Ultra-high energy cosmic rays: A review of the galactic-source conjecture

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Abstract: The idea that most ultra-high energy cosmic rays (UHECR) originate beyond the galaxy has been a common conjecture in the literature for some time. This extragalactic-source conjecture has been supported in part by the apparent difficulty of the galactic-source conjecture, i.e. the lack of objects in the galaxy that can accelerate 10^{20} eV protons and the lack of cosmic-ray (CR) anisotropy associated with the galaxy. However, if protons are sub-dominant above the ankle energy and instead intermediate and iron-like nuclei dominate the CR flux, much of the difficulty of the galactic-source conjecture is eliminated. In this contribution we review the plausibility of the galactic-source conjecture. We show that it is plausible that UHECR near the ankle gyrate in the disk of the galaxy and may scatter off of structures in the magnetic field effectively isotropizing UHECR to a level consistent with current observations. We review possible source candidates including trans-relativistic supernova and young, fast rotating pulsars, and discuss possible mechanisms for the ankle and the features in the cosmic-ray energy spectrum. We suggest that UHECR may be accelerated episodically in the galaxy with the period between acceleration events being $\sim 10^4$ yrs.

Keywords: UHECR, galactic magnetic fields, sources

1 Introduction

In this contribution, we review the galactic-source conjecture, i.e. that UHECR originate from sources located in the galaxy disk. We discuss the relevant questions of finding a galactic-source scenario that is consistent with observation. The motivation for this review comes from (1.) There is no clear convergence to a theory involving extragalactic sources and (2.) Our continued uncertainty regarding the composition of UHECR.

In Section 2 we discuss the problems with reconciling the postulate of a strongly anisotropic distribution of sources (i.e., in the Galactic disk) with the observed isotropic distribution of UHECR arrival directions. In Section 3 we discuss potential source candidates. In Section 4 we discuss the general attributes of the galactic-source conjecture and how to test it. We conclude the paper with a summary.

2 Anisotropy, Composition, and Magnetic Fields

The Galactic disk is 15 kpc in radius with an diameter/height ratio of 10:1 or more. The Sun is ~ 8.5 kpc from the center. It is reasonable to assume that the Galactic sources are somewhat evenly distributed in the disk. Therefore, in the absence of substantial magnetic deflections (i.e., gyration), it is natural to expect a strong large-scale anisotropy due to the asymmetry of matter relative to the Sun position. In particular, we would expect the arrival directions to be concentrated in a band corresponding to the equator of the galaxy. Magnetic deflection on the order of tens of degrees may displace, contort, and somewhat diffuse this band, but it should be quite obvious nevertheless. For example, we should expect a difference in flux on large angular scales to be a factor of 2 or more.

Indeed, there are no known significant departures from isotropy in the arrival directions of UHECR. There is a 2.3σ indication of anisotropy at the highest energies [1, 2], but because of the low significance little is known about the structure of this anisotropy. Recently, the Auger Collaboration published the most stringent upper limits on large scale anisotropy [3]. The upper limits on a dipole amplitude are 1.5% (1-2 EeV) and 11% ($>$ 8 EeV). The upper limits on a quadrupole amplitude are 2.9% (1-2 EeV) and 14% ($>$ 8 EeV).

How can a strong anisotropic source distribution be reconciled with the arrival directions of UHECR being nearly isotropic? The solution must certainly be because the particles gyrate in the magnetic field of the galaxy and scatter off of structures in the magnetic field (i.e., magnetic mirrors).

To investigate this further, we must assume a particular particle charge. We assume the highest charge that is in fair agreement with observation, say $Z = 2$ at 1 EeV and $Z = 6$ at 10 EeV. (Above 10 EeV we do not have strong constraints on anisotropy so we will put off examining these particles for now.) The corresponding magnetic rigidities are $E/Z = 0.5$ EeV and $E/Z = \sim 2$ EeV. This assumption is consistent with the measurement of depth of shower maximum reported by Auger [4, 5] and the interpretation of this data with the EPOS [6] interaction model, but there may be some tension with the results of HiRes [7, 8] or Yakutsk [9] or with other interaction models.

The Galactic magnetic field has been discussed extensively in the literature. For a thorough review see Ref. [10]. It is known that at the largest scales the Galactic magnetic field is mainly toroidal, with the large-scale field in the thin disk following the spiral arms with a pitch angle of $\sim 12^\circ$ and a characteristic strength of $\sim 2\mu$G. At a distance from the plane of $z \approx 500$ pc, the field drops to $\sim 1\mu$G. For $z > 500$ pc, the large scale field is usually termed the “thick disk” or “halo field”. The field in the thick disk may not have a pitch angle (i.e., it may be totally toroidal). Beyond $z = 500$ pc it continues to decrease in strength with a scale height of ~ 5 kpc. There may also exist a large-scale out-

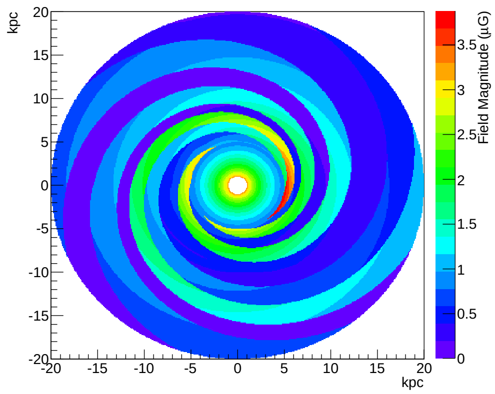

Figure 1: Field magnitude at $z = 10$ pc for the JF12 model of the galactic magnetic field. The Sun position is at $x = 8.5$ kpc $y = 0$ kpc

of-plane component. This may be part of an extensive halo field that dominates at $z > 5$ kpc.

There is more energy, by a factor of ~ 3, at scales smaller than these largest scales. This small-scale structure is referred to as the random or turbulent field. The characteristic coherence length of the small-scale structure is typically estimated to be 100 pc. But in actuality it is not well known how the energy is distributed over the smaller scales. The energy spectral density function most likely is different for the spiral arms, the inter-arm regions, the thick disk, and the halo [11, 12, 13].

The Larmor radius (gyration radius) of a charged particle is

$$R_L/(\mathrm{kpc}) \approx \frac{E/(\mathrm{EeV})}{ZB/(\mu\mathrm{G})}.$$

Comparing R_L with the scale heights, we should expect particles with $E/Z = 0.5$ EeV and $E/Z = 2$ EeV to gyrate in the thick disk, and particles with $E/Z = 0.5$ EeV to also gyrate in the thin disk.

To get of better idea of the typical trajectories, we simulated particles in the JF12 model [14] of the large-scale Galactic field. In Fig. 1, we show the magnitude of the field in the JF12 model at $z = 10$ pc. The parameters of the JF12 model were constrained with over 40,000 extragalactic rotation measurements. In our simulations, we did not introduce any small-scale structure to the field.

In Fig. 2 we show typical trajectories for $E/Z = 0.5$, 2, & 20 EeV particles backtracked from random directions at the Sun position. Particles with $E/Z = 20$ EeV do not gyrate though their trajectories are bent by several degrees. For particle with this rigidity we cannot expect to significantly reduce the anisotropy expected from the asymmetrical matter distribution. However, particles with $E/Z = 0.5$ & 2 EeV do gyrate. For these particles, we should expect much less anisotropy compared to non-gyrating particles. But can we expect the field to isotropize the particles to the level observed?

We performed a toy simulation (similar to Ref. [15]) where we backtracked particles from the Sun position in the JF12 model of the large scale field. We analyzed the correlation between the direction at the Sun position and the time spent in the plane. The time spent in the plane should be proportional to the probability of a CR from a source in the disk arriving at the Sun position. We found

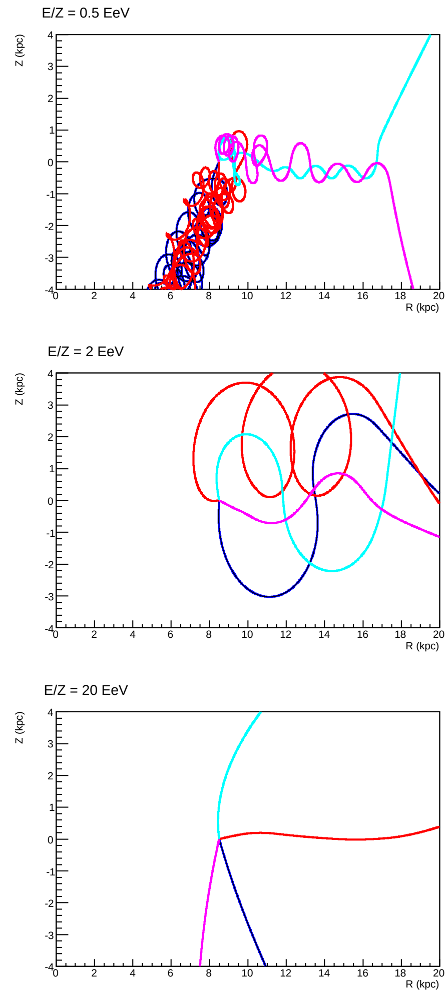

Figure 2: Example trajectories of charged particles of different rigidities backtracked from the Sun position in the JF12 model of the Galactic magnetic field.

that large-scale anisotropy still existed at a level of $\sim$10% for particles with rigidity $E/Z = 0.5$ EeV.

This toy simulation only includes the very largest scale structures of the Galactic field. Structure in the magnetic field certainly exists at smaller scales and these structures may effectively scatter the particles. Structures near the Larmor radius of the particle (100 kpc to 1 kpc) are particularly important as they can backscatter the particle in one collision. Structures at smaller scales cannot and their importance in isotropizing CRs must decrease as the structure size decreases.

It is interesting that the compression of the field lines does not have to be strong to produce a backscatter. In Fig. 3 we show a particle with $E/Z = 0.5$ EeV scattering off a magnetic mirror in an average field of 1 μG. The relevant size of the mirror is $\sim$1 kpc. The increase in the field strength from the injection point to the reflection point is $< 50\%$.

There has been substantial work on moving from a toy simulation to more detailed simulations (e.g., Ref. [16]). However, this is difficult because we do not know all the magnetohydrodynamics (MHD) and particular history that went into making the large-scale and small-scale structure (e.g., see Ref. [17, 18]). What turbulent structures and

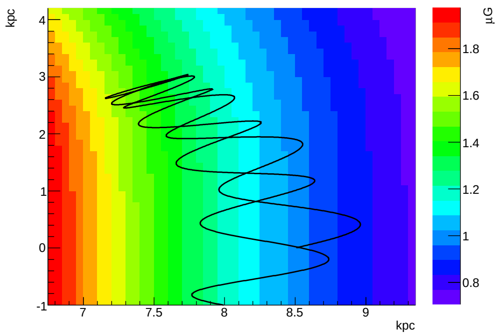

Figure 3: Example of a particle with $E/Z = 0.5$ EeV reflecting off a structure in a magnetic field. The field lines are not shown for clarity. They are mostly vertical in the figure. The initial direction of the particle was 30° from horizontal.

inhomogeneities with size $\sim > 1$ kpc are expected in the thick disk and halo? Furthermore, anisotropic turbulence and the use of more realistic source luminosity functions is probably important.

We know of no detailed studies that take these issues into account. Currently, we cannot strictly reject the idea that the Galactic magnetic field isotropizes UHECR consistent with observation. More work needs to be done.

3 Source Candidates

There is growing evidence that CRs below the knee are accelerated in the collisionless shock fronts of supernova explosions. The phenomenology is developed (e.g. Ref. [19, 20]), and there is evidence that the gamma-ray spectrum from supernova remnants (SNR) is indicative of hadron acceleration [21, 22].

If there is a transition to an entirely different class of accelerator above the knee, it is natural to expect either a significant drop in the flux or a hardening of the flux. Indeed, after the mild steepening of the spectrum at the knee, the spectrum is rather featureless up to the ankle energy. This suggests that supernova may be the source of CR up to at least the ankle energy and perhaps higher.

The maximum energy to which a particle can be accelerated is

$$E_{max} \sim Ze\beta_s B r_s,$$

where $\beta_s c$ is the velocity of the shock, B is the magnetic field in the preshock and postshock plasma, and r_s is the radius of the shock (e.g., Ref. [23, 24]). The charge of the particle, the shock decelerating in the interstellar medium, and the strength of the magnetic fields put firm limits on E_{max}. If the magnetic field is amplified by CRs (as suggested [25] and observed [26]), it has been shown [27] that it is plausible that supernova can accelerate particles to $Z \times 10^{17}$ eV. Although it has been argued that if ordinary SN accelerate particles via their fastest ejecta to energies approaching the ankle, then the flux of lower energy CR will be over produced.

Typical SN shocks have $\beta_s \approx 10^{-2}$. However, there are supernova that have a large fraction (i.e., $> 1\%$) of their kinetic energy in mildly relativistic ejecta but may have a total kinetic energy near that of ordinary SN. The terms "Low Luminosity GRB" and "Transrelativistic Supernova" (TRSN) have been introduced to describe this class of objects. These SN have total kinetic energies similar to ordinary SN (i.e., TRSN are distinct from the highly energetic hypernova). It has been suggested (e.g., [24, 28]) that the fast ejecta of these SN may accelerate nuclei to the highest energies. Because a large fraction of the star's mass is mildly relativistic, the problem of over-producing lower energy CR is circumvented [24].

TRSN seem to be associated with Wolf-Rayet stars. These stars loose their hydrogen and in some cases their helium by strong stellar winds. Thus when they explode (type 1b/c SN), their ejecta are enriched in intermediate elements.

A fast shock not only means a large E_{max}, but also that E_{max} is reached quickly, perhaps only years after the explosion. The rate of TRSN in the galaxy is $\sim 10^{-4}\text{yr}^{-1}$. This is ~ 10 times more frequent than hypernova [29]. We already have shown that it is plausible that UHECR near the ankle gyrate in the magnetic field of the galaxy. For a 0.5 EeV/Z particle gyrating in the disk, two gyration cycles is equivalent to $\sim 10^4$ yrs so the containment time must be much longer, and it is natural to expect a nearly constant flux at earth. For 10 EeV/Z particles, if they are strongly lensed and originate at a distance of several kpc, a time spread of $\sim 10^4$ yrs is possible.

If the UHECR are accelerated in transient events, then the expectation of observing neutral message particles associated with their acceleration is much reduced. Indeed, none have been detected (e.g., Ref. [30].

Another interesting source candidate is young, fast rotating neutron stars. Due to the strong magnetic field and fast rotation of the star, nuclei can be accelerated by unipolar induction to maximum energies of perhaps

$$E_{max} = 3 \times 10^{20} \frac{Z}{26} \frac{\Omega}{(10^4 \text{s}^{-1})} \frac{\mu}{10^{30.5}\text{cgs}} \text{eV}$$

where Ω is the spin rate and μ is the magnetic moment (see Ref. [31, 32]).

The spin-down time where particles can be accelerated to the highest energies is ~ 1 yr. Iron ions may be stripped off the crust of the neutron star and seeded into the pulsar wind [32]. So a composition enriched in heavy nuclei may be a natural expectation. The birth rate of pulsars with the magnetic field and spin rate capable of accelerating particles to the highest energies is $\sim 0.01\%$ of the birth rate of normal pulsars or $\sim 10^{-6}\text{yr}^{-1}$ [32]. Thus, pulsar acceleration events are $100\times$ more rare than TRSN, and the period between pulsar acceleration events may be longer than the containment time of UHECR in the Galaxy, especially at the higher energies.

Whether the particles are accelerated in the SN shock front, near the pulsar, or both (e.g., one seeding the other) we can still think of CRs as originating in one class of objects: SN explosions. The idea of one general source class is a sensible explanation for the observed smooth energy spectrum.

However, there are two prominent features in the UHECR energy spectrum: the Ankle at ~ 4 EeV and the Break at ~ 40 EeV. At the highest energies the flux may be originating from only a few acceleration events. It could be that the ankle and break are simply natural fluctuations of these few events.

4 Discussion

Currently the galactic-source conjecture is not firmly rejected if the particles in the UHE range are nuclei and there is a light-to-heavy trend in the composition. Particles with $E/Z \sim< 2$ EeV meet the minimum requirement of gyration in the large-scale field of the galaxy. Particles with $E/Z \sim> 20$ EeV do not. Thus the question of UHECR composition is highly constraining. Composition indicators from ground arrays or perhaps using ground observables and X_{max} measurements together (e.g., [33]) may better constrain the composition and its change with energy. Certainly, more work on understanding the systematic uncertainties with regard to composition observables is needed. With scientific collaborations working more closely with each other, and with new LHC data (e.g., [34]) there is real hope in this regard.

Structures in the Galactic magnetic field with a size $l > 100$ pc are probably needed to isotropize the particles to the level observed. Advanced MHD simulations may be required to produce realistic structures. Forthcoming large radio telescopes will give us valuable information on magnetic structures in galaxies [35]. Because isotropizing particles with $E/Z \sim> 2$ EeV is apparently marginal, we should expect that anisotropy will become apparent with not too much more time aperture. Even extragalactic-source conjectures predict an 0.3 - 0.6% dipole anisotropy [36]. New large-aperture observatories will be useful in this regard.

If there is a light-to-heavy composition trend, it is plausible that SN explosions and their remnants are sources of UHECR. Having one general class of accelerator is a sensible explanation for the overall smooth spectrum up to the Ankle. The acceleration events are necessarily episodic. For the accelerators discussed in Section 3, there is perhaps one acceleration event per 10,000 years. Even at the very highest energies, it is expected that the deflection of iron-like particles in the Galactic magnetic field can spread the time of flight by 10,000 years.

For the galactic-source conjecture, the Ankle and Break may be natural fluctuations of the last few acceleration events. The extra-galactic-source conjectures (i.e., the pair production dip model [37] and EG transition model [38]) have more fundamental and perhaps more beautiful explanations for these particular features, but we should not let this cause us to prematurely reject other plausible conjectures.

The expectation of photon and neutrinos secondaries from UHECR propagation is much reduced in the galactic-source conjecture over that of the extragalactic conjectures. This because the density of UHECR in extragalactic space is significantly reduced. Future UHE neutrino observatories (e.g., ARA, ARIANA) will be key to testing this idea.

There are other possible galactic-sources that we have not discussed (e.g., [39]). But perhaps the general scenario presented here has the least difficulty.

5 Summary

If UHECR are intermediate nuclei or heavier, the galactic-source conjecture is currently viable. There are several ways to test the galactic-source conjecture in the near future: (1.) Better composition measurement, (2.) Better understanding of particle acceleration associated with supernova, (3.) Better understanding of Galactic magnetic fields and better simulation of UHECR propagation in the galaxy, (4.) Increased time-aperture of UHECR observations in order to detect UHECR anistropy, and (5.) Searches for GZK neutrinos. These tests will increase our understanding of the sources of UHECR.

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