ed breakaway processes occur along the pinned dislocations,[3] a computer fitting method[18] can be used to map the true force-distance profile for the dislocation–point-defect interaction.

We believe that this technique can be used to measure the dislocation–point-defect interaction force under a wide variety of controlled conditions.

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Origin of Very High-Energy Cosmic Rays*

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It is suggested that a single source of cosmic rays (supernovas) occurring in all galaxies can produce the observed spectrum and the observed anisotropy, and is predictable from supernova shock theory. Below 10^{13-14} eV the source and observed spectrum are the same, $N(>E) \propto E^{-\alpha}$, $\alpha \simeq 1.75$. Above 10^{14} eV I predict a source with $\alpha \simeq 1.2$. Galactic leakage above 10^{15} eV is linear so that $\alpha \simeq 2.2$ as observed. Above 10^{19} eV cosmic rays fill the metagalaxy to a flux several times the anisotropic residual flux from a few events in our galaxy as observed.

Cosmic rays are assumed to be either galactic or extragalactic in origin. The total energy required for filling metagalactic space with all cosmic rays is improbably high and, in addition, very heavy nuclei and electrons must then have a separate origin.[1] On the other hand, the near isotropy at energies above where any reasonable galactic magnetic field could affect particle containment dictates an extragalactic origin.

I propose instead that the identical source mechanism occurs in all galaxies and that we observe at very high energy a combination of our own statistically distributed sources as well as an isotropic flux from all other galaxies. This assumption requires a source spectrum that is flatter by one power of E than the observed spectrum for $E > 10^{15}$ eV. The observed spectrum is then a result of leakage from our galaxy as well as attenuation in metagalactic space. The consequences of this assumption are as follows:

(1) The resulting spectrum agrees with observations, including the "bump" at $10^{13} < E < 10^{15}$ eV.

(2) The anisotropy becomes an increasing function of energy above 10^{15} eV, and the degree of anisotropy agrees with the recent large anisotropy interpreted[2] for all measurements $E > 10^{19}$ eV.

(3) The energy spectrum of the local anisotropy should be flatter than the isotropic flux as observed.[2] That is, the anisotropy should consist of a few local peaks of flux (not valleys) in solid

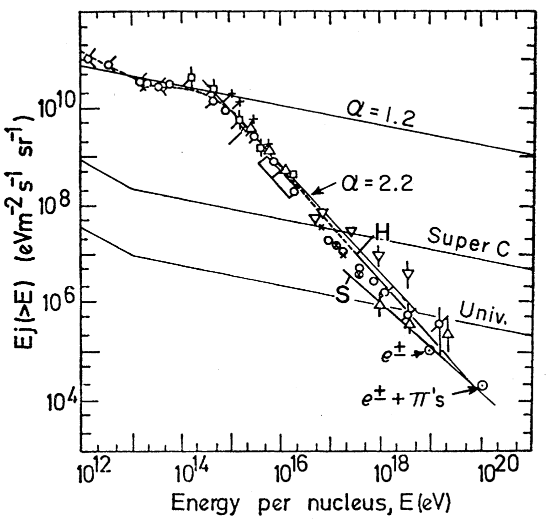

FIG. 1. Text in quotes from Wolfendale (Ref. 3): "The integral [energy] spectrum of cosmic-ray nuclei (Kempa *et al.* 1974) [Kempa, Wdowczyk, and Wolfendale, Ref. 4]. The key to the experimental points is given in that work; briefly the points below 2×10^{13} eV came from... nuclear-active particle spectra as a function of atmospheric depth; H denotes the best line through the Haverah Park measurements of Edge *et al.* (1973) [Ref. 5], S denotes the measurements of C. J. Bell *et al.* (1974) [Bell, Kota, and Wolfendale, Ref. 6]. The dotted line is an estimate of the overall best line." The line marked $\alpha=2.2$ is also the analytical result of taking a source spectrum of $\alpha=1.2$ fitted to the "bump" at $E=10^4$ eV and letting it "leak" out of the galaxy according to $\tau=2\times10^5(E/10^{15})^{-1}$ yr. The limiting spectra assuming no confinement and filling the supercluster or universe are indicated separately. The two points marked with circles are the calculated energy fluxes at 10^{19} and 10^{20} eV attenuated from the "universe" spectrum by the respective blackbody radiation interactions forming $e^{\pm}$ pairs and π's. Permission to use and reproduce part of the figure is kindly granted by A. Wolfendale.

angle that should become higher as a function of increasing energy as observed.

(5) Esthetically, theory need contend with only one canonical source in all galaxies rather than a local galactic source for low-energy, very heavy particles, and electrons, and conversely a high-energy extragalactic source(s) that just (by good fortune) matches onto the local flux at the correct energy.

(5) There is a natural reason in one theory of cosmic-ray origin, the supernova shock acceleration, to predict just such a flattening of the slope (α) at $E>10^{14}$ eV.

Figure 1 includes a composite of current experimental data of integral energy flux versus energy from a review by Kempa, Wdowczyk, and Wolfendale[4] as well as the proposed canonical source spectrum. This proposed source spectrum corresponds to an extrapolation of the observed spectrum at $E>10^{13-14}$ eV by the relation $N(>E)\propto E^{-1.2}$ and is marked "$\alpha=1.2$." Above the energy $E=10^{15}$ eV, we expect leakage from the galaxy to be linear in energy ($\propto E^{-1}$ as opposed to the usual[7] E^{-2}) because of a wide distribution in sizes of the magnetic field inhomogeneities associated with hydrogen clouds [Bell, Kota, and Wolfendale[6] (BKW)]. This produces the observed slope $N(>E)\propto E^{-2.2}$ up to $E\simeq3\times10^{18}$ eV, where I have assumed a factor of 3 larger confinement for a galactic model than for the galactic-arm confinement of BKW.

In addition the escaping cosmic rays will tend to fill metagalactic space,[8] and this becomes relatively more important because the proposed source spectrum is flatter than that observed. Confinement in the local supercluster requires an improbably high metagalactic field of $\simeq10^{-7}$ G,[3] in which case the local [$R\simeq20$ Mpc (megaparsecs)] space density of galaxies is 0.5 galaxy Mpc^{-3}. Without confinement the space density[9] is 0.02 galaxy Mpc^{-3}, derived from a value of the Hubble constant $H\simeq60$ km sec^{-1} Mpc^{-1}. Since the galaxy volume is 10^{11} pc^3, corresponding to a disk 300 pc thick and 10^4 pc in radius, the volume ratio is 2×10^7 or 5×10^8 depending upon supercluster confinement or escape, respectively.

The confinement time of cosmic rays in the galaxy is usually interpreted on the basis of nuclear spallation ratios as $\simeq2\times10^6$ yr. On the other hand the analysis of BKW based upon scattering from magnetic inhomogeneities predicts $\tau=2\times10^5$ yr for $E\leq3\times10^{15}$ eV. If additional scattering centers like hydromagnetic waves[10,11] extend the linear leakage down to $E\simeq10^{15}$ eV, as the break in the spectrum would indicate, then $\tau\simeq6\times10^5$ yr for $E\leq10^{15}$ eV, closer to the spallation value. If we choose the galactic confinement time of 2×10^5 yr of BKW, and the expansion time of the universe of 2×10^{10} yr, the ratio of galactic to extragalactic flux will be variously 5×10^{-3} or 2×10^{-4} depending upon confinement in the supercluster or not. On the other hand, if the confinement time is 2×10^6 yr at 10^{14} eV, then the extragalactic fluxes will be 10 times smaller.

The resulting theoretical extragalactic fluxes are shown in Fig. 1 as if there were (1) *no* galactic confinement, (2) "super c" (5×10^{-3} of the extrapolated $\alpha=1.2$ source), and (3) "univ." (2×10^{-4} of the extrapolated $\alpha=1.2$ source). Both these fluxes are greater than the measurements at high energy, but the transition from the presumed source curve of $\alpha = 1.2$ to the respective extragalactic curves by galactic leakage, $\tau \propto E^{-1}$, follows the slope $\alpha = 2.2$ and is in good agreement with observations provided the energy where "linear" leakage commences is reduced from 3×10^{15} eV. This may be the result of the interconnected-tunnel approximation of Cox[12] and reduces the extragalactic fluxes by 3.

It is evident that the supercluster approximation results in an extragalactic flux significantly greater than observed for $E \geq 10^{17}$ eV and the same comment possibly applies to the "universe" approximation for $E \geq 3\times10^{18}$ eV. However, for $E \geq 3\times10^{18}$ eV positron-electron pairs are produced by interaction with the blackbody radiation and π's are produced above 3×10^{19} eV.[13,14] The two circled points are calculated as a reduction of the "universe" curve due to these effects at the respective energies 10^{19} and 10^{20} eV according to BKW. The agreement with the Sydney array data is satisfactory, but it is still possible that a small contribution from the supercluster could flatten the slope in the very high-energy region in better agreement with the Haverah Park results.

Although this model was originally suggested[15] solely on the basis of the spectrum and the advantage of a single canonical galactic source, the recent strong evidence by Krasilnikov *et al.*[2] for anisotropy of cosmic rays at $E > 10^{19}$ eV (where roughly half of the world total of 104 events fall into three localized directions of a total of $\simeq 12\%$ of 4π sr) strongly supports a partially local origin. Hillas and Ouldridge[16] arrive at a similar conclusion and point out that previous anisotropy measurements at lower energy (either a lower limit or an actual anisotropy) show an anisotropy that increases as a function of increasing energy proportional to the presumed galactic leakage ($\propto E$).

I interpret isotropy along the lines originally proposed by Ramaty, Reames, and Lingenfelter,[17] where a combination of source distribution, frequency, and diffusion gives rise to a limiting statistical probability of anisotropy. What has been added to this model is a presumed isotropic extragalactic flux that becomes important above $E > 3\times10^{18}$ eV and local sources of flatter spectrum. I therefore expect the largest anisotropy to result from a supernova (or other cosmic-ray-producing event, 1 per 50 yr [18]) occurring close enough to the solar system such that the direct flux causes an observable anisotropy. If the source in the galaxy has a mean strength of $\dot{S}_0 \times E_{15}^{-1.2}$ particles per year, where E_{15} is the energy in units of 10^{15} eV, then the galactic flux is $\varphi_g = \dot{S}_0 E_{15}^{-1.2}\tau c/V$, where τ is the galactic confinement time and V is the effective cosmic-ray confinement volume of the galaxy.[19] Therefore, the local flux becomes $\varphi_g = 2\times10^3 \dot{S}_0 E_{15}^{-2.2}c$, where I have used $\tau = 2\times10^5 E_{15}^{-1}$ yr. The flux from a nearby supernova is the direct flux φ_d from an event of size corresponding to 50 yr of $\dot{S}_0$ arriving with a time spread Δt, or $\varphi_d = 50\dot{S}_0 E_{15}^{-1.2}/4\pi R^2 \Delta t$. The transit-time spread of various arrival paths will be approximately $\Delta t \simeq (R/c)(1-\cos\theta)$, where θ is the mean angle of deflection of a cosmic ray of energy E in the galactic field traversing a distance R. Since $(1-\cos\theta) \simeq \frac{1}{2}(R/R_L)^2$, where R_L is the Larmor radius, provided $R \leq R_L/2$, then the direct flux becomes $\varphi_d = 2\times10^{-6}\dot{S}_0 E_{15}^{0.8}c/R^5$, where R is in kpc and I have assumed a mean orthogonal galactic field of 2×10^{-6} G. The direct and average fluxes become equal when $R = 0.016E_{15}^{0.6}$ kpc. The condition $R \leq 2R_L$ for validity of the approximation for Δt requires that $E_{15} \geq 10^3$ and $R \geq 1$ kpc. Since the direct flux scales as R^5, the observation of anisotropy is strongly biased to nearby events where the direct and average fluxes are equal. The probability of this occurring is $\Delta t \times$(frequency of SN), where $\Delta t = 400E_{18}^{-0.2}$ yr and (frequency of SN) $\simeq \frac{1}{50}(R/10)^2$ per year, so that $P \simeq 8\times10^{-2}E_{18}$. At 10^{18} eV the probability of seeing the direct flux from a nearby event is small, but at 2×10^{19} eV we should be bathed in the flux of several supernovas lasting 200 yr at $R \simeq 6$ kpc. At this distance from the solar system the magnetic field geometry is such as to preferentially scatter out the direct flux by the approximate ratio of spiral-arm thickness to magnetic deflection, $\frac{1}{3}(R^2/R_L)^{-1} \simeq \frac{1}{5}$.

I note that in the analysis of Krasilnikov *et al.*[2] and Hillas and Ouldridge,[16] three peaks in the angular distribution are observed at an amplitude relative to the average of $\simeq 40\%$. These peaks are just below the statistical significance of the tests applied to the 87 events analyzed by Linsley and Watson.[20] If there were no extragalactic flux, then the expected peak-to-average ratio should be very much greater.

A flatter slope to the cosmic-ray spectrum for $E > 10^{13-14}$ eV is expected in the shock ejection of the outer supernova layers. It has been shown[21-23] both analytically and numerically how the relativistic shock in the stellar envelope from the supernova explosion increases in strength as $\Gamma_s \propto F^{-a}$, where Γ_s is the energy factor $(1-\beta_s^2)^{-1/2}$ assumed $\gg 1$, with $c\beta_s$ the velocity of the *fluid* immediately behind the shock; F is the fraction of the mass external to the radius in question, and $a = \frac{3}{8}[\sqrt{3}/(2+\sqrt{3})] = 0.174$. For an adiabatic expansion of the shocked fluid with internal energy $\epsilon_s = \mu_s \rho_s C^2$ where the Hugoniot relations demand that $\mu_s = \Gamma_s$, the final energy factor of the ejected matter becomes $\Gamma_f = \Gamma_s \mu_s^b$, where $b = \sqrt{3}$, resulting in $\Gamma_f = F^{-a(1+b)}$. If this ejected matter is presumed to be cosmic rays, then the integral spectrum $N(>E) \propto E^{-1/a(1+b)} = E^{-2.10}$ which is steeper than the observed slope $E^{-1.75}$ up to $E \simeq 10^{13-14}$ eV, $10^4 \leq \Gamma \leq 10^5$. I have suggested that radiation flow behind the shock should partially flatten this slope because the post-shock expansion would be more nearly isothermal than adiabatic. The limit of this approximation should apply after the shock reaches the stellar surface. The shock continues to propagate in the photosphere because it creates its own opacity in the form of pairs, but these pairs rapidly disappear after a small expansion. In the presupernova type-I model of high initial density and *no* red-giant envelope, $\Gamma_s \simeq 40$ to 80 at a surface $\int_r^\infty \rho\, dr = 10$ g cm^{-2} corresponding to $\Gamma_f \simeq 10^{4-5}$. If we assume that the outer layers rapidly become isothermal (modified by their relative Doppler shift, $T^4 \propto \Gamma_s^{-1}$) then $\mu_s \propto \rho_s^{-1}\Gamma_s^{-1}$ where the post-shock density $\rho_s \propto \Gamma_s F^{3/4}$ to $\Gamma_s F$ in the transition from the standard envelope radiative "zero" solution to the photosphere and where the shock compression is taken proportional to Γ_s. Then the final energy factor $\Gamma_f \propto \Gamma_s \mu_s^b \propto F^{-0.87}$ to $F^{-0.30}$ giving $N(>E) \propto E^{-1.15}$ to $E^{-0.77}$. The photosphere approximation is somewhat flatter than desired, but the approximations are a larger uncertainty.

I imply only that radiation flow behind the relativistic shock will give a flatter slope and that this flattening should commence at an energy that logically relates to present observations. Pulsar acceleration[24] also naturally favors high energy, but without predicting such a specific transition.

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