On an extragalactic origin of the dominant part of the hadronic cosmic rays

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Abstract

The possibility that the major part of all extrasolar hadronic cosmic rays with energies above 10 MeV/n is of extragalactic origin is discussed. Recent observational results on the galactocentric cosmic-ray density gradient and very high γ-ray emission do not support expectations from the simplest models with a Galactic origin of cosmic rays. The hypothesis that “flux trapping” of extragalactical cosmic-rays occurs in the Galactic confinement volume is advanced. Taking this phenomenon into account, all the usual objections against an extragalactic origin of hadronic cosmic rays loose their strength. The local energy density of hadronic cosmic rays and other observational facts can be understood in a very natural way assuming an extragalactical origin. A promising scenario seems to be a Galactic origin of electrons and an extragalactic origin of hadrons.

1. Introduction

This report is a short summary and update of a more detailed article (Plaga, 1997). In addition, in the third part counterarguments against an extragalactic origin of cosmic rays are explicitly answered. The possibility of an extragalactic origin of the dominant part of all extrasolar hadronic cosmic rays has been considered since the early days of cosmic-ray research (Baade and Zwicky, 1934). In the modern era it was discussed by Burbidge, Hoyle and Brecher (see e.g. Brecher and Burbidge, 1972; Burbidge, 1974). It has long been clear that the electron component of cosmic-rays is of Galactic origin, and recently there has been new impressive evidence for a supernova origin of this component from TeV astrophysics (Tanimori et al,1997; T.Kifune, these proceedings).

Since about 30 years, using arguments which I will discuss below, the standard view about the origin of extrasolar cosmic rays has been that they must be produced in our Galaxy. In this case the only objects which seem to be capable to sustain the observed cosmic-ray energy density in the Galaxy against losses to intergalactic space are supernova remnants (Berezinskii et al.,1990). This idea is eminently plausible because shock-wave acceleration is expected to operate in these objects (Berezhko and Volk, 1997; H.Völk, these proceedings). There are two observational facts, however, which seem not to be in complete agreement with the most simple quantitative models of a Galactic origin of the main part hadronic cosmic rays:

1. A classical problem in cosmic-ray physics and γ-ray astrophysics is to infer cosmic-ray density as a function of the distance from the Galactic center. This is done by measuring the γ-ray intensity due to cosmic-ray - interstellar medium interactions. Taking into account the

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known density of the interstellar medium, the cosmic-ray density can be inferred. Fig. 1 shows the resulting density from $\gamma$-ray data with $\gamma$-ray energies above 2 GeV from the publication of Erlykin et al. (1996) based on EGRET data. This result (in basic agreement with other independent analyses) seems to indicate that beyond about 8 kpc there is no clear gradient, i.e. the cosmic-ray density seems to remain constant, or at least does not fall by more than about 30% between 8 and 18 kpc. Because supernova remnants and all other proposed Galactic accelerators are strongly concentrated towards the Galactic center, one expects in simple diffusion models of Galactic propagation a fall in cosmic-ray intensity by more than a factor of 10 in cosmic-ray density between 8 and 18 kpc (Case and Bhattacharya, 1996). While it is certainly possible to devise more complicated models with an extended halo of cosmic-rays and transport with winds rather than diffusion (Erlykin et al., 1997) which explain this strong disagreement, it should be noted that a constant density of cosmic-rays at different distances from the Galactic center (as observed), has always been considered as the signature for an extragalactic origin of cosmic rays. The observed small gradient at distances smaller than 8 kpc can be naturally interpreted as due to electrons, which are of Galactic origin.

2. Another recent clue from TeV astrophysics have been strict upper limits on $\gamma$-ray emission from certain supernova remnants (Heß 1997; Lessard et al., 1997). For two special cases (SNR G78.2+2.1 and IC443) these limits lie at the lower end of the the uncertainty range for $\gamma$-radiation of hadronic origin, made under the assumption of a Galactic supernova origin of cosmic rays. Though clearly these results do not signal a crisis for the Galactic scenario for cosmic-ray origin, they underline the fact that no direct evidence of any sort has been found for it up to now.

The question I ask is not “do Galactic supernova remnants accelerate also ions in addition to electrons?”. It seems to me very likely that they do that. The question is rather: “Do they accelerate them in the required amount (i.e. about a factor of 100 times more efficient than the electrons) to explain the local cosmic-ray energy density?"

2. Magnetic flux trapping

2.1. The physical idea
The new idea of this contribution is “magnetic-flux trapping”, a mechanism that might lead to enhancement of the intergalactic cosmic-ray density in the Galactic confinement volume by a
factor $e$. If cosmic rays escape from an extragalactic production site with a high magnetic field $B_{er}$ into intergalactic space with a low magnetic field $B_{IGM}$ conserving the adiabatic invariant, they have small pitch angles below a maximal angle $\theta_{\text{max}} = \arcsin(\sqrt{B_{IGM}/B_{er}})$. Under these conditions the particles can freely enter the Galactic confinement volume via the open field lines, if the Galactic field has a general topology as depicted in figure 2.

It is generally agreed that the adiabatic invariant is not conserved inside the Galaxy due to various scattering mechanisms. All Galactic field lines are expected to be filled with particles of all pitch angles. If the only cosmic-ray loss path is via open field lines connected to intergalactic field lines, the cosmic ray density inside the Galaxy is a factor

$$b_{\text{conc,eqn}} = 2B_{\text{Gal}}/B_{\text{IGM}}$$

enhanced over the intergalactic value. Here $B_{\text{Gal}}$ is the Galactic field strength. This could lead to concentration factors on the order of $10^5$ with plausible values for the intergalactic and Galactic magnetic field. This enhancement mechanism was first discussed in a related context by Sciama (1962). The main speculative parts of the hypothesis are that:

1. the incoming intergalactic cosmic rays have very small pitch angles so that they can freely enter the Galactic confinement volume. This will be the case if their place of origin lies in regions with magnetic fields higher than about a $\mu$G.
2. The adiabatic invariant is strictly conserved during intergalactic propagation. Presently it is not possible to say whether this assumption is true or not, due to our very poor knowledge of intergalactic fields.

2.2. Galactic propagation in the extragalactic scenario

If the concentration factor $b_{\text{conc,eqn}}$ is very large, the resulting cosmic-ray density can become too large to be confined in the Galactic magnetic field. Cosmic rays then mainly escape through additionally formed Parker loops which are unconnected to the intergalactic magnetic field. As a limiting case one expects an equilibrium situation in which standard Galactic cosmic-ray propagation remains approximately valid. In this case the only difference to the standard picture is that hadronic cosmic rays are supplied from the outside instead from Galactic sources.
One can then show that the effective concentration factor $e$ is given as:

$$e = \frac{d c}{D_G} \simeq 3 \cdot 10^4$$

Here $D_G$ is the diffusion coefficient of Galactic propagation, $d$ is the linear size of the confinement volume and $c$ is the speed of light.

2.3. The origin of extragalactic cosmic rays

It is a completely open question presently if the intergalactic hadronic cosmic-ray density was mainly produced in normal galaxies or active objects. If the latter dominate, radio galaxies like Cen A seem to be the most natural accelerators for the locally observed hadronic cosmic rays in the present scenario. In the local supegalaxy it seems quite possible that the intergalactic medium at the lobes is chemically processed. But also a supernova-remnant origin in normal or “bright phase” galaxies is an attractive possibility!

3. The counterarguments against an extragalactic origin of hadronic cosmic rays

The idea of an extragalactic origin has long been unpopular because of strong arguments against it. I will now briefly discuss why all of these arguments lose their strength if “flux trapping” is assumed to operate.

3.1. The expected energy density of intergalactic cosmic rays is too small

A generally accepted estimate for the density of intergalactic hadronic cosmic rays $\rho_{eg}$ expected from normal galaxies and active objects is about $10^{-4}$ of the local value $\rho_{loc}$ (Ginzburg, 1993). Remarkably one gets as a natural and “untuned” consequence of our scenario: $\rho_{loc} \simeq \rho_{eg} \cdot e$ (see eq.(2)). The predicted enhancement factor $e$ has the right order of magnitude to explain the local energy density of cosmic rays, under the assumption of an extragalactical cosmic-ray energy density which is considered likely by most workers in the field. More detailed figure 3 shows a speculative explanation of the observed cosmic-ray spectrum under the assumption of an extragalactic origin. Here it was taken into account that the enhancement factor $e$ is expected to be energy dependent in the standard theory of cosmic-ray propagation. While the “knee” remains enigmatic in all scenarios, the position of the “ankle” follows as a natural consequence of the extragalactic scenario.

3.2. There is no $\gamma$ radiation from the SMC

Sreekumar et al. (1993) have argued that their non-detection of $\gamma$-radiation above 100 MeV from the Small Magellanic cloud (SMC) rules out an extragalactic origin of cosmic-rays. Their argument is based on the assumption that the cosmic-ray density in the SMC is equal to the local Galactic one in extragalactic scenarios. This assumption does no longer hold in the present special extragalactic scenario: because of the small size and dynamically disintegrating state of the SMC, the “concentration factor” for this galaxy is expected to be smaller than the one for our Galaxy. In fact this expected smaller concentration factor is effectively also the main explanation for the low $\gamma$-ray luminosity in the standard “local” explanation for cosmic-ray origin.

3.3. The chemical and isotopical composition of the hadronic cosmic radiation is very similar to the one of the solar system, this is in favor of a local Galactic origin
Fig. 3: An extragalactical scenario for the origin of the observed cosmic-ray spectrum near earth. Plotted is the differential flux of hadronic cosmic rays multiplied by $E^2$ as a function of the cosmic-ray energy per nucleus $E$. The thin line is a schematic representation of experimental results. They are explained by an extragalactical spectrum outside the Galaxy (thick line) which is enhanced in the Galaxy by a factor $e$ (symbolized by the arrows). This factor varies $\sim E^{-0.5}$. Only at energies above the “ankle” the extragalactical spectrum is equal to the observed spectrum.

The measured abundance pattern is thought to be determined by general nucleosynthetic principles which probably operate in all galaxies. It is possible (though not necessary) that chemically processed plasma is accelerated in extragalactic sources. Moreover in a Galactic scenario cosmic rays are “young” (about $10^7$ years) whereas the solar system is about 5 billion years old. Because of this, the very good consistency of cosmic-ray and solar-system abundances is not a priori expected in a Galactic scenario (Fields et al., 1993).

3.4. Cosmic-ray clocks measure a small age of cosmic rays, thus the heavy ions cannot be of extragalactic origin

Cosmic-ray clocks like $^{10}$Be indicate an “age” of cosmic rays of a few tens of million years. This is much less than the expected time since acceleration in an extragalactical scenario, which is on the order of the age of the universe $t_U \simeq 1.5 \cdot 10^{10}$ years. This might be interpreted as evidence against an extragalactical origin. What cosmic-ray clocks measure, however, is the time since they propagate in a medium dense enough to lead to nonnegligible spallation processing (the radioactive $^{10}$Be is a spallation product from nuclear reactions during propagation and not a remnant from the acceleration site). If extragalactic cosmic rays were accelerated in regions with low matter density (like giant radio lobes) or left the acceleration site on a very small time scale (like in an early galaxy with a strong galactic wind) and then propagated in the intergalactic medium which has a very low ambient density, the measured “age” merely measures the time since entering the Galaxy, which is on the order of the confinement time $t_{conf}$, like in the Galactic scenario of cosmic-ray origin.
3.5. *It’s a priori unlikely that the electrons and hadrons in the cosmic radiation have a completely different origin.*

There could be a plausible physical mechanism for this “breaking of the tie”: as opposed to hadrons, electrons cannot propagate over cosmological distances due to inverse Compton scattering on the 3 K° background at the energies of interest here. It is also remarkable that observations of electrons in several supernova remnants seem to indicate a “break off” in energy spectrum around 10 TeV (Allen, 1997), in good agreement with an expected maximum energy of about 100 TeV for older SNRs (both for electrons and hadrons). There is no evidence for any sharp feature in hadronic cosmic rays up to much higher energies (the “knee” at 2 PeV).

4. **Conclusion**

The assumptions made for the basic hypothesis of “flux trapping” are speculative and perhaps controversial. A better understanding of very complex magnetohydrodynamic processes in intergalactic space is needed to make a firm decision whether they are realistic or not. From a purely phenomenological point of view the following point of view seems interesting: *Galactic SNRs produce the observed electron cosmic-ray flux. The required acceleration efficiency is modest and the high-energy cutoff lies in the region of 10 TeV, in good agreement with theoretical expectation (see e.g. Mastichiades and de Jager (1996)). Protons and nuclei are perhaps accelerated with a roughly similar efficiency (i.e. much less than with a 100 times higher efficiency) and high-energy cutoff, and therefore produce a local hadronic cosmic-ray intensity comparable to the electron intensity (on the order of 1% of the total intensity below the cutoff). The main part of hadronic cosmic rays is due to intergalactic cosmic radiation which has an enhanced density in the Galactic confinement volume.*

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