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Galactic γ-ray bursters – an alternative source of cosmic rays at all energies

Arnon Dar[1,2] **and Rainer Plaga**[2]

[1] Department of Physics and Space Research Institute, Technion, Haifa 32000, Israel
[2] Max-Planck-Institut für Physik, Föhringer Ring 6, D-80805 München, Germany

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Abstract. We propose a new hypothesis for the origin of the major part 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 are seen as cosmological gamma-ray bursts (GRBs) in other galaxies when their beamed radiation happens to point towards Earth. This source of CRs is located in the Galactic halo. It therefore explains the absence of the Greisen-Zatsepin-Kuz'min cutoff in the spectrum of the ultra-high energy CRs. The position in energy of the "ankle" in the CR energy spectrum is shown to arise in a natural way. Moreover, an origin of lower energy CRs in the Galactic halo naturally accounts for the high degree of isotropy of CRs around 100 TeV from airshower observations, and the small galactocentric gradient of low-energy CRs derived from gamma-ray observations.

Key words: acceleration of particles – ISM: cosmic rays – Galaxy: halo – galaxies: jets – gamma rays: bursts

1. Introduction

The origin of non-solar cosmic rays, discovered in 1912, is a major unsolved puzzle in physics. Recent observations do not confirm some expectations in the currently accepted framework for hadronic CR origin, where cosmic-ray nuclei with energies below 3×10^{15} eV (the "knee") are accelerated in Galactic supernova remnants (SNRs) (Ginzburg 1957), and those above 3×10^{18} eV (the "ankle") (UHE CRs), for which a disk origin is unlikely due to their isotropy, in sources far beyond our Galaxy (Burbidge 1962). Some observational anomalies are:

- The "GZK cutoff" in the CR intensity at energies above $\sim 10^{20}$ eV, due to interactions of the extragalactic CRs with the cosmic microwave radiation, as predicted by Greisen (1966) and by Zatsepin & Kuz'min (1966) seems to be absent (Takeda et al. 1998). At the same time the directions of the events with the highest energy do not line up with nearby potential extragalactic CR sources. It is difficult to understand these two observations within any model of an extragalactical origin of UHE CRs (Hillas 1998).
- No very-high energy γ-rays, due to proton interactions, are observed from some SNRs, for which a measurable flux is expected in simple models (Aharonian et al. 1994) within the conventional framework (Prosch et al. 1996; Heß1997; Buckley et al. 1998).
- Detailed models (e.g., (Strong & Moskalenko 1998)) yield a significantly larger galactocentric gradient in the sky distribution of high-energy ($>$100 MeV) γ-rays from interaction of CRs from SNRs in the Galactic interstellar medium than the one observed by the EGRET detector on the Compton Gamma-Ray Observatory (Hunter et al. 1997; Strong & Mattox 1996; Erlykin et al. 1996).
- Diffusive propagation of CRs from sources sharply concentrated towards the Galactic disk and centre (such as SNRs) yields anisotropies in the distribution of charged CRs at an energy of about 100 TeV in excess of the observed value (Aglietta et al. 1995) by more than an order of magnitude. This is consistently found both in simple order-of-magnitude estimates (Gaisser et al. 1995) and sophisticated calculations of CR propagation (e.g., Ptuskin et al. 1997).

The last three observations suggest that, perhaps, SNRs are not the main accelerators of Galactic hadronic CRs at energies below the knee.

Maybe these anomalies can be resolved in more sophisticated models within the conventional framework; e.g. by modifying standard ideas about intergalactic CR propagation for the first (Sigl et al. 1998) and interstellar CR propagation for the third and fourth (Erlykin et al. 1997) anomaly, respectively. Spectral cutoffs at energies much below the knee could be the reason for the absence of TeV γ-rays from some fraction of SNRs (Baring et al. 1997). Here we explore the possibility that the anomalies are first indications that the current framework for the origin of hadronic CRs is wrong, and propose an alternative origin.

Gamma-ray bursts (GRBs) are short and intense bursts of γ-rays from distant galaxies that are detected by space satellites at a rate of $R_{\rm GRB} \sim 10^3$ per year (Fishman & Hartmann 1997). Their origin is unknown, but various observations suggest an association with the formation of black holes or the birth or

Send offprint requests to: plaga@mppmu.mpg.de

collapse of neutron stars (NSs) due to mass accretion or phase transition, in close binaries or alone. The strongest indication for a connection with the birth of NSs are the coincidences of supernovae with GRBs, e.g. SN 1998bw and GRB 980425 (Galama et al. 1998) and of SN 1999E and GRB 980919 (Thorsett & Hogg 1999; Kulkarni & Frail 1999). A connection between events in the life of NSs and GRBs at cosmological distances was first suggested by Paczynski (1986), Goodman et al. (1987) and Dar et al. (1992).

The rest of the introduction discusses the assumptions we make about GRBs in our scenario, beaming in GRBs and previous work on CR acceleration in GRBs. Sect. 2 turns to a more detailed quantitative discussion of our picture of GRBs. Sect. 3 discusses the propagation of the ejecta of GRBs in the Galaxy and Sect. 4 treats energy spectrum of CRs which is expected in our scenario. Sects. 5 and 6 describe how our scenario resolves the above-mentioned anomalies of UHE CRs and lower energy CRs respectively. Sect. 7 concludes the paper.

1.1. Basic assumptions for our scenario

We make two basic assumptions for our scenario.

- GRBs are not rare events, but common phenomena in the life of neutron stars; i.e., in our Galaxy they occur with a frequency comparable to the NS birth rate. We argue in the next subsection that a necessary implication from this and the observed rate of GRBs $R_{\rm GRB}$ – that the emission from GRBs is strongly beamed - seems likely in view of recent GRB observations.

- Jetted ultra-relativistic ejecta ("plasmoids") emit the beamed radiation in GRBs and carry a considerable fraction of the total binding energy of a NS. The ejecta remain confined to a small size until slowed down – via interaction with an ambient medium – to mildly relativistic speeds. Only then do they dissipate most of their kinetic energy – partly by particle acceleration – and release most of the previously accelerated particles. We give arguments in favour of this assumption – based on a special interpretation of NS kicks and analogies with similar astrophysical systems – and describe it in more detail in Sect. 2.

We return to the question whether these assumptions are overly speculative in the conclusion.

1.2. Beaming in GRBs

If the true rate of GRBs is similar to the birth rate of NSs, $R_{NS} \simeq 0.02\,{\rm year}^{-1}$ in galaxies like our own (van den Bergh & Tamman 1991), the radiation emitted in GRBs must be narrowly beamed into a solid angle $\Delta\Omega \simeq \pi\times 10^{-6}$ in order to explain their rate inferred from $R_{\rm GRB}$ (Wijers et al. 1997) in such galaxies:

$$R_{\rm GRB}({\rm MW}) \simeq 2R_{\rm NS}(\Delta\Omega/4\pi) \sim 10^{-8}\ {\rm year}^{-1}. \qquad (1)$$

Indeed GRBs could be produced by highly relativistic, collimated jets with bulk motion Lorentz factors $\Gamma = 1/\sqrt{1-v^2/c^2} \sim 10^3$ (Shaviv & Dar 1995; Blackman et al. 1996; Mészáros & Rees 1997; Chiang & Dermer 1997; Dar 1998a).

In this connection – and always in this paper – the term "jet" is meant to imply only collimated ejecta into a small opening angle and not an emission stationary in time. The very large redshifts recently measured in some GRBs and their host galaxies – e.g. z=3.42 for GRB 971214 (Kulkarni et al. 1998) – seem firmly to require jetted emission for energetic reasons. For instance, the assumption of isotropic emission implies that $\geq 4\times 10^{54}$ erg – which is hardly obtainable in the birth or collapse of any stellar object – was emitted by GRB 990123 as γ-rays (Djorgovski et al. 1999; Kippen 1999), while only $\sim 10^{48}$ erg was emitted if the emission was narrowly beamed into a solid angle $\Delta\Omega \sim \pi\times 10^{-6}$. Hjorth et al.(1999) found a complete absence of optical polarisation in GRB 990123 and mention a relativistic jet which is seen at a small viewing angle as one possible explanation for their somewhat surprising observation. Emission from "narrow" jets with bulk motion Lorentz factors $\Gamma \sim 10^3$ is indeed beamed into a solid angle $\Delta\Omega \sim \pi/\Gamma^2 \simeq \pi\times 10^{-6}$ consistent[1] with Eq. (1). Here "narrow" means that the angle of the emitted ejecta θ subtended from the burst site is smaller than $1/\Gamma$. There is some evidence that under the assumption of jetted ejection this condition is fulfilled in GRBs (though the following cannot be considered as proof for jetted ejection): Schaefer & Walker (1999) argued from timing data of the BATSE detector that for the burst GRB 920229, $\theta < 1'$; this fulfils the "narrow"-jet condition for $\Gamma < 3000$. The amount of beaming and physical structure of the GRB jet assumed in our paper is very similar to the one in a model of Chiang & Dermer (1997) for GRB afterglows.

If such strong beaming is typical – and this we assume – we observe only a very small fraction of a large rate of the events that can produce GRBs. We call these events "Galactic" (if they occur in our Milky Way (MW) galaxy) and "Cosmological" (if they occur in distant galaxies) gamma-ray bursts" (GGRBs and CGRBs), respectively.

1.3. CR acceleration in GRB ejecta

Gamma-ray bursters have been proposed as efficient accelerators of ambient material to CR energies before, but GGRBs with isotropic CR emission (Dar et al. 1992; Milgrom & Usov 1996) cannot supply the bulk of the Galactic cosmic rays for energetic reasons. Nor can the idea of UHE CRs from CGRBs (Vietri 1995; Waxman 1995; Böttcher & Dermer 1998) explain the absence of the GZK cutoff (Dar 1999). In this paper we show that the effects of strong beaming make GGRBs plausible sources of non-solar hadronic cosmic rays at *all* energies (from $\simeq 100$ MeV to 3×10^{20} eV) observed near Earth.

[1] Such Lorentz factor values are required from GRB observations independent of whether beaming takes place (see, e.g., Baring & Harding 1997).

2. Quantitative properties of the plasmoids ejected in GRBs

The ejection of highly relativistic jets from accreting or collapsing compact objects, and especially the physical mechanism for their observed collimation "remains a major unsolved problem in astrophysics (Longair 1997)". Therefore, instead of relying on theoretical models, we have tried to estimate the properties of those jets that may produce the GRBs and cosmic rays from data about NSs and – by way of analogy – from observations of similar jets.

NSs are observed to possess a large mean velocity of $v \approx 450 \pm 90\ \mathrm{km\,s^{-1}}$ (Lyne & Lorimer 1994). Burrows & Hayes (1996) argue that an anisotropic stellar collapse – rather than proper motions due to orbital speeds in binaries – is the mechanism responsible for the necessary "kick" and and that matter – rather than neutrinos – carries most of the momentum. Janka & Raffelt (1998) find that works in which deformed neutrino spheres impart large kicks to NSs are incorrect and that it is in general difficult to impart the necessary momentum via neutrinos. In this light – and making the above assumptions – it seems plausible that the ejection of relativistic jets in the birth or collapse of NSs is responsible for their observed large mean velocity. Momentum conservation then implies that the kinetic energy of the jets is

$$E_K \approx cP \sim vM_{NS}c \sim 4 \times 10^{51}\ \mathrm{erg}, \tag{2}$$

where we used the typical observed NS mass, $M_{NS} = 1.4 M_\odot$. If two antiparallel jets are ejected, then the above estimate becomes a lower limit for the jet kinetic energy, that may be of the order of $E_\mathrm{k} \sim 10^{52}\ \mathrm{erg}$. Thus, already a modest fraction $f \simeq 0.01$ of the total energy injected into the MW in jets from GGRBs, at a rate $R \sim 0.02\ \mathrm{year}^{-1}$, similar to the NS birth rate, can supply the estimated Galactic CR luminosity $L_{MW}[CR] \sim 1.5 \times 10^{41}\ \mathrm{erg}$ (e.g., Drury et al. 1989).

Highly relativistic jets are emitted by all astrophysical systems where mass is accreted at a high rate from a disk onto a central black hole (BH). They are observed in Galactic superluminal sources, such as the micro-quasar GRS 1915+105 (Mirabel & Rodriguez 1994), where mass is accreted onto a stellar BH, and in many active galactic nuclei (AGN), where mass is accreted onto a super-massive BH (Begelman et al. 1984). Mildly relativistic jets from mass accretion were seen both in AGN and in star binaries containing NSs such as SS433 (Margon 1984) and Sco X-1 (Fomalont et al. 1983).

High-resolution radio observations of the micro quasar GRS 1915+105 resolved the narrowly collimated relativistic jets into clouds of plasma (plasmoids) that are emitted in injection episodes which are correlated with sudden removal of the accretion disk material (Mirabel & Rodriguez 1994). In GRS 1915+105, during the first five days after ejection, these plasmoids appear to have expanded with the speed of sound in a relativistic gas, $c_\mathrm{s} \sim c/\sqrt{3}$ in the plasmoid rest frame, corresponding to vertical expansion speed of $\sim c/\Gamma\sqrt{3}$ in the lab frame), until they reach a radius $R_\mathrm{p} \sim 2 \times 10^{15}\ \mathrm{cm}\ (\sim 0.001\ \mathrm{pc})$ (Rodriguez & Mirabel 1998; Mirabel & Rodriguez 1994). Their expansion seems to be slowed afterwards, probably due to some confinement mechanism (Mirabel & Rodriguez 1994; Mirabel & Rodriguez 1999). Likewise, jets from quasars and radio galaxies can also often be resolved into the ejection of distinct clouds at the pc scale (e.g., Giovannini et al. 1999) and might be governed by mechanisms similar to the jets emitted by micro quasars. These jets retain a constant radius after initial expansion (see, e.g., (Swain et al. 1998)) and some confinement mechanism is clearly at work. The repeated ejection of plasmoids (often called "plasmons" in the older literature) is a well known model for extragalactic jets (Begelman et al. 1984; de Young & Axford 1967; Christiansen 1973).

The confinement mechanism which collimates plasmoids is not understood; two possibilities are magnetic confinement (Begelman et al. 1984) and inertial confinement via the ram pressure of the ambient medium (de Young & Axford 1967). The plasmoids slow down by sweeping up the ionised interstellar medium in front of them.

It is one of our assumptions that the plasmoids from the birth/collapse of NSs evolve in a similar way to the ones apparently ejected in galactic superluminal sources and AGNs (Dar 1998a). The plausibility of this idea was recently endorsed by Mirabel & Rodriguez (1999) in their review about relativistic jets the Galaxy; they write: "the study of the less extreme collimated outflows in our own Galaxy may provide clues for a better understanding of the super-relativistic jets associated with... GRBs". The plasmoids in GRS1915+105 could only be followed up to distances of about 0.03 pc from the central source. A non-thermal jet with a radius of about 0.1 pc at a distance of about 60 pc from the central source GRS1915+105 and pointing back to it was observed recently in the radio range (Rodriguez & Mirabel 1998a). No connection between the central source and this jet was observed. A possible interpretation is that this jet is a collimated plasmoid that was ejected by the central source. These various observations of jets motivate the first part of our second assumption in the Introduction that:

– after an initial expansion – and until their final dissipation phase – the plasmoids retain a radius of about 0.01 pc, collimated by the as yet ill-understood mechanism apparently at work in the plasmoids and jets discussed above.

Plasmoids ejected in the birth/collapse of NSs – as opposed to the ones in micro quasars and AGNs – are "isolated", i.e. their central source is active on a time scale smaller then their propagation time. Our assumption is that this fact does not invalidate the qualitative similarity between the mentioned three object classes.

In extragalactic double-lobe radio galaxies like Cyg-A (Begelman et al. 1984) it is observed that apparently bulk kinetic energy of the jet is dissipated mainly in a "hot spot". The non-thermal jet at a large distance from GRS1915+105, mentioned above, is an indication that "isolated" plasmoids might show a similar behaviour. A rising internal kinetic pressure – due to the sweep up of relativistic particles – and dissipation of their internal magnetic energy might lead finally to their expansion and stopping in "hot spots", where a considerable part of their initial kinetic energy is released in highly relativistic particles. Another factor leading to a final expansion could be a decrease in inertial confinement due to the a falling ram pressure in decelerating plasmoids, but the detailed physics of hot spots produced by "isolated" plasmoids remains unclear. This set of observations motivates the second part of the second assumption in the Introduction:

– the plasmoids dissipate most of their energy in turbulent motion of inter-halo matter and CR production only when they have been slowed down – via sweeping up ambient matter – to mildly relativistic energies. Most of previously accelerated particles are also released in the phase.

In the case of a GGRB there is no stationary flux of particles whose energy is dissipated at a relatively sharply defined "working surface", as in the case of the jets of active galaxies (Begelman et al. 1984). Under the above assumptions most of the dissipation and particle acceleration will take place in a region which is small compared with the total distance travelled by the plasmoid and which we might still call "hot spot".

The possibility that relativistic jets responsible for GRBs are sometimes formed in supernova (SN) explosions has been discussed by various authors (Cen 1998; Wang & Wheeler, 1998; Eichler & Levinson 1998). It is conceivable that a considerable fraction of SN explosions leads to GRBs with the properties required in our scenario. The jet like features observed in many SNRs (Gaensler et al. 1998) may even hint towards this possibility (though they certainly do not prove it). However, this idea is not mandatory for our scenario; other events in the life of NSs might be responsible for most GRBs.

Because the accretion rates and magnetic fields involved in events leading to GRBs are larger than in all other systems discussed above, an initial Lorentz factor of $\Gamma \sim 10^3$, as required by GRBs observations, does not appear excessive. The initial equipartition magnetic fields in such plasmoids can be estimated to be $B > 100$ G. Extragalactic jets, which might be qualitatively similar objects, have been identified as prolific CR accelerators (Burbidge 1962), in particular their hot spots (Biermann & Rachen 1993). Highly magnetised relativistic plasmoids are both efficient CR accelerators (Chiang & Dermer 1997; Dar 1998b) (through Fermi acceleration) and strong emitters of beamed γ-rays through synchrotron emission, inverse Compton scattering and resonance scattering of interstellar light. When they point in (or precess into) our direction from external galaxies, they produce the observed GRBs and their afterglows.

3. Propagation of the ejected plasmoids in the Galaxy

For our discussion, we adopt an extremely simplified picture of our Galaxy, namely, a Galactic thin disk surrounded by a spherical halo with an approximate radius of $R_{\rm h} \sim 50$ kpc ($V_{\rm h} \sim 1.5 \times 10^{70}\ cm^3$) and a mean gas density of $n_{\rm h} \sim 10^{-3}\,{\rm cm}^{-3}$. The highly relativistic plasmoids which are emitted with $E_k \sim 10^{52}$ erg perpendicular to the Galactic disk are assumed to be decelerated mainly by sweeping up ambient matter.

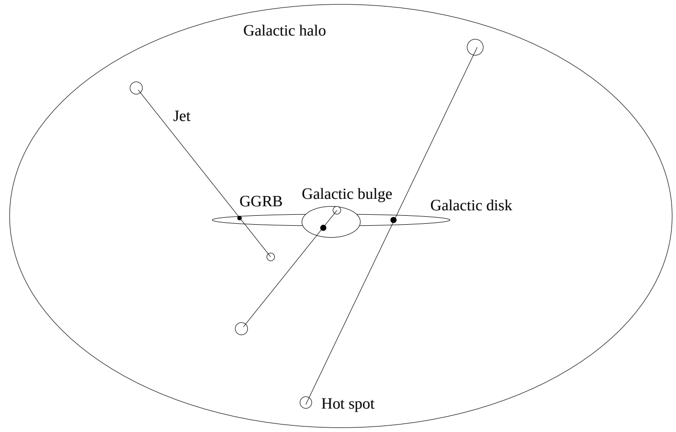

Fig. 1. A highly schematic sketch of our scenario. The birth or collapse of NSs in the disk of our Galaxy leads to an ejection of two opposite jets that produce "hot spots" when they stop in an extended Galactic halo.

Whether this is an accurate description depends on whether the swept-up material "sticks" to the plasmoid and is incorporated into it, rather than e.g. forming a hot expanding wake behind the plasmoid. A full dynamic treatment of the propagation of ultrarelativistic plasmoids is required, a problem that is however beyond the scope of this paper. The plasmoids then stop in the Galactic halo, when the rest mass energy of the swept-up ambient material is equal to their initial kinetic energy: The column density of gas required to stop jets with a radius smaller than $R_{\rm p} \sim 0.01$ pc is

$$N_{\rm c} \geq 2.2[(E_{\rm k}/10^{52}\ {\rm erg})/(R_{\rm p}/0.01\ {\rm pc})^2)] \times 10^{21}\ {\rm cm}^{-2}. \quad (3)$$

The mean column density of gas (mainly molecular, atomic and ionised hydrogen) perpendicular to the Galactic disk, is $N_c < 10^{21}\ {\rm cm}^{-2}$ (Berezinskii et al. 1990). From Eq. (3) one reads that the jets stop in the Galactic halo when their radius reaches $R_p \sim 0.1$pc (if $n_{\rm h} \geq 10^{-4}\ {\rm cm}^{-3}$) and form hot spots. This is illustrated in Fig. 1.

The "decelerating plasmoid model" of Chiang & Dermer (1997) for GRB afterglows makes similar assumptions and works out some consequences in more numerical detail. In particular, in their model the plasmoid expands only slowly, and decelerates mainly via sweeping up ambient matter. In their case a plasmoid with a radius of about 10^{-4} to 10^{-3} pc, ejected by the CGRB with a kinetic energy of 10^{50} ergs, travels 30–100 pc in the first 3–10 days after the GRB (measured in the observer frame) and does not slow down to non-relativistic speeds during the simulated propagation.

4. Energy spectrum of CR produced by the plasmoids

4.1. High-energy limit for the acceleration of CR in the plasmoids

The typical equipartition magnetic fields in the hot spots discussed in the previous section may reach $B \sim (3E_{\rm k}/R_{\rm p}^3)^{1/2} \sim 1$ G. Synchrotron losses cut off Fermi acceleration of CR nuclei with mass number A at $E \sim \Gamma A^2 Z^{-3/2} (B/G)^{-1/2} \times 10^{20}$ eV. Particle escape cuts off Fermi acceleration when the Larmor radius of the accelerated particles in the plasmoid rest frame becomes comparable to the radius of the plasmoid, i.e., above $E \simeq \Gamma Z (B/G)(R_p/0.1\ pc) \times 10^{20}$ eV. In the hot spots, $R_p \sim 0.1$ pc, $\Gamma \sim 1$ and $B \sim 1$ G. Consequently, CR with $E > Z \times 10^{20}$ eV can no longer be isotropised by acceleration or deflection in the hot spots. Thus, CR with energies above 10^{20} eV are heavy nuclei in our scenario.

4.2. The energy spectrum at lower energies

Fermi acceleration in or by the highly relativistic jets from GRBs could produce a broken power-law spectrum, $dn/dE \sim E^{-\beta}$, with $\beta \sim 2.2$ below a knee around $E_{\rm knee} \sim A\,{\rm PeV}$ and $\beta \sim 2.5$ above this energy (Dar 1998b). Spectral indices $\beta \sim 2$–3 are expected in relativistic shock acceleration with tangled magnetic fields (Ballard & Heavens 1992). Galactic magnetic confinement increases the density of Galactic CR by the "concentration factor" c = $c\tau_{\rm h}/R_G$, where $\tau_{\rm h}(E)$ is the mean residence time in the halo of Galactic CR with energy E and R_G is the radius of the Galactic magnetic-confinement region. With the standard choice for the energy dependence of the diffusion constant (observed, e.g., in solar-system plasmas (Berezinskii et al. 1990)) one gets: $\tau_{\rm h} \propto (E/Z)^{-0.5}$. Consequently, the energy spectrum of CR is expected to be

$$dn/dE \sim C(E/E_{\rm knee})^{-\alpha} \qquad (4)$$

with $\alpha \simeq \beta + 0.5 \simeq 2.7$ ($\simeq 3$) below (above) the knee. The normalisation constant cannot yet be determined – except by the rough total-energy argument mentioned in Sect. 2 after Eq. (2) – but is universal for all energies. In this respect our scenario and the conventional framework are in the same status.

This power-law is expected to continue as long as the Galactic magnetic field confines the CRs, i.e., up to energies near the "ankle".

4.3. Explanation of the "ankle"

Part of the kinetic energy released by GGRBs is transported into the Galactic halo by the jets. Assuming equipartition of this energy, without large losses, between CR, gas and magnetic fields in the halo during the residence time of CR there, the magnetic field strength $B_{\rm h}$ in the halo is expected to be comparable to that of the disk $B_{\rm h} \sim (2L_{\rm MW}[CR]\tau_{\rm h}/R_{\rm h}^3)^{1/2} \simeq 3\ \mu G$ where $\tau_{\rm h} \sim 5 \times 10^9$ years is the mean residence time of the bulk of the CR in the Galactic halo (see Sect. 4.4) cosmic rays with Larmor radius larger than the coherence length λ of the halo magnetic fields (Lampard et al. 1997), i.e., with energy above

$$E_{\rm ankle} \sim 3 \times 10^{18} (ZB_{\rm h}/3\mu{\rm G})(\lambda/{\rm kpc})\ {\rm eV}, \qquad (5)$$

escape Galactic trapping. Our "preferred" values indicated in Eq. (5) are well within the range of possible values preferred by other researchers (Lampard et al. 1997). Thus, the CR ankle is explained as the energy where the mean residence time $\tau_{\rm h}$(E) of CR becomes comparable to the free escape time from the halo

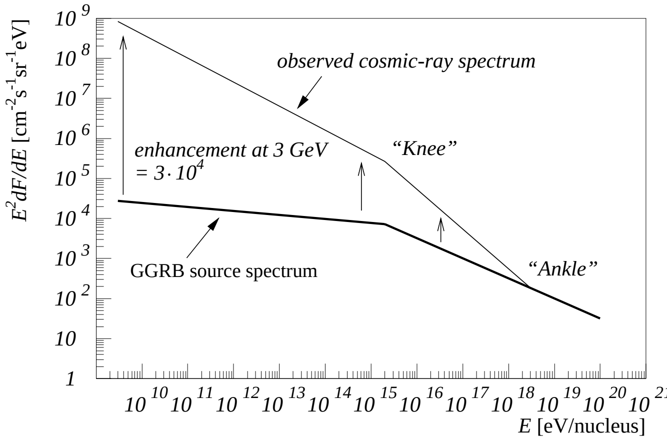

Fig. 2. The observed flux of cosmic rays (thin line) as a function of primary energy E is well described by a power law that changes its slope sharply at only two energies, the "knee" and the "ankle". At energies below the ankle it is enhanced (by a factor $(E/E_{ankle})^{-0.5}$) over the GGRB source spectrum (thick line, a power law with differential power law index of -2.2 below the knee and $\simeq$ -2.5 above it) by way of trapping in the Galactic halo magnetic fields

$\tau_{\rm free} \sim 1.6 (R_{\rm h}/50\ {\rm kpc}) \times 10^5$ years. This explanation for the ankle was already proposed by one of us (Plaga 1998) in the context of a proposed extragalactic origin of hadronic CRs, to which the present proposal bears of course some similarity (in both cases all hadronic CRs have a common origin outside the Galactic disk).
The spectrum of CRs with energies above the ankle that do not suffer Galactic magnetic trapping is then the CR spectrum produced by the jet, i.e.,

$$dn/dE \sim C(E_{\rm ankle}/E_{\rm knee})^{-3}(E/E_{\rm ankle})^{-2.5}; \quad E > E_{\rm ankle}. \qquad (6)$$

This predicted spectral index of 2.5 has to be compared with the one recently determined by the AGASA collaboration (Takeda et al. 1998) of $2.78^{+0.25}_{-0.33}$. In the conventional framework – where only UHECRs have an extragalactic origin – the position of the ankle at just the energy where Galactic magnetic fields can no longer confine CRs is pure coincidence.

4.4. The "knee" in the CR spectrum and low-energy propagation

The knee in the CR source spectrum still lacks a complete explanation (see however Dar (1998b)), but we think that a single source population over the whole CR energy range offers a more natural framework to understand the CR spectrum than the prevailing one where a "fine tuning" in the intensity of different source components is often required at the knee. The "concentration factor" c (see Sect. 4.2 above) over the GGRB source spectrum reaches 3×10^4 at GeV energies (see Fig. 2), corresponding to a confinement time in the Galactic halo of about 5×10^9 years. We interpret the experimentally measured "lifetime" of low-energy CR, of the order 2×10^7 years (Berezinskii et al. 1990; Connel et al. 1998), as the residence time in the

Galactic disk, in which we are located as observers, rather than the time since acceleration, as in most other models. The mean residence time τ_d of low-energy particles in the disk is given as:

$$\tau_\mathrm{d} \simeq \tau_\mathrm{h} \cdot (d_\mathrm{d}/d_\mathrm{h})^2 (D_\mathrm{h}/D_\mathrm{d}). \quad (7)$$

If the diffusion coefficient D_d in the disk is smaller than that in the halo (D_h) by about a factor 10^3 – due to a stronger turbulence in the disk induced by SN explosions – then τ_d is of the observed order of magnitude.

5. A prediction of our scenario: angular clustering of UHE CRs

Small deflections of UHECR by turbulent magnetic fields along their arrival trajectory, with a length d, spread their arrival times over

$$\Delta t \sim 750(d/50\ \mathrm{kpc})^2(\lambda/\mathrm{kpc}) \times (ZB/3\mu\mathrm{G})^2(E/100\ \mathrm{EeV})^{-2}\ \mathrm{years}. \quad (8)$$

The nearly isotropic release of CR in the halo by GGRBs and the spread in their arrival times, during which many GGRBs occur, accounts for the nearly isotropic sky distribution of the UHECR. Jets which stop in the Galactic bulge or the Galactic disk (see Fig. 1) may produce a detectable enhancement in the flux of UHECR from these directions.

First data from the Akeno Giant Air Shower Array (AGASA) (Hayashida et al. 1996) suggested a clustering in the arrival directions of the UHECR, these indications have recently been reaffirmed with an enlarged database (Takeda et al. 1999). The directions of these clusters do not coincide with any known nearby extragalactical objects which would seem a plausible candidate for acceleration the UHECR; this is consistent with a Galactic halo origin. Such clustering is predicted if the UHE CRs are produced/released in hot spots in the Galactic halo. Their accumulated r.m.s. deviation angle over a distance d by random walk in the turbulent magnetic field is

$$\theta \sim 5.4^0(d/50\ \mathrm{kpc})^{1/2}(\lambda/\mathrm{kpc})^{1/2}(ZB/3\mu\mathrm{G}) \times (E/100\ \mathrm{EeV})^{-1}. \quad (9)$$

Therefore, if the origin of UHECR is ~ 0.1 pc-sized hot spots in the halo, the arrival direction of CR with energies around $100\ \mathrm{EeV}$ is predicted to cluster around $\sim$ 30 (arrival time spread $\times$ GGRB rate) fixed hot spot positions in the sky whose number and spread around them decrease with increasing energy.

An origin of UHE CRs from the decay or annihilation of ultra-massive new particles in the Galactic halo has recently been discussed (Hillas 1998; Berezinskii et al. 1997; Kuz'min & Tkachev 1998). In such a scenario clustering is not possible if the the UHE CRs are nucleons from the decay or annihilation of relic particles with mass smaller than the Planck mass, $m_\mathrm{p} = \sqrt{\hbar \mathrm{c}/\mathrm{G}} \approx 1.22 \times 10^{19}\ \mathrm{GeV/c}^2$, which are distributed isotropically in the sky. Even if all the rest mass energy was converted into two opposite jets of 10^{19} eV nucleons with transverse momentum of $\sim 1\ GeV/c$ with respect to the jet axis, the mean number of UHE CR events that such a jet from a typical halo distance of 30 kpc could produce in the AGASA detector ($100\ \mathrm{km}^2$) is still only $\sim 5 \times 10^{-6}$.

6. Some experimental data on CRs compared to expectations in our scenario

The CR spectrum which is suggested in our scenario is displayed in Fig. 2. As discussed in the previous sections it agrees well with the measured spectrum. There is no GZK cutoff because of the small distance to the sources (O(50 kpc)), over which absorption of UHE nucleons in the microwave-background radiation is negligible. As the major part of the hadronic CRs are not produced in SNRs in our scenario, the predicted flux of high-energy γ-rays due to proton interaction from these objects can be low, thus resolving the second anomaly mentioned in the introduction. A quantitative calculation of the expected density of hadronic CRs as a function of galactocentric radius in our scenario is difficult because of the ill-understood propagation properties of the plasmoids in different part of the Galaxy (halo, bulge, etc.). In first approximation this density is predicted to fall with a halo scale (i.e., tens of kpc). This is in better agreement with observations than the ~ 5 kpc scale height of SNRs, which is expected to be close to the characteristic decay scale in the conventional scenario (third anomaly in the Introduction; Strong & Moskalenko 1998[2]). Recent determinations of the gradient from EGRET data yield for the exponential decay scale between 5 kpc and 20 kpc (read off diagrams in these publications): 16 kpc (Hunter et al. 1997), 34 kpc (Erlykin et al. 1996), 23 kpc (Strong & Mattox 1996).

Moreover – due to the near isotropy of their sources – the large-scale anisotropy of CRs must be very small in our scenario at all energies. This resolves the fourth anomaly mentioned in the Introduction.

7. Properties of decaying plasmoids in the halo

Electrons suffer large energy losses by synchrotron emission and inverse Compton scattering while diffusing out of their jet acceleration sites. Thus, CR electrons in the Galactic disk could have their origin mainly in Galactic SNRs (Ginzburg 1957); this theory has recently received experimental support from X-ray (Allen et al. 1997) and TeV γ-ray (Tanimori et al. 1998) observations of Cas-A and the remnant of SN 1006, respectively. Totani (1998) argued that synchrotron radiation from accelerated protons is an important emission mechanism in GRB afterglows. Assuming hot spots accelerate mainly baryons on a time scale of about 1000 years over which they irradiate 10^{50} ergs in proton synchrotron radiation, their resulting radio intensity will be less than a mJy (Plaga et al. 1999). The hot spots are thus not expected to be particularly conspicuous radio sources. The detailed observational consequences of hot-spot remnants in the halo of the Milky Way will be discussed elsewhere (Plaga et al. 1999).

[2] The propagation models assuming a SNR origin of CRs in this publication predict decay scales between 4.5 to 9 kpc.

8. Conclusion

We proposed an alternative source for the origin of hadronic CRs at all energies which is in better accord with some observational facts than the conventional one. Some of the assumptions on which it is based are certainly speculative. However, our ideas seem conservative when compared to the audacity of some proposals by outstanding scholars to explain the puzzling properties of ultra-high energy CRs – like, e.g., a violation of Lorentz invariance (Coleman & Glashow 1998), the existence of a new class of super-massive elementary particles in the Galactic halo (Berezinskii et al. 1997; Kuz'min & Tkachev 1998; Hillas 1998) or supersymmetric light strongly-interacting particles (Biermann & Farrar 1998). Further observations of GRBs and their afterglows will reveal if the contention that a GRB is a common phenomenon in the life of a neutron star – crucial for our scenario – is tenable. The next generation of UHE CR detectors (Mantsch 1996) will rule out or confirm our prediction about their angular clustering properties. Basic issues of our scenario which require more work are the exact nature of the event giving rise to a GRB and the observational properties of "hot-spot remnants" in the Galactic halo.

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