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Ultrahigh Energy Cosmic Rays

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It is suggested that essentially all of the UHECR we detect originate in our Galaxy. It is shown that even if the density of sources decreases with Galactic radius, assuming it originates from the same material as low energy cosmic rays, then the anisotropy and composition can be better understood. Inward anisotropy, as recently reported by the Auger collaboration can be understood as drift along the current sheet of UHECR originating outside the solar circle, while those oriignating within the solar circle exit the Galaxy at high latitudes.

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1. Introduction

Could ultrahigh energy cosmic rays, even at the highest energies, be Galactic in origin? The widely held belief to the contrary is based on the argument that, if of Galactic origin, they could hardly be as isotropic as presently observed. However, we suggest that the isotropy can be understood in the context of Galactic production if a sufficiently careful treatment of cosmic ray propagation is undertaken. In particular, we cite earlier work (Kumar & Eichler, 2014) in which both anisotropic diffusion and drift are taken into account. In order to understand the cosmic rays above 10^{19} eV as being of Galactic origin, we propose that, above several EeV, they are partly or mostly heavy elements and that their energy/charge is the same as for protons at $E \sim 1$ EeV. That the highest energy cosmic rays are mostly heavy elements has been motivated by the recent discovery (though still somewhat controversial) that while cosmic rays below the ankle are mostly light nuclei, their abundances become more iron-like at the highest energies.

In this picture, the UHECR display a cutoff at $\sim 5 \cdot 10^{19}$ eV not because of any energy threshold for a high energy process (such as photopion production threshold or photodissociation threshold), but simply because the sources cannot accelerate nuclei much beyond that value. This so called "maximal energy" scenario has been proposed before in the context of extragalactic UHECR (for a review, see Olinto 2012) but it has been noted by Aloiso, Berezinsky and Blasi (2014) that the presence of intermediate elements such as C,N,O, implies an "antiankle" rather than an ankle for any spectrum that is reasonably expected of shock acceleration. [However, the spectrum of *escaping* UHECR may be sufficiently hard, given that all others suffer adiabatic losses, so this requires further investigation (see below).]

There is one important difference between the compositions of shock accelerated particles within the Galaxy and of extragalactic ones: At a given energy E, heavy nuclei have *smaller* rigidity $R \simeq E/Q$ by the factor Q, the nuclear charge. So if the escape rate from the Galaxy goes as R^{α}, where at low energies $0.2 \lesssim \alpha \lesssim 0.4$, then the heavy nuclei are enhanced relative to protons by an additional factor Q^{α}. This factor is besides the factor A^{2+p} that obtains when going from relative abundances at a given energy/nucleon to a given total nuclear energy (where the production spectrum goes as $E^{-2-p}dE$). When using the relative abundances at 10GeV, the value of 2+p should also be at that energy, and this provides the relative abundance at a given total energy per nucleus until the exponential cutoff at high energy. Altogether, the relative abundance of species i, a_i, goes as the relative abundance at low energy $a_{i,low}A^{2+p}Q^{\alpha}$, whereas for extragalactic sources the relative abundance enhancement factor should be merely $a_{i,low}A^{2+p}$. (Here kE^{α} (for some constant k) is the escape rate in the energy range of Auger, which for protons is about 1 to 3 EeV. Test particle simulations show that the escape rate from the Galaxy at near-ankle energies is nearly proportional to E (figure 5 of Kumar and Eichler, 2014), so we consider $0.4 \leq \alpha \leq 0.8$.

Figure 1 shows the predicted UHECR total energy spectrum assuming that Galactic sources of UHECR can accelerate protons to 1 EeV, and and that the spectrum for each species is $N(E)dE \sim E^{-2.0}e^{[-E/(3EeV)Z]}dE$, where Ze is the nuclear charge. The composition clearly goes from proton-dominated at low energies to transiron dominated at large energy. The "anti-ankle" noted by Aloiso et al (2014), in the context of extragalactic UHECR, disappears when the extra Q^{α} factor, corresponding to lifetime in our Galaxy, is included.

We have considered the possibility that UHECR are extragalactic and have a very hard spec-

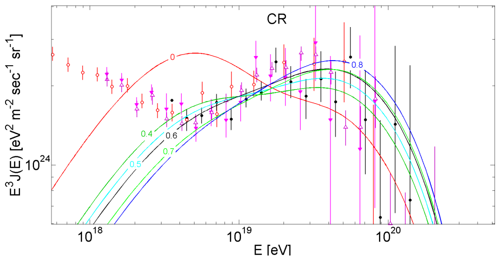

Figure 1: The expected cosmic ray flux is plotted (top blue line) assuming a) that they have the measured Galactic CR abujndance at low energy, b) that they have a high energy exponential cutoff in a given energy per charge (3 EV), and c) that they escape from the Galaxy with an energy dependent escape rate that is E^{α}; $0.4 \leq \alpha \leq 0.8$. The orange lines show the case for $\alpha = 0$, which corresponds to extragalactic cosmic rays, since their residence in our Galaxy would be unaffected by energy dependent escape from their sources.

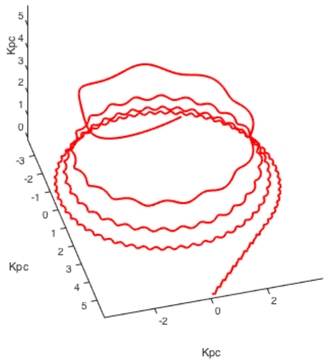

Figure 2: The drift-trajectory of an ultrahigh energy cosmic ray ion with finite angular momentum along the Galactic rotation axis) is displayed in the case of zero scattering. The magnetic field is assumed to completely toroidal and to reverse sign at the equator, meaning that there is a current sheet at the equator. The UHECR are injected at the current sheet at a radius of 6 Kpc.

trum because all but the highest energy CR are trapped and adiabatically cool near the source. The problem with this scenario is that heavy nuclei are much less likely to escape because they have much lower rigidity at a given energy than light nuclei, and this would make the UHECR *deficient* in heavy nuclei rather than enriched.

A major concern for the Galactic model is the remarkable isotropy displayed by EeV cosmic rays, as well as the anticenter anisotropy displayed at somewhat higher energies. The magnetic field that is assumed for the Galaxy includes a current sheet at the magnetic equator. Details of the computation are described in Kumar and Eichler (2014), which predicted an anticenter flux (i.e. towards the center)at suficiently high energy when there is a current sheet of a particular sign. The flux *towards* the Galactic center measured at Earth is counterintuitive given that the sources are assumed to have higher surface density in the disk inside the solar circle than outside it. It results from the presence of a current sheet at the magnetic equator associated with the reversal of the sign of the toroidal field. UHECR ions execute ∇B drift at this current sheet inward, while eventually

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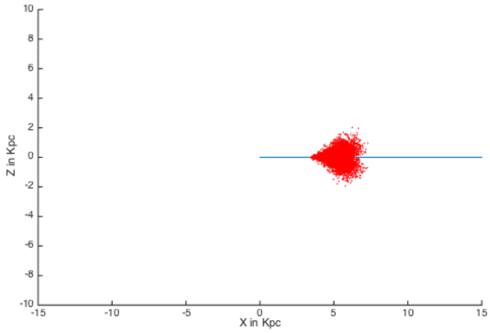

Figure 3: The particle distribution after 30 scattering times with constant injection at the Galactic equator at a Galactic radius of 6 Kpc.

drifting outward along the magnetic poles. A typical drift trajectory is shown in figure 2.

A particle distribution after 30 scattering times is shown in figure 3. It is clear that UHECR injected at a finite Galactic radius on the equator tend to drift in along the current sheet even while diffusing outward along a density gradient. This can be seen in the indentation of the distribution on the current sheet.

The composition of UHECR at E=2.4 EeV is, in the proposed picture, mostly heavy elements with less than 40 percent protons, so the predicted anisotropy is less, by a factor of ~ 2.5 than calculated in Kumar and Eichler (2014). This is entirely consistent with the observational limits.

The implication is that UHECR originating inside the solar circle are unlikely to reach Earth, while those originating from sources outside the solar circle are more likely to. This results in an inward anisotropy.

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