# Origin of Cosmic Radiation

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**Abstract.** I give a brief overview of cosmic ray physics, highlighting some key questions and how they will be addressed by new experiments.

## I INTRODUCTION

There are several new experiments in cosmic-ray physics and related fields running now or planned for the near future. These include measurements of antiprotons with balloons and from space, new gamma-ray detectors to cover the full energy range from $< 100$ MeV to $> 10$ TeV, studies of the knee region with a variety of experiments, giant air shower detectors for the highest energy particles, and huge, deep neutrino detectors to find astrophysical sources of high energy neutrinos. In this talk, I will review the key questions driving these experiments and, where possible, put them in a larger context and relate them to each other.

After some brief remarks about the sun as a cosmic-ray source, I review cosmic rays of galactic origin and then extragalactic cosmic rays. Energy content of the various components of the cosmic radiation and the corresponding power to maintain the observed fluxes are used as a guide to possible sources.

## II SOLAR COSMIC RAYS, A PARADIGM

One class of solar cosmic rays consists of solar energetic particles accelerated during solar flares [1]. The high energy accelerated particles can be detected with neutron monitors [2]. Gamma-radiation produced by interactions of the accelerated particles in the solar atmosphere are also seen, including the contribution from $\pi^0 \to \gamma\gamma$ [3]. Therefore we can infer that secondary neutrinos must also be present. In this sense the sun is an ideal cosmic ray source, in that both the accelerated particles and the secondaries from their interactions at the source are directly identified and associated with the particular accelerator.

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The large coronal mass ejections associated with some solar flares drive shocks into the interplanetary medium at which particles are energized by diffusive shock acceleration. This is but one example of acceleration by shocks in the heliosphere. Energetic particles are typically observed in spatial association with shocks as they pass by a spacecraft such as ACE [4], concentrated particularly in the downstream region.

The anomalous cosmic rays are a distinct subset of particles accelerated in the heliosphere, which are now understood to be particles of interstellar origin accelerated at the termination shock in the solar wind [5]. This phenomenon reminds us that cosmic-ray acceleration typically occurs in regions with structure created by strong stellar winds and past supernovae. An important analog for galactic cosmic rays is the wind-blown bubble surrounding a massive star. The *astropause*, by analogy with the heliopause, is the contact discontinuity between the fast stellar wind and the surrounding medium. There is both a bow shock outside the astropause and a termination shock inside [6]. An interesting possibility is to consider the signatures for acceleration by a supernova blast wave propagating through this kind of environment [7]. In addition, acceleration at multiple shock structures may have significant effects, both as a way of achieving higher energy [8,9] and for modifying the low energy spectral shape [9] for particles injected after acceleration by individual shocks.

## III GALACTIC COSMIC RAYS

While solar cosmic rays are identified by their temporal association with solar flares or spatial association with interplanetary shocks, or by the compositional and spectral signatures of anomalous cosmic rays, the steady, nearly isotropic flux of high energy particles comes from sources far outside the heliosphere. These sources still lack definitive identification nearly a century after their discovery. The fundamental difficulty is that diffusive propagation in the turbulent interstellar medium smooths out spatial and temporal variations that may characterize the sources.

Fig. 1 shows a global view of the cosmic-ray spectrum. This is the differential "all-particle" spectrum (flux of all particles summed over all species as a function of total energy per nucleus) multiplied by $E^{2.7}$. Because of the low intensity at high energy, information from direct measurements made with balloons and spacecraft above the atmosphere is sparse for $E_0 > 100$ TeV. This is therefore the realm of indirect extensive air shower experiments. The equivalent laboratory energies of several major terrestrial accelerators are noted as a reminder that interpretation of measurements of air showers depends on models of hadronic interactions to extrapolate beyond the reach of laboratory measurements. 0 of high energy cascades in the atmosphere is governed by properties of interactions of pions and nucleons with nuclei in the atmosphere, primarily in the forward fragmentation region (i.e. the region of phase space in which the secondaries carry a non-vanishing fraction

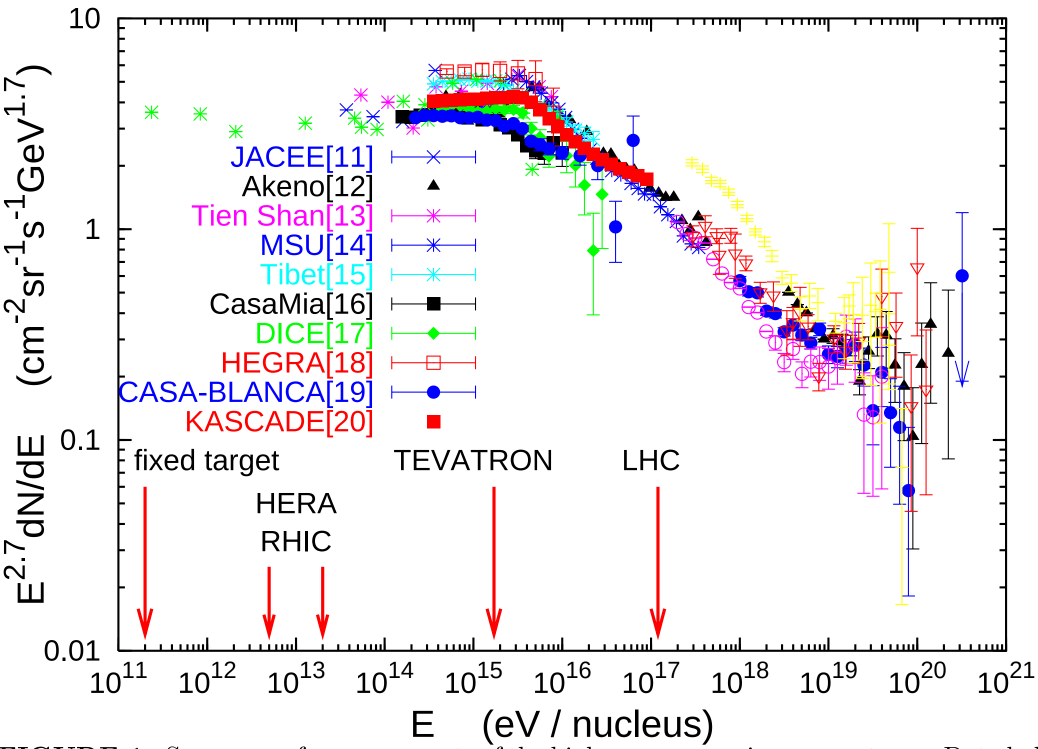


**FIGURE 1.** Summary of measurements of the high energy cosmic-ray spectrum. Data below 100 TeV are from a satellite detector [10]. Data in the knee region are from Refs. [11–20]. References for data above $10^{17}$ eV are given in Fig. 4.

of the incident energy as $E_0$ increases). In contrast, the highest energy collider experiments study primarily the central region of phase space for proton-proton (antiproton) collisions. The two features in the spectrum as shown in Fig. 1 are the *knee* between $10^{15}$ and $10^{16}$ eV and the *ankle* around $10^{19}$ eV, which will be discussed below.

## A Low energy galactic cosmic rays

There are several recent, independent measurements of the primary proton and helium spectra for $E < 100$ GeV made with balloon-borne spectrometers [21–25]. Fig. 2 is a compilation of proton spectra from these measurements as well as the newly published data from the test flight of the AMS detector on the Space Shuttle [26]. At higher energy into the TeV region the principal data is still that of the calorimeter measurement of Ryan, Ormes and Balasubrahmanyan [27]. The differential spectra are multiplied by $E^2$ so that equal areas on the semilogarithmic plot correspond to equal contributions to the energy content of the cosmic radiation.

Also shown in Fig. 2 (by the line) is an estimate of the interstellar spectrum after accounting for the effects of solar modulation, which suppresses the intensity

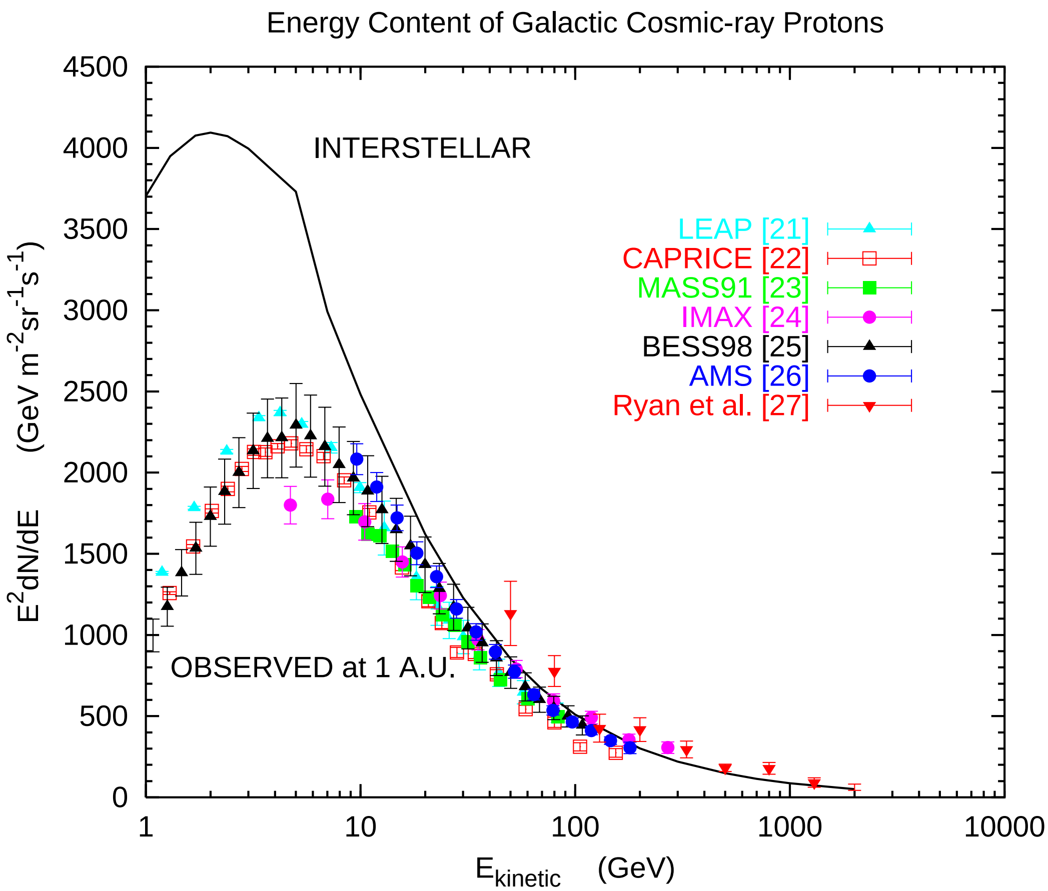

**FIGURE 2.** Summary of direct measurements proton spectra made with detectors on balloons and in space.

of low-energy particles in the inner heliosphere [28]. The median energy in the local interstellar medium (ISM) is about 6 GeV, and more than 90% of the energy is carried by particles with $E < 50$ GeV. The energy density in cosmic rays in the local ISM is

$$P_{CR} \;=\; \rho_{E,CR} \;=\; \frac{4\pi}{c}\int E\,\frac{dN}{dE}\,dE \;\sim\; 10^{-12}\ \ \mathrm{erg/cm^3}. \tag{1}$$

Assuming this is typical of the entire galactic disk, the power required to maintain this cosmic-ray energy density in steady state can be estimated as

$$\frac{\rho_{E,CR}\,V_{disk}}{\tau_{esc}} \;\sim\; \frac{10^{-12}\times 10^{67}}{10^{14}} \;\sim\; 10^{41}\,\frac{\mathrm{erg}}{\mathrm{s}}, \tag{2}$$

where $\tau_{esc}$ is the average time spent by cosmic rays in the disk of the Galaxy before they are lost into intergalactic space. The similarity of this power requirement to the power available in kinetic energy of supernova ejecta ($10^{51}$ erg/30 yrs $\sim 10^{42}$ erg/s) is one of the principal arguments for supernova explosions as the source of cosmic rays [29].

The characteristic time in Eq. 2 is an effective parameter that emerges from a range of more realistic models for diffusion and propagation of cosmic rays in the disk and halo of the Galaxy [30]. In general $\tau_{esc}$ depends on energy. The relation between the source spectrum, $Q(E)$ and the observed spectrum is

$$\tau_{esc}(E)\, Q_{source}(E) \;\propto\; \frac{dN}{dE}_{observed} \;\propto\; E^{-\alpha}. \tag{3}$$

The observed differential spectral index is $\alpha \approx 2.7$ for protons and primary nuclei such as carbon, oxygen, etc., with small but interesting differences among the various nuclei [31].

The energy dependence of $\tau_{esc}$ can be measured by comparing the spectrum of a secondary nucleus to that of a parent primary nucleus (e.g. B/C or sub-Fe/Fe). Primary nuclei are those accelerated in the sources. Secondary nuclei are those essentially absent in the source but which can be produced by spallation of primary nuclei of larger mass number. As a consequence, their spectral index at production is known. To the extent that spallation cross sections are approximately constant in energy, the spectral index at production for a secondary nucleus is the *observed* spectral index of its parent. Thus the analog of Eq. 3 for a secondary nucleus is

$$\tau_{esc}(E) \times \frac{dN}{dE}_{observed} \;\propto\; \frac{dN}{dE}_{secondary}. \tag{4}$$

The data on the secondary to primary ratio up to 20–50 GeV may be fit as a power law with the result,

$$\tau_{esc}(E) \;\propto\; E^{-\delta}, \tag{5}$$

with $\delta \sim 0.6$ [32].

The energy-dependence of $\tau_{esc}$ must be taken into account in estimating the power requirement for cosmic rays. Since $\tau_{esc}(E) \;\propto\; E^{-\delta}$, it follows from Eq. 3 that $Q_{source}(E) \;\propto\; E^{-\gamma}$ with $\gamma = \alpha - \delta \approx 2.1$. Thus the source spectrum is harder than the observed spectrum, and a more correct version of Eq. 2 is

$$P_{CR} \;=\; \frac{4\pi}{c}\int E\, Q_{source}(E)dE \;=\; \frac{4\pi}{c}\int E\,\frac{dN}{dE}_{observed} \times \frac{1}{\tau(E)}\, dE. \tag{6}$$

This relation between observed flux and source power is true in general for other components of the cosmic radiation and will be used below in other contexts.

The basic picture described above has been known and understood for a long time. A recent result relevant to cosmic-ray propagation in the Galaxy is the measurement with high statistics of the spectrum of antiprotons from $\sim 300$ MeV to $\sim 3$ GeV with the BESS detector [33]. It is an interesting test of the model because most of the antiprotons are produced by cosmic-ray protons, which could in principle have a completely different distribution of sources from the heavier nuclei like carbon, oxygen and iron on which the model is based. Instead, the measurements are quite consistent with the propagation parameters determined from the ratios of secondary to primary nuclei [34].

The canonical tracer of cosmic-ray propagation is the production of gamma-radiation by interactions of cosmic rays in the ISM [35], as reviewed by Hunter at this conference. The EGRET data [35] fits the general picture well with, however, the exception that the spectral index above a GeV is harder than expected. The GeV range for secondary photons is sufficiently high that the relevant production cross sections approximately scale with energy. As a consequence, at such energies the production spectrum of the photons from decay of $\pi^0$ produced by cosmic-ray interactions in the ISM should have the same spectral index as the parent nucleons (mostly protons). Since the photons propagate directly, their observed spectral index should also be $\alpha \approx 2.7$. Instead it is more like $\alpha_\gamma \approx 2.4$. An important possibility to consider is that there may be some contribution of interactions at the source with a characteristically harder spectrum. [36,37]

## B Supernova model of cosmic-ray origin

If supernovae are the sources of galactic cosmic rays capable of accelerating particles to $\sim 10^{15}$ eV or higher, then *at some level* they should also be point sources of $\gamma$-rays produced by interactions of the accelerated particles in or near the source [38]. The intensity depends, however, on the degree of mixing between the high energy particles and the gas nearby. Certain supernova remnants (SNR) may be sources of GeV photons [39], but they have not been detected by the TeV air Cherenkov telescopes at the levels that would be expected if the parent proton spectrum extended to $\sim 100$ TeV and the source spectrum were hard ($\alpha \approx 2.1$) [40].

Theoretical calculations of first order diffusive acceleration at shocks driven by supernova blast waves show that the spectral index should be approximately $\alpha \approx 2.1$, not far from the ideal value of 2.0 for test particle acceleration at strong shocks [41]. The calculations include the non-linear effect of back-reaction of the cosmic-rays on the shock. The conclusion is that a large fraction ($> 10\%$) of the kinetic energy of the supernova remnant is deposited in accelerated particles and that the spectrum extends to $E_{max}$ approaching $10^{15}$ eV.

There are several possibilities for explaining the absence of TeV $\gamma$-rays at the level expected by using a hard spectrum to extrapolate the GeV observations of Ref. [39]. It is possible [42] that the spectrum of accelerated particles in the source is significantly steeper than ($\alpha \sim 2.4$), in which case the extrapolation to $E_\gamma >$ TeV of fits to $\sim$GeV data can be consistent with the upper bounds from air Cherenkov telescopes. Alternatively, the observed photons in these sources may be not be associated with acceleration of cosmic rays or the maximum cosmic-ray energy may be low in these particular remnants.

TeV gamma-rays have now been detected from the supernova remnants

SN1006 [43] and CasA [44], and the potential importance of inverse Compton scattering by high energy electrons is emphasized [45,46]. The contribution of $\pi^0 \to \gamma\gamma$ associated with cosmic ray acceleration is still uncertain. (For a review see Ref. [47].)

## C The *knee* of the spectrum

One interpretation of the knee of the spectrum is that it reflects a change in propagation of galactic cosmic rays, perhaps corresponding to more rapid escape from the galaxy (effectively an increase in $\delta$) [48]. A problem for this interpretation is that the spectrum in the knee region may have more structure than would be the case for a steepening of the rigidity spectrum of each elemental component of the cosmic radiation. This can be seen best by following one of the individual data sets through the bend above $10^{15}$ eV in Fig. 1, but there are significant differences among the different measurements. An alternate interpretation is that this part of the spectrum may be produced by only one or a few sources [49].

Another problem is that simple extrapolation of $\tau_{esc}(E) \propto E^{-\delta}$ with $\delta \approx 0.6$ breaks down around $3 \times 10^{15}$eV since the effective escape length $c\tau_{esc} \sim 300$ pc at that energy. This is corresponds to just one crossing of the disk and would tend to produce a large and increasing anisotropy approaching this energy. The measured anisotropy does increase around $10^{15}$ eV [49,50], but even at high energy the amplitude of the first harmonic is only a few percent. For $E < 10^{15}$ eV it is $\sim 10^{-3}$ or somewhat less [51]. It has been noted [52,53] that a Kolmogorov spectrum of turbulence in the interstellar medium indeed predicts that the diffusion coefficient should increase like $E^{\frac{1}{3}}$, which corresponds to $\delta = \frac{1}{3}$ rather than 0.6. The compilation of low energy measurements of the ratios of secondary to primary nuclei [32] can be made consistent with this by invoking reacceleration of the injected spectrum in the ISM [52,53]. Note that the source spectral index in this scenario would need to be larger ($\gamma \approx 2.4$) to maintain $\alpha = \gamma + \delta \approx 2.7$ at high energy, in contradiction to the calculations of diffusive shock acceleration in shock waves from SNR mentioned above [41]. Measurement of the ratio of boron to carbon can be fit well with a hard source spectrum and $\delta \approx 0.6$ [54]. The highest energy point of Ref. [54] is about two $\sigma$ below the fit [52] that uses reacceleration and $\delta = 0.33$. Measurements of the secondary/primary ratios at higher energy are needed.

An important diagnostic of the knee region is the way in which the average depth of shower maximum ($X_{max}$) depends on energy. ($X_{max}$ is defined as the depth along the shower axis at which the shower has maximum size or number of charged particles.) The most direct (mass independent) measurements of $X_{max}$ are made with optical detectors, which collect light over a significant portion of the shower, including the maximum. One approach is to use the Cherenkov light projected around the shower axis as it develops through the atmosphere [17–19,55–57]. At sufficiently high energy, fluorescence light can be used to map out the shower profile and hence determine depth of shower maximum [58]. The intermediate energy range is probed by the hybrid HiRes/MIA coincidence experiment [59] and by indirect methods. [60]. There is currently much activity in this field, as summarized in Fig. 3.

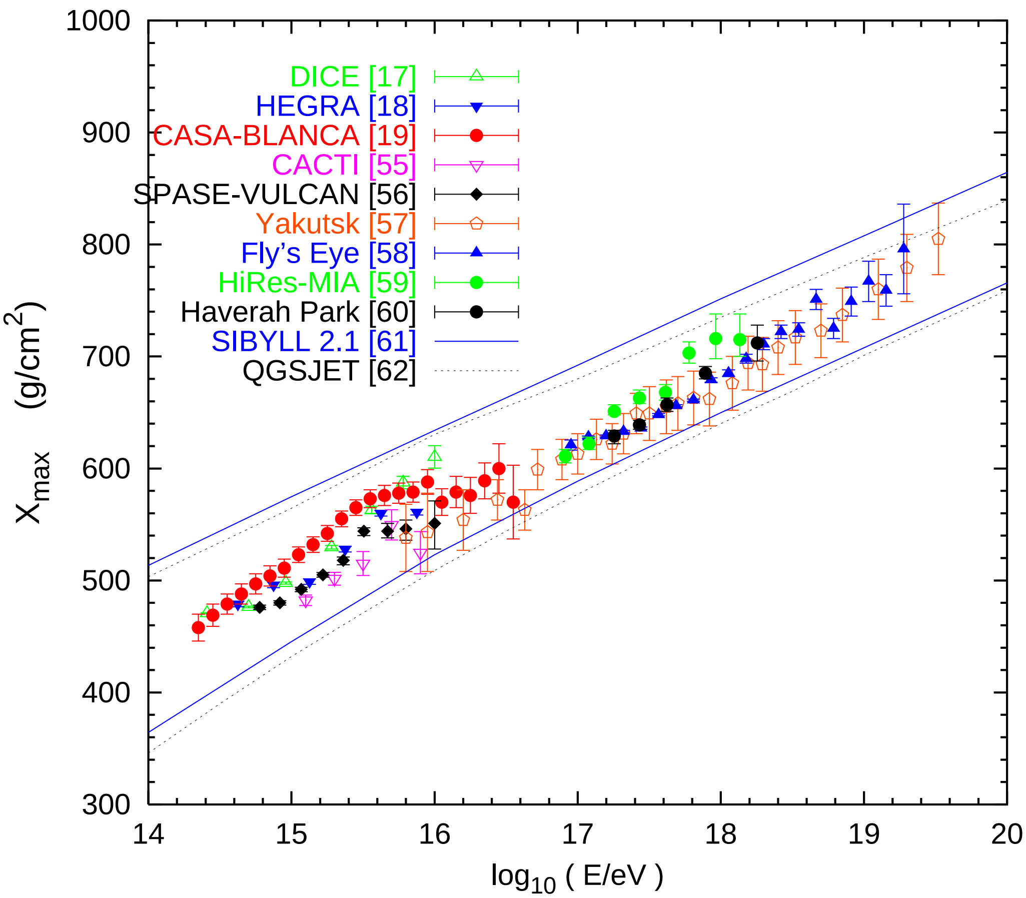


**FIGURE 3.** Summary of measurements of average depth of shower maximum vs. primary energy. Plots of model curves over the full range of energy are given in Ref. [63].

Calculations are needed to interpret the data. Results of two calculations [61,62] are shown in Fig. 3. The upper pair of lines is for showers initiated by protons and the lower pair for iron-initiated showers. Note the tendency, most clearly visible in Ref. [19], for a transition from heavies to a larger fraction of protons above $10^{15}$ eV, followed by a transition back toward heavies above the knee, around $10^{16}$ eV. There are many systematic uncertainties, so this can only be considered suggestive, but it would fit in with the suggestion [49] of one or two specific sources contributing in the knee region. The increase of protons just above $10^{15}$ eV would be from the high energy source with the heavy nuclei of the same rigidity showing up in the all-particle spectrum at higher energy.

# IV EXTRAGALACTIC COSMIC RAYS

If the cosmic rays in the knee region and above were all of extragalactic origin, as has been suggested from time to time (e.g. [64]) then the isotropy in the knee region would no longer be a problem, assuming particles of this energy could diffuse into the galaxy sufficiently easily. There is at least one piece of evidence, however, that the cosmic radiation below $3 \times 10^{18}$ eV is indeed of galactic origin. This is the anisotropy reported by AGASA [65]. There is an enhancement of particles in the energy bin around $10^{18}$ eV from near the galactic center. This anisotropy disappears rather quickly at higher energy. Data from Fly's Eye [66] and the SUGAR array [67] show a similar behavior.

## A Transition from Galactic to extragalactic

Somewhere around $10^{18}$ eV or a bit higher, one indeed expects a transition to cosmic rays of extragalactic origin because the gyroradius in a $3\,\mu$Gauss galactic field is comparable to kpc galactic scales. The Fly's Eye presented circumstantial evidence for such a transition from their stereo data [58]. It consists of an apparent transition from heavy to light primary nuclei coupled with a hardening of the spectrum, both around $3 \times 10^{18}$ eV. The transition from heavy to light with increasing energy is also present in the recent coincidence data from the HiRes prototype and the CASA-MIA detectors [59], although it seems to appear at lower energy than in the original Fly's Eye stereo data.

The stereo Fly's Eye result was challenged by Akeno [68], who reported no evidence for a transition based on their measurements of the ratio of low energy muons to electrons in the showers. The analyses of the two groups are based on different measurements and different calculations. Dawson *et al.* [69] compare the two analyses in a common framework and find some weaker but consistent evidence for a transition. The transition from heavier toward lighter composition is also model-dependent, as can be seen from Fig. 3 above $10^{18}$ eV.

An expanded view of the highest energy part of the spectrum is shown in Fig. 4. The Fly's Eye stereo spectrum [58,70] most clearly shows a hardening around $3 \times 10^{18}$ eV. It could be that this is a consequence of a difference in energy resolution among the different experiments. Energy resolution should in principle be best for stereo Fly's Eye, as compared to monocular Fly's Eye [70] or ground based experiments [71–73].

## B Models of extragalactic cosmic rays

One approach to sources of the highest energy cosmic rays is to examine the energy content of the observed cosmic rays and estimate the power needed to supply them. The idea is to proceed by analogy with the analysis for galactic cosmic rays, as in Eq. 6. I have discussed this in detail elsewhere [74].

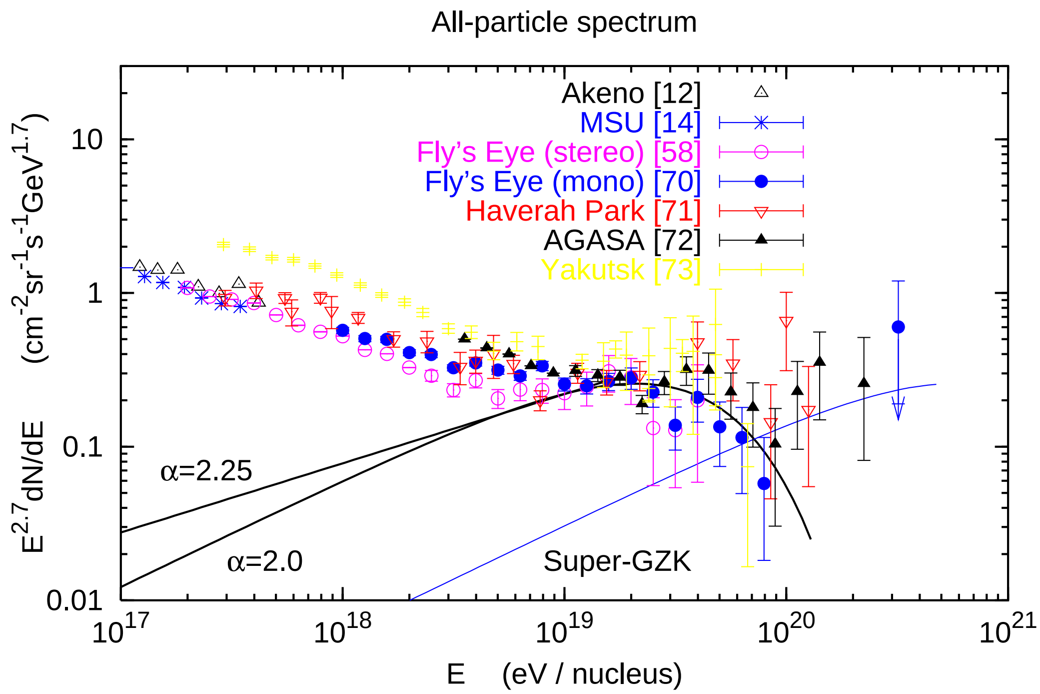


**FIGURE 4.** Summary of measurements of the cosmic-ray spectrum above $10^{17}$ eV.

Briefly, the curves labelled $\alpha = 2.0$ and $\alpha = 2.25$ in Fig. 4 are estimates of the extragalactic component of the observed cosmic radiation. The sources are assumed to be distributed over cosmological distances, which gives rise to a cutoff caused by energy loss due to photo-pion production. The energy content estimated for this diffuse component depends on the assumed spectral index. If $\alpha = 2.0$ is assumed for the 0 to low energy, then the local energy density in this diffuse, extragalactic component is $\rho_{CR} \sim 2 \times 10^{-19}$ erg/cm$^3$. This estimate assumes that the sources accelerate a spectrum of particles from $E_{min} \sim 1$ GeV to $E_{max} \sim 10^{20}$ eV. An estimate of the source power needed to produce this is then obtained, dividing by the Hubble time, as $\sim 10^{37}$ erg/s/Mpc$^3$. If the spectrum is steeper (as for relativistic shocks with $\alpha \sim 2.25$ [75,76]), then the power required is correspondingly higher (although in the case of acceleration at relativistic shocks $E_{min}$ may be large [77]).

Comparing the power estimate of $\sim 10^{37}$ erg/s/Mpc$^3$ to observed densities of galaxies, clusters of galaxies and active galactic nuclei (AGN), and to rates of gamma-ray bursts (GRB), one finds in each case that the power required per source is comparable to the power observed from that class of object in electromagnetic radiation. For example, a density of $10^{-7}$ AGN/Mpc$^3$ corresponds to a power requirement of $10^{44}$ erg/s/AGN in high energy cosmic rays. A rate of 300 GRB/yr would require $10^{53}$ erg/GRB.

## C Highest energy cosmic rays

Particles with energies of $10^{20}$ eV and above must be from relatively nearby. The attenuation length due to interaction with the microwave background ($\lambda_{2.7^\circ}$) decreases with energy. For example, $R_{50\%}$ [78] is 100 Mpc for a proton injected at $10^{20}$ eV but only 20 Mpc at $2 \times 10^{20}$ eV. One possibility is a cosmologically local overdensity of the same sources that produce all extragalactic cosmic rays [79,80]. The line labelled "Super-GZK" in Fig. 4 can be used to estimate the energy density in the nearby component as $4 \times 10^{-20}$ erg/cm$^3$, but the relevant characteristic time $\tau(E) \sim \lambda_{2.7^\circ}/c$ decreases with energy. Thus the power requirement from Eq. 6 is significantly higher than an estimate based on the Hubble time. Such a large local overdensity of sources is difficult to reconcile with the observed distribution of galaxies [81].

There are at least two alternative possibilities. One is that the highest energy cosmic rays are from nearby objects, for example from young pulsars in the our galaxy, including the halo [83] or from rapidly spinning magnetars in galaxies within the GZK radius [82]. Another is exotic sources, such as topological defects [84,85] or decaying massive relics [86]. Exotic sources produce parton cascades starting at some mass scale much higher than the ultra-high energy cosmic rays. The ratio of photons and neutrinos to protons at such sources would be large because most of the hadronization is to pions. For distant topological defects, photons would cascade down to lower energy (which also puts constraints on the models [87,88]), but for the decaying massive relics in the galactic halo, the observed Super-GZK events themselves would have to be generated largely by photons. Indications are that this is not the case [89,90].

# V OUTLOOK: NEW EXPERIMENTS

There is currently a great deal of experimental activity underway or planned that is motivated by questions raised by recent results. By way of summary, I briefly list some of the new experiments and the questions they will address.

## A Galactic cosmic rays

One focus of the new gamma-ray detectors [91,92] is to close the gap that now exists around 100 GeV between space telescopes and ground-based detectors. Another is to accumulate data and find new sources of high-energy transients. Both of these quests are of great importance for identifying potential sources of extragalactic cosmic rays. In the process, GLAST should extend the measurement of the diffuse flux from the Galaxy and help clarify the reason for the hardness of the diffuse spectrum observed with EGRET [35]. Another challenge for gamma-ray telescopes is to increase the sensitivity and resolution in the study of supernova remnants to resolve the question of whether there is production of secondary pions associated with acceleration of cosmic-ray protons at appropriate levels for the source.

Experiments on balloons and in space (e.g. AMS [93] on Space Station and PAMELA [94] as a free-flyer) will extend direct measurements of the primary spectra of hydrogen, helium and other nuclei beyond 100 GeV. Precise measurement of these primary spectra into the multi-TeV region is needed for better understanding of the expectations for atmospheric neutrinos, especially for neutrino-induced, upward muons. Another important goal of these detectors is to extend the measurement of antiprotons to higher energy, both as a probe of cosmic-ray propagation and to search for an exotic contribution to the antiproton flux [95]. They will also provide sensitive searches for anti-nuclei.

At higher energy, the ACCESS [96] experiment under development for deployment on Space Station will extend composition measurements to approaching the knee of the spectrum. An interesting question is whether changes in composition characteristic of contributions from individual sources will appear. This detector should also have the capability to extend the measurement of secondary/primary nuclei to significantly higher energy than at present. This will address the problem of cosmic-ray propagation in the galaxy and how the source spectrum is related to the observed spectrum. Is the source spectrum really a power law with differential spectral index $\alpha \approx 2.1$, as expected from theory of diffusive shock acceleration?

## B Extragalactic cosmic rays

The principal experimental goal is to increase the aperture for large events in order to accumulate sufficient statistics to clarify the origin of the highest energy cosmic rays. The AGASA experiment accumulates events with $E > 10^{20}$ eV nominal energy at a rate of one to two per year. Based on the spectrum measured by AGASA [72] the corresponding rate for the Hi-Res Fly's Eye [97], which is now running, should be $\approx 8$ events/yr, after taking account of the duty factor for the fluorescence technique, which is of order 10%. The Auger detector [98], now under construction in Argentina with an aperture of $\approx 7000$ km$^2$sr, would increase this to approximately 60/yr. The proposed Telescope Array of fluorescence telescopes [99] would have a similar effective aperture and rate, as would the proposed Northern Auger detector.

Another objective for the stereo Hi-Res Fly's Eye experiment will be to study the spectrum over a long range of energy (from $< 10^{18}$ to $> 10^{20}$ eV) to clarify the evidence for a transition from a galactic to an extra-galactic population of cosmic rays.

The next big step in increased aperture for detection of giant air showers would come from the proposed fluorescence detectors in space. The Extreme Universe Space Observatory [100] is under study for deployment on the Space Station. It would aim for event rates an order of magnitude higher than the largest ground-based detectors above $10^{20}$ eV. A free-flying OWL detector [101] with an optimized orbit could expect to accumulate events at an even larger rate.

High-energy gamma-ray emitters such as AGN and GRB may also be sources of ultra-high energy cosmic rays. If so, then they might be sources of high energy neutrinos as well. In the simplest case the relation would be through production of pions by hadronic interactions in or near the source. A discussion of the possible relationship between extragalactic cosmic rays and $\gtrsim$ TeV neutrinos is presented elsewhere [74] (see also Ref. [102]). Halzen [103] has reviewed the subject of high energy neutrino astronomy at this conference. Detectors are operating or proposed for deep underwater sites and deep in the Antarctic ice. In addition to such dedicated neutrino telescopes [104], the largest air shower detectors may also have significant aperture for neutrinos with $E > 10^{19}$ eV [105], such as might be radiated from topological defects [85].

In the long run, the goal would be to identify specific sources of cosmic rays, both galactic and extragalactic, and to see photons, neutrinos and even gravitational waves that might be associated with them.

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