Is the Present Day, Local Cosmic Ray Spectral Index Representative of the Average?

DAVID EICHLER[1], RAHUL KUMAR[1], MARTIN POHL[2,3],

[1] *Physics Department, Ben-Gurion University, Be'er-Sheva 84105, Israel*
[2] *Institut für Physik und Astronomie, Universität Potsdam, 14476 Potsdam-Golm, Germany*
[3] *DESY, 15738 Zeuthen, Germany*

eichler.david@gmail.com

Abstract: The hypothesis is considered that the present, local Galactic cosmic ray spectrum is, due to source intermittency, softer than average over time and over the Galaxy. Measurements of muogenic nuclides underground could provide an independent measurement of the time averaged spectrum. Source intermittency could also account for the surprising low anisotropy reported by the IceCube collaboration. Predictions for Galactic emission of ultrahigh-energy quanta, such as UHE gamma rays and neutrinos, might be higher or lower than previously estimated.

Keywords: cosmic rays, cosmogenic nuclei

1 Introduction

The measured residence spectrum of Galactic cosmic rays (CR) is $N_r(E)dE \propto E^{-2.7}dE$ from 1 GeV to $E_{knee} = 3$ PeV, and $E^{-3.3}$ from E_{knee} to $E_{ankle} = 4$ EeV, considerably steeper than the theoretical expectation for the injection spectrum of $N_i(E)dE \propto E^{-2.0}dE$ for diffusive shock acceleration (DSA) by strong shocks (Blandford and Eichler, 1987, Ellison and Eichler, 1985). Much of the difference is attributed to energy dependent escape rate R(E) from the Galaxy $R(E) \propto E^d$, $d \sim 0.3$. (That the escape rate scales as E^d, $d \sim 0.3$, is inferred from secondary spectra that are steeper by this amount than the primary spectra [Trotta et al., 2011].) However, this may be insufficient to account for the whole difference. It could also be a) that the source spectrum is steeper than we have supposed, and/or b) that discreteness of sources causes variation of the cosmic ray spectrum in location and in time, and that the *time and space average* cosmic ray spectrum in the Galaxy is harder than the one we measure at our particular location and time.

There could be many reasons for the injection index to be much steeper than 2.0, but it would in any case be good to know its exact value, as the total energy requirements for Galactic CR are a sensitive function of it. Moreover, the UHE emission that could be expected from dense environments that offer a thick target to such CR are an extremely sensitive function of the injection index. In this letter we consider the unconventional possibility that the time average residence spectrum is actually flatter than -2.7 by some small amount ε. We would then conclude that the injection index is -(2.4- 2ε).

A flatter time average is predicted by some models. Intermittency, most likely to be pronounced at high energies, can lower the anisotropy relative to steady state during the lulls between the intermittent production episodes (Pohl and Eichler, 2011, Pohl and Eichler, 2013, Kumar and Eichler, 2013). The recently reported anisotropies and/or upper bounds may be at least partly understandable in these terms. This explanation for the unexpectedly low anisotropy would then predict a slightly steeper present day spectrum than the time averaged spectrum. (There does exist, however, the possibility that an improbably close source is placed so as to cancel some of the expected anisotropy.) The discreteness of supernovae, assuming they are the main source of CR, should in any case provide an *a priori* case for some time variability in the CR flux at Earth.

Abundances of terrestrial cosmogenic nuclides (TCN) can set limits on recent time averaged variations of the cosmic ray flux at Earth, though not on short term variability. They demonstrate that the cosmic ray number flux in the Solar System could not have varied on average by more than about 20 or 30 percent of its presently measured value. (Some weak constraint on even short term cosmic ray variability is placed by the continued existence of life on Earth for hundreds of millions of years. The possibility remains that astrophysically brief fluctuations had interesting terrestrial impact that fell short of total lethality.)

We suggest that the variation of the CR spectral index over time in the GeV to TeV range could affect at detectable levels the rate of muogenic nuclei production in deep rock formations that exceed 3 Myr in age. The depth would need to be large enough to be unaffected by possible uncertainties in the erosion rate at the surface. Variations in the CR intensity (due to nearby supernovae, or due to long term magnetic field change in the sun or Earth) within the past 3 Myr could possibly be tested by ^{10}Be abundance, to measure the exposure age - and, at the same geographical location, at depths of at least several meters, to isolate the muogenic component. Alternatively, measurements deep enough to give reliable exposure ages, independent of uncertainties in erosion rates, would give an absolute measurement of the past muon flux. The cross section for muogenic ^{53}Mn (half life 3.7 Myr, exponential decay time 5.3 Myr.) from an iron target is 3.8 mb at $E_\mu = 190$ GeV. (Heisinger et al, 2002). The production rate per target atom, with a muon flux that is the same as at sea level, is then 10^{-21}/yr (equation 17 of Heisinger, et. al, 2001). Here we have allowed for the fact that the mean energy at sea level is only ~ 10 GeV, and that the cross section for muogenic ^{53}Mn production varies as $\sim E_\mu^{0.86}$. The production flux remains within an order of magnitude of the sea-level value down to depths of 10^4g/cm^2, and analysis of the ^{53}Mn content of subterranean iron ore would give a straightforward measurement of the exponentially-weighted average muon flux over the past 5 Myr. Comparison with muogenic ^{10}Be (half life 1.6 Myr, production cross section on O at 190 GeV of 0.094 mb), could help date the contribution of recent nearby supernovae within the residence time in the disk ($\sim$ 3 Myr).

Measuring changes in the CR spectrum that are restricted to energy range $E_p \gg 1$ TeV would be more difficult, so a time averaged CR flux that is well above the present only at $E_p \geq$1 TeV (such as might result from CR injection by ultrarelativistic shocks with Lorentz factors exceeding 100) would be hard to rule out. Muons from primaries at $E_p \gg 1$ TeV dominate the total flux only at depths at or beyond $\sim 10^5$ g cm^{-2}, where the nuclear muogenesis rate per target atom is only about 10^{-23}/yr. A net collection of 10^6 ^{53}Mn atoms, accumulating over $10^{6.5}$ yr, would thus require a purified sample of $10^{22.5}$ iron nuclei, i.e. several grams.

The dependence of muon secondary flux, and its depth dependence, can be estimated with a simple analytic model: Muons at sea level come mainly from primaries at $E \geq 100GeV$, which create center-of-mass Lorentz factors that are larger than the ratio of the muon flight time to its rest frame lifetime. A detailed account of the physics is given in Dorman (2004), and a look-up table for muon production as a function of primary energy is given by Atri and Melott (2011). Using a rough analytical estimate, or the look up tables of Atri and Melott, we find that a variation of the spectral index -2-p from -2.7 to -2.6 leads to a change in the all sky muon flux of $(20g)^{0.1}(1.7/1.6)(2.7/2.6) \sim 1.5g^{0.1}$, where g is the grammage above the sample in units of atmospheric grammage (1030 g/cm^2).

Variations of the spectral index are expected on principle (e.g. Erlykin and Wolfendale, 2010 and references therein, Pohl et al, 2003, Pohl and Esposito, 1998) assuming the escape rate of cosmic rays is energy dependent. Variations in this index of 0.1 are quite reasonable for a realistic model of Galactic cosmic ray propagation that takes into account the discreteness of supernova and the variations of the supernova rate in the spiral arms (Kumar and Eichler, 2013). We have calculated an expected intensity vs. time plot for randomly placed CR sources in the Galaxy, weighted according to location in proportion to local starlight production. The two figures plot the "effective" escape index (EEI) - i.e. the log of the ratio, as a function of energy, of the CR flux to the source spectrum at the same energy - assuming a value for d of 1/3 and assuming that the cosmic ray sources are dominated by bright supernovae. This index differential can vary from -0.2, within the spiral arm, to -0.45 between spiral arms. This is discussed in more detail elsewhere (Kumar and Eichler, in preparation). Over timescales of 3 Myr, the variation could be of the order of 0.05, which would produce a ^{53}Mn anomaly of ≥ 10 percent. This variation would be detectable if the muon flux averaged over the ^{53}Mn lifetime could be measured to ~ 10 percent accuracy at $g \sim 100$.

The solar system now lies between two major spiral arms but inside a minor spiral arm. There are certainly several nearby, recent supernovae, and they and others may have contributed to some fluctuation of the spectral index over the past several million years. In addition, however, the excursion into and out of major spiral arms, as illustrated in the figures, may introduce variations of as much as 0.1 or larger in the effective escape index around its average value. The timescale of this variation is longer than several million years, and would not be manifest in ^{53}Mn anomalies, but perhaps would be in longer lived isotopes. If the CR residence time in the halo is larger than the residence time of the Solar System inside a spiral arm, then the time-averaged value of the EEI is perhaps closer to -0.4 than to 0.3, and the implied source spectral index is flatter by 0.2 than implied by an EEI of -0.3. That is, the inferred source spectrum in closer to -2.2 than -2.4.

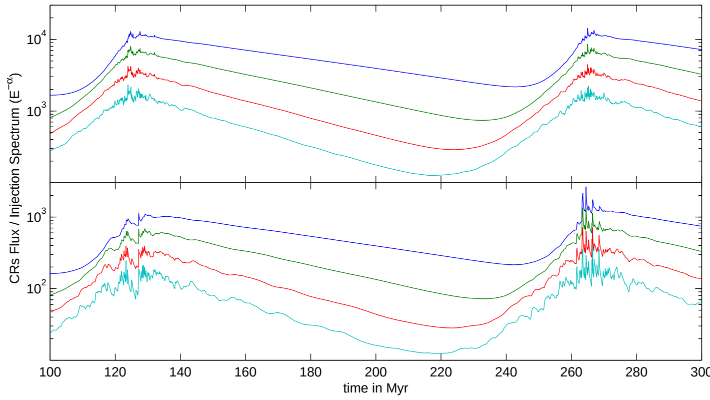

Figure 1: CRs flux variation at four different energies for isotropic diffusion in disk geometry, as sun crosses spiral arms at about 120 Myr (relative time) and 260 Myr. Diffusion coefficient for CRs of energy E is taken to be $6 \times 10^{27}\,(E/1GeV)^{1/3}\,cm^2 s^{-1}$ and disk boundary is at 1 Kpc. Top and bottom panels are for source rates 10^{-2} and 10^{-3} yr^{-1} respectively. The blue, green, red, and cyan lines are for 1 GeV, 10 GeV, 100 GeV, and 1 TeV respectively, in each panel.

The expected emission by the Galaxy of ultrahigh-energy neutrinos, typically generated by primaries in excess of $\sim 10^{14}$ eV, would be raised by about a factor of 3 for each change of 0.1 in the EEI, and the contrast between the spiral arms and the spaces between them might be enhanced by an even larger factor. According to figure 1, this factor could be as high as an order of magnitude or more at such high energies. Similar considerations apply to UHE gamma ray emission from young sources. Neutrino emission from the spiral arms, and UHE gamma ray emission from supernovae remnants are sensitive functions of their respective local CR spectral index. For a given gamma ray flux at 10^2 MeV, they could set useful limits on the spatial variation of the CR spectral index.

The hypothesis that we are living in an unusual era, when the CR flux at high energies is well below its average value in the Galaxy, might be motivated by anthropic considerations: e.g., if a normal CR flux were somehow detrimental to intelligent life. The present level of ionizing radiation from CR flux is less than the component due to terrestrial radon, so it is hard to see how changes of less than a factor of 2 in the CR flux could have serious astro-

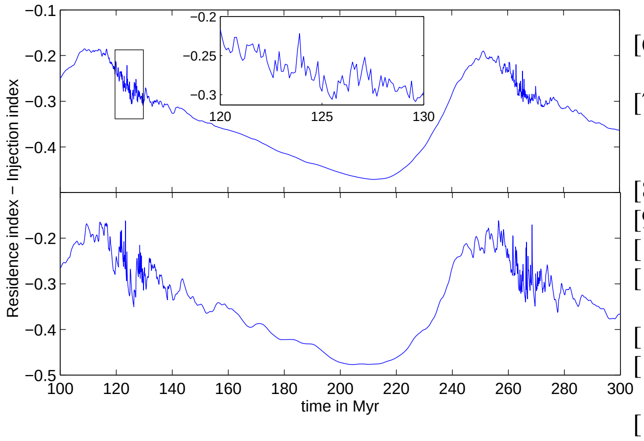

Figure 2: Temporal variation of difference in residence and injection indices, considering the CRs spectrum between 1 GeV and 1 TeV (figure 1). As in figure 1, top and bottom panels are for source rate 10^{-2} and 10^{-3} yr^{-1} respectively. Sub-panel in the top panel shows the variation between 120 Myr and 130 Myr (a period when Earth lies just inside a spiral arm) on a smaller time scale (0.1 Myr).

biological consequences, though it cannot be ruled out beyond reasonable doubt. At very high energy ($\sim 10^2$ PeV), intermittency can cause much larger fluctuations in the CR intensity, and if high energy airshowers have astrobiological connections (such as lightning [Gurevich et al., 1992], cloud cover [Svensmark et al., 2009] and nitrate formation at low altitudes) then it is conceivable that the not unexpected changes in the spectral index of CR could conceivably affect terrestrial affairs and the development of life and civilization. Even if very high energy CR are produced by the same events as lower energy CR, changes in the spectral index of order 0.1 are not unexpected, and even this modest change could influence the flux at 100 PeV by nearly an order of magnitude.

We thank Gunther Korchinek, Michael Paul and Nir Shaviv for helpful conversations. MP acknowledges support by the Helmholtz Alliance for Astroparticle Physics, HAP, funded by the Initiative and Networking Fund of the Helmholtz Association. DE and RK acknowledge support from the Israel-U.S. Binational Science Foundation, the Israeli Science Foundation, and the Joan and Robert Arnow Chair of Theoretical Astrophysics.

References

[1] Atri, D. and A.L. Melott, Radiation Physics and Chemistry, 2011, 80(6), 701

[2] Blandford, R.D. & Eichler, D.E., 1987, Physics Reports, 154, 1

[3] Dorman, L., ”Cosmic rays in the Earth’s Atmosphere and Underground”, (Springer, 2004)

[4] Ellison, D.C. and Eichler, D., 1985, Phys. Rev. Lett., 55, 273

[5] Erlykin, A.D., and Wolfendale, A.W., 2010, Surveys in Geophysics, Volume 31, Issue 4, 383

[6] Gurevich, A.V., Milikh, G.M., Roussel-Dupre, R., 1992, Phys. Lett. A 165, 463.

[7] Heisinger, B., Lal,D.,Jull, A.J.T., Kubik, P. Ivy-, Neumaier, S., Knie, K., Lazarev, V., Nolte, E. 2002, Earth and Planetary Science Letters 200, 345

[8] Kumar, R., & Eichler, D. 2013, ApJ, submitted

[9] Pohl, M., & Eichler, D. 2011, ApJ, 742, 114

[10] Pohl, M., & Eichler, D. 2013, ApJ, submitted

[11] Pohl, M., Perrot, C., Grenier, I., Digel, S. 2003, A& A 409, 581

[12] Pohl, M., & Esposito, J. A. 1998, ApJ, 507, 327

[13] Svensmark, H., Bondo T., & Svensmark, J. 2009, Geophysical Research Letters, , 2009, 36, L15101,

[14] Trotta, R., Jóhannesson, G., Moskalenko, I. V., et al. 2011, ApJ, 729, 106