an angular extension *and proper motion per year* of a few tenths of an arcsec. The clearest evidence in favour of an identification of GRO J1835+5921 as a hot spot - rather than as a very nearby Geminga like radio-quiete pulsar (Mukherjee et al., 1995) or a flaring star (Özel & Thompson, 1996) - would be the detection of VHE energy  $\gamma$ -radiation at energies well above the range thought likely for pulsar emission, say above 100 GeV (eq. 5). The hot spots could also have spectral synchrotron breaks below  $E_{\max}$  and could then be identified with softer high-latitude UI sources. This work made use of the Nasa Extragalactic Database (NED), for references of catalogues refer to this source.

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