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Extragalactic and galactic sources: New evidence, new challenges, new opportunities

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Abstract. Recent data bring in sharper focus the issue of relative contributions of galactic and extragalactic sources of ultrahigh-energy cosmic rays. On the one hand, there is some new evidence, from gamma-ray observations of blazars, that cosmic rays are, indeed, accelerated in AGNs. On the other hand, recent measurements of composition reported by Pierre Auger Observatory can be explained by a contribution of transient galactic sources, such as past GRBs and hypernovae, if nuclei accelerated in such events get trapped in the turbulent galactic magnetic fields. The likely contamination of UHECR data by the nuclei from past galactic stellar explosions creates new challenges for cosmic-ray astronomy. At the same time, it creates new opportunities for reconstructing galactic magnetic fields, understanding the history of transient galactic phenomena, and for using gamma rays to identify astrophysical nuclear accelerators outside Milky Way.

1. EXTRAGALACTIC SOURCES

It has long been suspected that active galactic nuclei (AGNs) should accelerate cosmic rays to the highest energies. However, identification of the arrival directions of ultra-high energy cosmic rays is complicated because of the deflections in the local galactic magnetic fields. On the other hand, gamma-ray observations of distant blazars provide new evidence that these objects accelerate cosmic rays. The hardness of gamma-ray spectra of distant blazars can be naturally explained by the line-of-sight interactions of cosmic rays accelerated in the blazar jets [1–8]. The cosmic rays with energies below $10^{17} - 10^{18}$ eV can cross large distances with little loss of energy and can generate high-energy gamma rays in their interactions with cosmic background photons relatively close to the observer. Such *secondary* gamma rays can reach the observer even if their energies are well above TeV. In the absence of cosmic-ray contribution, some unusually hard intrinsic spectra [9] or hypothetical new particles [10, 11] have been invoked to explain the data.

As long as the IGMFs are smaller than $\sim$10 femtogauss, secondary gamma rays come to dominate the signal from a sufficiently distant source. One can see this from the way the flux scales with distance for primary and secondary gamma rays [3]:

$$F_{\text{primary}}(d) \propto \frac{1}{d^2} e^{-d/\lambda_\gamma} \tag{1}$$

$$F_{\text{secondary}}(d) \propto \frac{\lambda_\gamma}{d^2}\left(1 - e^{-d/\lambda_\gamma}\right) \propto \begin{cases} 1/d, & \text{for } d \ll \lambda_\gamma, \\ 1/d^2, & \text{for } d \gg \lambda_\gamma. \end{cases} \tag{2}$$

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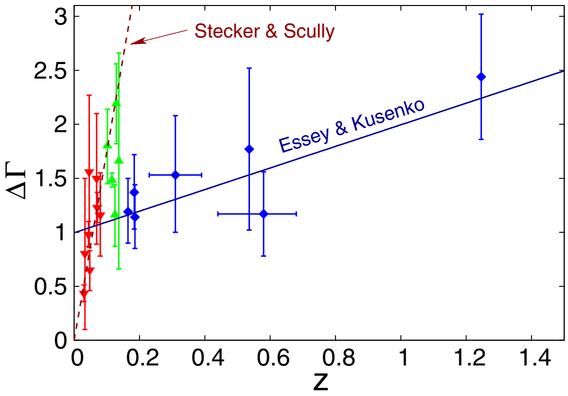

Figure 1. Spectral index difference $\Delta\Gamma = \Gamma_{\text{GeV}} - \Gamma_{\text{TeV}}$ as a function of redshift. While the low-redshift blazars agree with the Stecker–Scully relation [12], the data indicate the existence of an additional, distinct population with a weak redshift dependence at redshifts 0.15 and beyond [5]. In particular, the recently measured redshift [13] of PKS 0447-439 is in agreement with the trend.

Obviously, for a sufficiently distant source, secondary gamma rays must dominate because they don't suffer from the exponential suppression as in Eq. (1). The predicted spectrum turns out to be similar for all the distant AGN, depending only on their redshift. These predictions are in excellent agreement with the data [1–3].

One can see the transition from primary to secondary gamma rays in Fig. 1, which shows the GeV–TeV spectral difference for blazar spectra as a function of their redshifts. At small redshifts, the data confirm the Stecker – Scully relation [12], but, at redshifts 0.15 and beyond, there is clearly a new population of blazars, whose observed spectral index shows only a weak dependence on the redshift. The nearby population is obviously the blazars from which primary gamma rays are observed. The distant blazars are observed in secondary gamma rays, which are produced in line-of-sight cosmic ray interactions. These secondary gamma rays are produced relatively close to the observer, regardless of the distance to the source. Hence, their redshift dependence is much weaker [5]. Finally, there is an intermediate population around redshift 1.2 which is composed of some blazars seen in primary gamma rays and some seen in secondary gamma rays.

A recent redshift measurement of PKS 0447-439 redshift [13] further strengthens this interpretation. Gamma rays with energies above 1 TeV have been observed from this blazar by HESS [14]. The spectral properties agree with the trend (Fig. 1). Furthermore, there is no way for primary gamma rays to reach us from such a distant source, while protons with energies $\lesssim 10^{18}$ eV can reach Earth and produce secondary photons observable on Earth. This motivates future observations by ACT of blazars with known large redshifts. Secondary gamma rays with TeV and higher energies can be observed even from a source at redshifts $z \sim 1$.

2. TRANSIENT GALACTIC SOURCES

Let us now turn to another phenomenon related to cosmic rays and magnetic fields, only this time we will concentrate on the magnetic fields inside the galaxy and their effect on the observed fluxes of ultrahigh-energy nuclei [15, 16].

There is a growing evidence that long GRBs are caused by a relatively rare type(s) of supernovae, while the short GRBs probably result from the coalescence of neutron stars with neutron stars or black holes. Compact star mergers undoubtedly take place in the Milky Way, and therefore short GRBs should occur in our galaxy. UHE nuclei produced in such transient sources could make a non-negligible contribution to the observed flux of UHECR, hence explaining the composition results reported by PAO [41]. Although there is some correlation of long GRBs with star-forming metal-poor galaxies [17], many long GRBs are observed in high-metallicity galaxies as well [18–20], and therefore one expects that long GRBs should occur in the Milky Way. Less powerful hypernovae, too weak to produce a GRB, but can still accelerate UHECR [21], with a substantial fraction of nuclei [22, 23].

GRBs have been proposed as the sources of extragalactic UHECR [23–25], and they have also been considered as possible Galactic sources [26–28]. GRBs occur in the Milky Way at the rate of one per $t_{\rm GRB} \sim 10^4 - 10^5$ years [29–32]. Such events have been linked to the observations of positrons [33–36].

If the observed cosmic rays originate from past explosions in our own Galaxy, PAO results have a straightforward explanation [15]. If local sources, such as past GRBs, hypernovae, and other stellar explosions in Milky Way, produce a small fraction of heavy nuclei [37], the observed fraction of UHE nuclei is greatly amplified by diffusion. This is because the galactic magnetic fields are strong enough to trap and contain nuclei but not protons with energies above EeV. This observation leads to a simple explanation of the composition trend observed by PAO [41].

Diffusion depends on rigidity, and, therefore, the observed composition can be altered by diffusion [15, 38]. Changes in composition due to a magnetic fields have been discussed in connection with the spectral “knee” [38], and also for a transient source of UHECR [39]. The “knee” in the spectrum occurs at lower energies than those relevant PAO, and at higher energies the cosmic rays effectively probe the spectrum of magnetic fields on greater spatial scales, of the order of 0.1 kpc [40].

One can use a simple model [15] to show how diffusion affects the observed spectrum of the species “i” with different rigidities. Let us suppose that all species are produced with the same spectrum $n_i^{(\rm src)} = n_0^{(\rm src)} \propto E^{-\gamma}$ at the source located in the center of Milky Way and examine the observed spectra altered by the energy dependent diffusion and by the trapping in the Galactic fields.

In diffusive approximation, the transport inside the Galaxy can be described by the equation:

$$\frac{\partial n_i}{\partial t} - \nabla(D_i \nabla n_i) + \frac{\partial}{\partial E}(b_i n_i) = Q_i(E, \mathbf{r}, t) + \sum_k \int P_{ik}(E, E') n_k(E') dE'.$$

Here $D_i(E, \mathbf{r}, t) = D_i(E)$ is the diffusion coefficient, which we will assume to be constant in space and time. The energy losses and all the interactions that change the particle energies are given by $b_i(E)$ and the kernel in the collision integral $P_{ik}(E, E')$. For energies below GZK cutoff, one can neglect the energy losses on the diffusion time scales.

The diffusion coefficient $D(E)$ depends primarily on the structure of the magnetic fields in the Galaxy. Let us assume that the magnetic field structure is comprised of uniform randomly oriented domains of radius l_0 with a constant field B in each domain. The density of such domains is $N \sim l_0^{-3}$. The Larmor radius depends on the particle energy E and its electric charge $q_i = eZ_i$:

$$R_i = l_0 \left(\frac{E}{E_{0,i}} \right), \text{ where } E_{0,i} = E_0 \, Z_i, \tag{3}$$

$$E_0 = 10^{18} \text{eV} \left(\frac{B}{3 \times 10^{-6}\,\text{G}} \right) \left(\frac{l_0}{0.3\,\text{kpc}} \right). \tag{4}$$

The spatial energy spectrum of random magnetic fields inferred from observations suggests that $B \sim 3\mu$G on the 0.3 kpc spatial scales, and that there is a significant change at $l = 1/k \sim 0.1 - 0.5$ kpc [40]. This can be understood theoretically because the turbulent energy is injected into the interstellar medium by supernova explosions on the scales of order 0.1 kpc. This energy is transferred to smaller scales by direct cascade, and to larger scales by inverse cascade of magnetic helicity. Single-cell-size models favor $\sim$0.1 kpc scales as well [40].

Diffusion occurs in two different regimes depending on whether the Larmor radius is small or large in comparison with the correlation length. As a result, the diffusion coefficient changes its behavior dramatically at $E = E_{0,i}$:

$$D_i(E) = \begin{cases} D_0 \left(\frac{E}{E_{0,i}}\right)^{\delta_1}, & E \leq E_{0,i}, \\ D_0 \left(\frac{E}{E_{0,i}}\right)^{(2-\delta_2)}, & E > E_{0,i}. \end{cases} \tag{5}$$

Here the two parameters $0 \leq \delta_{1,2} \leq 0.5$ reflect the distribution of magnetic domain sizes.

The approximate solution of the transport equation in our simple model yields

$$n_i(E, r) = \frac{Q_0}{4\pi r \, D_i(E)} \left(\frac{E_0}{E}\right)^{\gamma}. \tag{6}$$

Since diffusion depends on rigidity, the composition becomes energy dependent. Indeed, at critical energy $E_{0,i}$, which is different for each nucleus, the solution (6) changes from $\propto E^{-\gamma}$ to $\propto E^{-\gamma-2}$ because of the change in $D_i(E)$, as discussed in the caption of Fig. 1. Since the change occurs at a rigidity-dependent critical energy $E_{0,i} = eE_0 Z_i$, the larger nuclei lag behind the lighter nuclei in terms of the critical energy and the change in slope. If protons dominate for $E < E_0$, their flux drops dramatically for $E > E_0$, and the heavier nuclei dominate the flux. The higher Z_i, the higher is the energy at which the species experiences a drop in flux.

One can also understand the change in composition by considering the time of diffusion across the halo is $t_i \sim R^2/D_i$. The longer the particle remains in the halo, the higher is the probability of its detection. At higher energies, the magnetic field's ability to delay the passage of the particle diminishes, and the density of such particles drops precipitously for $E > E_{0,i}$. Since E_i is proportional to the electric charge, the drop in the flux occurs at different energies for different species.

The model [15] provides a qualitative description of the data. To reproduce the data more accurately, it must be improved. First, one should use a more realistic source population model. Second, one should include the coherent component of the Galactic magnetic field. Third, one should not assume that UHECR comprise only two types of particles, and one should include a realistic distribution of nuclei. Finally, one should include the extragalactic component of UHECR produced by distant sources, such as active galactic nuclei (AGN) and GRBs (outside the Milky Way). The discussion above, which shows that very high energy gamma rays observed by Cherenkov telescopes from distant blazars are likely to be secondary photons produced in cosmic ray interactions along the line of sight, lends further support to the assumption that cosmic rays are copiously produced in AGN jets [1, 2]. For energies $E > 3 \times 10^{19}$ eV, the energy losses due to photodisintegration, pion production, pair production and interactions with interstellar medium become important and must be included. The propagation distance in the Galaxy exceeds 10 Mpc, so that the Galactic component should exhibit an analog of GZK suppression in the spectrum. Extragalactic propagation can also affect the composition around 10^{18} eV [42].

Galactocentric anisotropy in this case is small [15]. Although the anisotropy in protons is large at high energies, their contribution to the total flux is small, so the total anisotropy was found to be $< 10\%$, consistent with the observations. The latest GRBs do not introduce a large degree of anisotropy, as it would be in the case of UHE protons, but they can create "hot spots" and clusters of events (Fig. 2). It is possible that a doublet of UHECR originating from the galactic center [44] is a manifestation of such a hot spot.

The model [15] leads to the following prediction for the highest-energy cosmic rays. Just as the protons of the highest energies escape from our Galaxy, they should escape from the host galaxies of remote sources, such as AGN. Therefore, UHECR with $E > 3 \times 10^{19}$ eV should correlate with the extragalactic sources. Moreover, these UHECR should be protons, not heavy nuclei, since the nuclei are trapped in the host galaxies. If and when the data will allow one to determine composition on a case-by-case basis, one can separate $E > 3 \times 10^{19}$ eV events into protons and nuclei and observe that the protons correlate with the nearby AGN. This prediction is one of the non-trivial tests of our model: at the highest

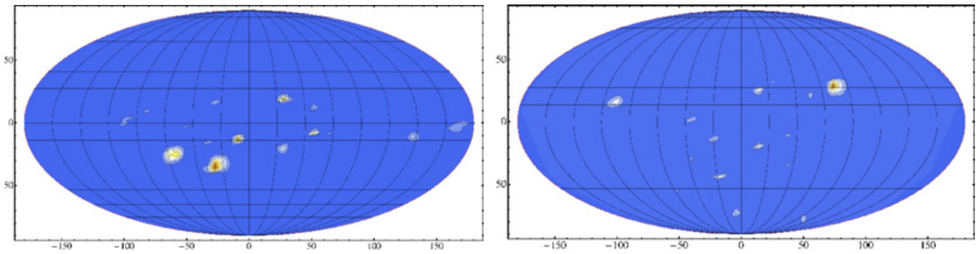

Figure 2. Monte Carlo simulation of a typical set of "hot spots" in the directions of the closest, recent GRBs or hypernovae, in the model of Calvez *et al.* [15]. The distribution of transient sources was modeled for long GRBs (left) and short GRBs (right).

energies the proton fraction should exist and should correlate with known astrophysical sources, such as AGN. The microgauss magnetic fields in Milky Way cause relatively small deflections for the highest-energy protons. As for the intergalactic magnetic fields, the first detection and a measurement of such fields, using the data from *Fermi Gamma-ray Space Telescope*, points to relatively weak, femtogauss field strengths [43], which should not affect the protons significantly on their trajectories outside the clusters of galaxies.

If local, Galactic GRBs are the sources of UHECRs, the energy output in cosmic rays should be of the order of 10^{46} erg per GRB. This is a much lower value than what would be required of extragalactic GRBs to produce the same observable flux. Indeed, in our model the local halo has a much higher density of UHECR than intergalactic space, and so the overall power per volume is much smaller. The much higher energy output required from extragalactic GRBs [23–25] in UHECR has been a long-standing problem. The same issue does not arise in our case because it seems quite reasonable that a hypernova or some other unusual supernova explosion would generate 10^{46} erg of UHECR with energies above 10 EeV.

3. A GAMMA-RAY SIGNATURE OF NUCLEAR ACCELERATORS

A spectral feature, namely an "iron shoulder" at 5–10 GeV can help identify cosmic nuclear accelerators [45]. Nuclei are likely to come out of acceleration regions unstable because they can lose a nucleon or a few nucleons to photodisintegration in the high-density photon environments accompanying some accelerators [37]. An unstable nucleus decays, and most of such decays are β-decays. With a probability of order one, the β-decay electron is captured by the Coulomb potential of the fully ionized atom [46]. Hence, a non-negligible fraction of nuclei come out of astrophysical accelerators in the form of one-electron ions. In a narrow energy range, CMB photons have energies $\approx$7 keV in the rest frame of the ion. Such photons can excite the ion, which later emits a 7 keV photon (in the ion's rest frame). Multiple excitations and de-excitations can take place resulting in emission of gamma rays, which have energies of 5–10 GeV in the laboratory frame. The spectral feature around 8 GeV can be used for identifying astrophysical sources of nuclei, or (in the case of non-detection) for setting the upper limits on nuclear acceleration [45].

4. CONCLUSIONS

Recent PAO results on chemical composition [41] suggest a contribution of transient galactic sources, such as GRBs and hypernovae that took place in the past $\sim 10^6$ years in Milky Way. PAO results are in agreement with the Yakutsk experiment [53], but they have not been corroborated by the HiRes experiment [54], and there remains a significant experimental uncertainty due to possible systematic errors. Nevertheless, the energy dependent composition of UHECR, with heavier nuclei at high energy, may be evidence of transient galactic sources [15]. Diffusion in turbulent Galactic magnetic field traps the nuclei more efficiently than protons, leading to an increase in the nuclear fraction up to the energy at which iron escapes ($\sim 30\,\mathrm{EeV}$). At higher energies, the extragalactic protons should dominate the flux of UHECR, and their arrival directions should correlate with locations of the known sources.

The possible contamination of UHECR data by nuclei produced in Milky Way makes it more difficult to identify the sources of UHECR. One can hope to separate heavy nuclei from protons on a statistical basis and to test the correlations of the proton-like component with extragalactic sources. At the same time, gamma-ray observations may offer new ways of studying the sources of UHECR. Gamma rays detected from most distant blazars are most likely dominated by the secondary photons produced in line-of-sight interactions of cosmic rays. This supports the long-held belief that UHECR can originate from AGN. This interpretation also allows one to set both upper and lower bounds on intergalactic magnetic fields, $10^{-17}\mathrm{G} < B < 10^{-14}\mathrm{G}$ [4].

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