But there is no Vulcan, and that problem was solved in an entirely unexpected way by Einstein's general theory of relativity. That theory gave a language to talk about a much larger world than that of the Ancients or of Newton's World System – but that, as the bartender said to Irma, is another story.

Suggestions for further reading, references and footnotes

The theme of this presentation has been so well studied for so long that excellent sources are available in plenty. Only a very select set of possible references will therefore be presented here.

1. This figure is taken from Hanbury-Brown, R., *The Wisdom of Science – its relevance to Culture and Religion*, Cambridge University Press, 1986, p. 43.
2. Giorgio Abetti, *The History of Astronomy*, Sidgwick and Jackson, London, 1954; Arthur Berry, *A Short History of Astronomy*, Dover, New York, 1961; Mathews, P. M., 'Galileo and Kepler – Precursors of Newton', in Proceedings of the Seminar on '300 Years of Newton's *Principia*' (eds Shrivastava, S. K. and Mukunda, N.), ISRO–IISc Space Technology Cell, Indian Institute of Science, Bangalore, 1986.
3. Taken from Brown–Hanbury, R. ref. 1 above, p. 46.
4. Abetti, G. ref. 2 above, p. 70.
5. Richard S. Westfall, *The Life of Isaac Newton*, Cambridge University Press, 1993, p. 39.
6. Richard S. Westfall, ref. 5 above, ch. 8.
7. In this connection, see the highly interesting account given by D. Speiser, '*Newton's Principia*', CERN Report 80–02, 25th February 1980, CERN, Geneva, Switzerland.

Origin of the highest energy cosmic rays*

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After briefly recalling the history of discovery of cosmic rays, the present status of the subject is discussed. Cosmic-ray particles with energy exceeding 10^{20} eV have been detected. The origin of cosmic rays remains an unsolved problem in physics and astrophysics. The nature of the source(s) as well as the physical mechanism(s) responsible for endowing the cosmic-ray particles with extremely high energies are not known with certainty. We discuss some recent ideas in this context with special emphasis on the problem of origin of the highest-energy cosmic rays.

1. A brief history of cosmic rays

The story of the discovery of cosmic rays forms one of the most fascinating episodes of the history of science in the very early part of the current century. It is hard to associate the discovery of cosmic rays entirely with any one single experiment. Indeed, a number of remarkable experiments performed by a number of adventurous physicists, many of whom were tantalizingly close to the 'discovery', preceded the actual announcement of the discovery. A nice account of this history is given in the book by Pomerantz[1] which forms the basis of the historical aspects of the subject described in this section.

The Austrian physicist Victor Hess announced his discovery of 'an extra-terrestrial source of penetrating radiation' in 1912 after a series of heroic balloon-borne experiments performed by him over the previous one year. The 'penetrating radiation' was later christened 'cosmic rays' by Robert Millikan in 1926. The word *extra terrestrial* is important here, for it was well known at the time of Hess's experiments that our own Earth is also a source of 'penetrating radiation' due to natural radioactivity of soil and various rocks.

Natural radioactivity was the 'in' physics in the closing years of the nineteenth century and the early years of the twentieth century. Within a year of the discovery of X-rays by Röntgen in 1895, Becquerel discovered natural radioactivity (in 1896). Even before the discovery of radioactivity, experiments with gold-leaf electroscope, an instrument that could measure the presence of free electric charges (i.e. ionization) in a medium, and which played a major role in the history of discovery of cosmic rays, showed presence of leakage currents associated with ionization in sealed containers even in apparent absence of any obvious ionizing source; the leakage current seemed to correspond to an average rate of formation of ions of ~ 10 ions/cm^3/sec. This ionization was naturally attributed to the presence of 'radioactive material' in air and in soil. As revealed by later experiments, this conclusion was largely correct, but not entirely so!

In 1898 Rutherford established two different kinds of radioactive emissions: (i) α-rays and (ii) β-rays. The α-rays were found to be of high ionizing capacity, easily absorbable in media (range ~ few cm), and were later identified as the nuclei of ^{4}He atoms. The β-rays, in

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contrast, were more penetrating, and were quickly identified as electrons. In 1900 Villard discovered γ-rays, which were found to be very penetrating. The γ-rays suffered no deviation in external magnetic fields, which revealed their electrically neutral nature. (It was much later, in 1914, that Rutherford and Andrade were able to identify γ-rays as highly energetic electromagnetic radiation by observing reflection of γ-rays from crystal surfaces.)

In the meantime, experiments performed on the ground as well as underground continued to show the presence of leakage currents associated with ionization. Physicists like C. T. R. Wilson, E. Rutherford and many others were involved in these experiments. McClennan and others performed experiments on sea. In 1910 the Italian physicist Pacini made detailed analyses of the data of several earlier ground-based as well as sea-based measurements of residual ionization of air, and concluded that it was hard to attribute the observed residual ionization entirely to the known radioactive substances.

Was the observed residual ionization caused entirely by Earth's natural radioactivity? To settle this question an obvious experiment to do would be to measure the level of ionization of air high up in the atmosphere where the effects due to Earth's radioactivity should diminish. Such an experiment was performed by the German Jesuit Fr. Wulf in 1910. He measured a rate of ionization of ~ 6 ions/cm^3/sec at ground level at Paris, and about 64% of this value when measured on top of the Eiffel Tower (~ 300 m above the ground). At the time of Wulf's experiment, γ-rays were the most penetrating form of radiation known, and any ionization associated with Earth's radioactivity at such a height was expected to be essentially due to γ-rays. However, Wulf's measured value of the rate of ionization on top of the Eiffel Tower was about 6.4 times more than what was expected on the basis of the then known attenuation properties of γ-rays in air. On the basis of these measurements Wulf concluded that there might exist another γ-ray source in the upper atmosphere(!), or, that the γ-ray absorption coefficient in air might be actually smaller than the then not-so-well known value. In retrospect, we thus see that Wulf was indeed very close to 'discovering' the cosmic rays.

It was, however, left for Hess to take the crucial step of measuring the variation of ionization *as a function of altitude.* Hess's experiments consisted of carrying a charged electroscope in an open gondola flown by a balloon filled with hydrogen – physically a rather dangerous experiment! Hess attained a height of about 1000 m in 1911 and finally ascended to about 5300 m in the following year. What Hess found was that the ionization inside his sealed electroscope first decreased with altitude, but then started to increase beyond a height of ~ 800 m, and continued to increase steadily to the highest altitudes attained by him. Hess also made separate measurements of γ-ray absorption in air using an intense radium source which showed that γ-rays from ground were completely absorbed at a height of ~ 500 m from the ground. Hess's analysis of his data was unambiguous – it pointed towards the '... presence at great altitudes of previously unknown matter or ... of an extra-terrestrial source of penetrating radiation', a discovery for which Hess was awarded the Nobel Prize in 1936. A balloon ascent to a height of 9300 m by the German physicist Kolhörster in 1914 confirmed Hess's conclusions. The outbreak of the World War I in 1914 stopped further balloon flights until around 1922 when Robert Millikan and his coworkers in the USA undertook further balloon-borne experiments.

Millikan's initial results seemed to be contradictory to Hess's. In fact, in 1924, Millikan announced that there were 'no such penetrating radiation'. But in 1926, after a series of careful measurements of the ionization level over snow-fed lakes at different altitudes above the sea level, Millikan was finally convinced that 'very hard etherial rays of cosmic origin were entering the earth uniformly from all directions'. Together with G. H. Cameron, Millikan went one step further; based on the prevailing (wrong!) notion at the time, that the 'penetrating radiation' responsible for the ionization of air consisted of very high-energy γ-rays, and by extrapolating the known penetrating power of low-energy γ-rays to very high energies, they tried to derive the spectrum of these cosmic 'γ-rays'. Their derived 'γ-ray' spectrum seemed to consist of discrete monoenergetic components corresponding to the binding energies of nuclei of some common elements like C, N, O, Na, Mg, etc. This, together with the fact that the process of formation of any element (starting with hydrogen as the basic element) would be expected to be associated with release of the nuclear binding energy corresponding to that element, led Millikan to conclude that cosmic rays represented 'the birth cries' of elements in 'the depths of space'. Indeed, because of this supposed 'cosmic' connection, Millikan referred to the penetrating radiation as 'cosmic rays'. In retrospect, we now know that the assumption of Millikan and Cameron that cosmic rays were γ-rays, was wrong, and so was their conclusion about the implied relationship of cosmic rays with element formation process.

We now know that cosmic rays are mostly electrically charged particles, *not* γ-rays. This came about with the discovery of the so-called latitude effect, published in 1927 by the Dutch physicist J. Clay, according to which, the cosmic ray intensity was systematically less near the equator than at higher latitudes. This could be adequately explained only if the cosmic-ray particles were assumed to be electrically charged particles. For in that case, the particles, being of extraterrestrial origin, would encounter greater difficulty in reaching the Earth's surface near the equator where the Earth's magnetic field lines are nearly parallel to the surface, than they would near the poles where the magnetic field lines are almost vertical.

In 1930s the distinction between the *primary* and the *secondary* cosmic rays was established. The primary cosmic rays (consisting mostly of protons, and with a lesser abundance, nuclei of other heavier elements like helium, carbon, nitrogen, etc.), striking the top of Earth's atmosphere from outside at relativistic velocities interact with the air atoms in the upper atmosphere and generate a lot of other secondary particles. Indeed, the residual ionizations measured in the early experiments that led to the discovery of cosmic rays were mostly due to the secondary (and higher generation) electrically charged particles originating from the interaction of primary cosmic-ray particles in the upper atmosphere. The primary cosmic-ray particles can be directly measured only by experiments at those high altitudes at which there is practically no residual atmosphere above the detector, which correspond to heights (above the sea level) of ~ 40 km and above. Knowledge about the primary cosmic rays has been obtained by means of these high-altitude balloon-borne (and, of course, unmanned!) experiments. Satellites and space probes have also added to our knowledge of the spectrum and composition of the primary cosmic rays.

In the next section we briefly review our current knowledge of some of the general characteristics of the observed cosmic rays, in particular, their energy spectrum, flux, and composition. There are a large number of reviews and monographs on cosmic rays giving details. For a recent review and references, see, Drury[2]. In §3 we discuss the question of origin of cosmic rays, highlighting the problems posed by recent experimental results on the extremely high energy cosmic rays (having energies in excess of 10^{20} eV). In §4 we discuss the recent idea of their having a fundamentally different origin (*vis-à-vis* the lower-energy cosmic rays) in the sense that they may not be produced by any astrophysical acceleration mechanisms (that are believed to be responsible for producing the lower energy cosmic-ray particles) but rather by some non-acceleration process, one example of the latter being production of energetic particles from decay of massive particles released in the process of collapse or annihilation of cosmic topological defects like monopoles, cosmic strings, etc. We summarize our discussions in §5.

2. General characteristics of the observed cosmic rays: Composition and energy-spectrum

As mentioned above, the cosmic rays that reach the Earth's surface are the byproducts of interactions of the *primary* cosmic rays (that strike the top of Earth's atmosphere) with the air nuclei. In the following, by cosmic rays we will always mean the primary cosmic-ray particles unless explicitly stated otherwise.

The cosmic rays are mainly composed of nuclei of common elements such as H, He, C, Fe and so on, constituting almost 98% of the total composition; the rest are mainly electrons. There is also a small percentage of positrons and antiprotons, which are mostly, if not entirely, of secondary origin resulting from interactions of the galactic cosmic-ray particles with the interstellar medium. The composition of cosmic rays is different in different ranges of energy. Up to ~ 10^{12} eV, the nuclear component (often referred to as the 'hadronic' component) of cosmic rays is dominated by protons (p) (about 87%), followed by the He nuclei (α) (about 12%), and heavier nuclei like those of C, Fe, etc. (about 1%). The mean abundances of various elements in cosmic rays are roughly the same as the average 'cosmic abundances' of these elements, although there are important differences for certain elements; these differences are, however, well-understood in terms of spallation of some of the heavier nuclei into lighter nuclei in collision with the material in the interstellar space. At TeV (10^{12} eV) and PeV (10^{15} eV) energies, the composition is roughly 50% protons, 25% α-particles, 13% C, N, O and 13% Fe. The measurement of the composition at higher energies becomes increasingly difficult since the flux of cosmic rays at energies above ~ 10^{15} eV is so low that direct measurements are not possible – one has to take recourse to methods such as extensive air-shower techniques (see below).

The kinetic energy of the hadronic component ranges from about 0.1 GeV per nucleon (1 GeV = 10^9 eV) to extremely high energies ~ 10^{20} eV and more per nucleus. (The composition of cosmic rays at the highest energies is not known with certainty; so the measured energy at high energies is usually given in terms of energy per nucleus as opposed to energy per nucleon used at low energies where the composition is known.) Between ~ 1 GeV and ~ 10^{15} eV, the differential energy spectrum of the hadronic component is roughly a power-law, $\propto E^{-\alpha}$, with α lying between roughly 2.5 and 2.7. Below about 0.1 GeV, the spectrum drops off sharply because the magnetic field carried by the solar wind blowing out from the Sun sweeps these low-energy particles away from the inner solar system, thereby reducing the intensity of these low-energy particles on Earth significantly. This phenomenon is called 'solar modulation', which is stronger at sunspot maximum than at sunspot minimum.

At about 10^{15} eV, the spectrum steepens to a power-law with $\alpha \sim 3.2$. This is believed to be due to relatively large (compared to the thickness of the galactic disk) gyro-radius of the lighter cosmic-ray particles in the

~ 10^{-6} G magnetic field of our Galaxy. In other words, the galactic magnetic field is unable to contain the more energetic but lighter cosmic-ray particles (protons) within the galactic disk. Thus the overall flux decreases and at the same time the composition of cosmic rays changes towards a relatively higher abundance of heavier nuclei for which the magnetic containment within the Galaxy is relatively more effective, the gyro-radius being smaller for a heavier particle. Above an energy of about 10^{18} eV, the spectrum changes slope again, this time becoming less steep, with $\alpha \sim 2.6$ again. Recent measurements seem to indicate that the composition changes back to dominance of lighter particles over heavier ones. These 'ultra high-energy' (UHE) particles are so energetic that the galactic magnetic field would be too weak to contain them within the Galaxy, and therefore, these particles are believed to be mostly of extragalactic origin. This cosmic-ray spectrum is now known to extend to at least ~3×10^{20} eV. This is almost a macroscopic amount of energy, all of which is essentially in the form of kinetic energy. In other words, the particles have been somehow accelerated to speeds almost that of light. Where do these UHE cosmic-ray particles come from and how do they attain such high energies? These remain some of the unresolved issues in physics and astrophysics of cosmic rays. We shall return to these issues in the next two sections. For the moment, we continue with our discussion of the general characteristics of the observed cosmic rays.

The integral particle flux in cosmic rays, i.e. the total flux of particles above a given energy E, is about 1 particle/cm^2/sec at $E \sim 10^{10}$ eV; about 1 particle/m^2/year at $E \sim 10^{17}$ eV; and about 1 particle/km^2/century at the highest energies. The particle flux is thus a steeply falling function of energy (see Figure 1). Nevertheless, since the particles themselves are very energetic, the total energy density in the form of cosmic rays in the universe is ~ 1 eV/cm^3, which is comparable to, e.g. the total energy density in the form of starlight (~ 0.6 eV/cm^3), or that in the form of galactic magnetic field (~ 0.2 eV/cm^3). Thus cosmic rays constitute an important component of the total energy budget of the Universe.

Since the intensity of cosmic rays is a steeply falling function of energy, it becomes increasingly difficult to measure directly the charge and energy of cosmic rays as energy increases. Indeed, the particle flux of cosmic rays at energies above about 10^{15} eV is so low that balloon- and satellite-borne experiments become impractical; they have too little effective detector area to capture sufficient number of cosmic ray events for measuring the spectrum. Fortunately, at high energies, another method becomes available. This is the method of extensive air shower (EAS), discovered by the French physicist Auger and his group in the 1930s. When a high-energy primary cosmic-ray particle (say, a proton) strikes an air atom (more specifically, say, a nitrogen or an oxygen atom) in the atmosphere, it creates a lot of secondary particles through high-energy nuclear interactions. The energetic secondary particles, in turn, further interact with other air atoms and generate tertiary particles, and so on, until the energies of the created particles fall below the threshold for the relevant multiparticle production processes. The high-energy multiparticle production processes are typically 'forward' processes, i.e. the daughter particles are produced with their momentum vectors confined within a narrow cone whose axis lies along the momentum vector of the parent high-energy particle. Moreover, the daughter particles all travel with more or less the same relativistic speed. Thus, at any time, the particles' positions lie on a thin disk, which thus propagates down the atmosphere with relativistic speed and can even reach sea level, typically if the energy of the primary particle exceeds ~ 10^{15} eV. The 'disk', whose radius can be several hundred metres, can contain several millions of particles (mostly electrons and photons) depending on the energy of the primary particle that initiates the shower. The shower particles can be sampled and detected by an array of particle detectors placed several metres apart on the ground, each detector covering an area of a few square metres.

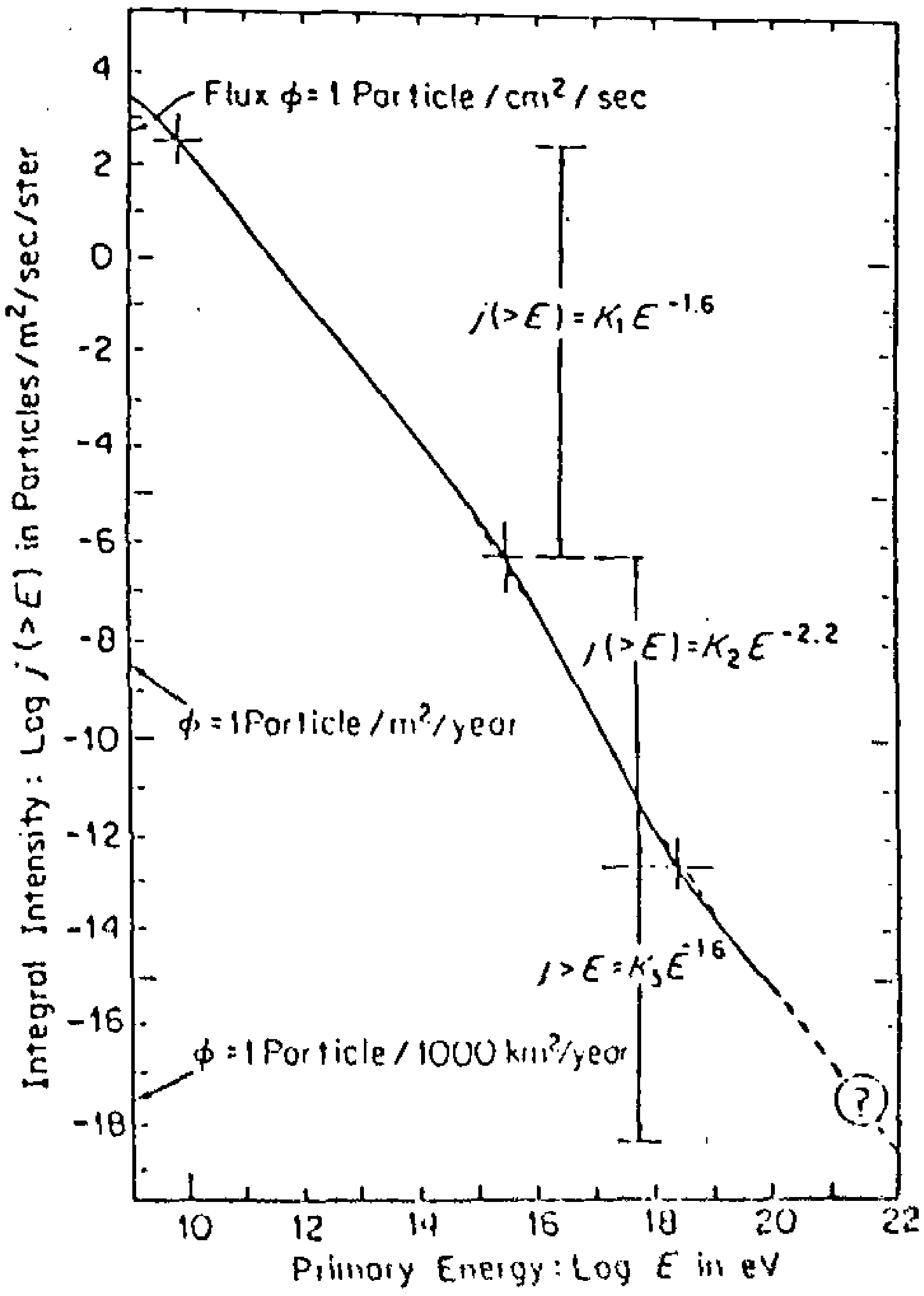

Figure 1. Integral energy spectrum of primary cosmic rays (from ref. 1).

(The total area covered by the array can, in principle, be as large as desired, say, hundreds or even thousands of square kilometers, although there are practical problems in building very large arrays.) From the measured difference in the arrival times of the shower particles at different locations on the ground, the inclination of the disk axis to the vertical direction can be worked out, thereby giving information on the arrival direction of the primary particle. The energy of the shower-initiating primary particle can be worked out from the measured profile of the density of the shower particles on the ground.

The method of EAS has been employed by various experimental groups to arrive at the spectrum of cosmic rays to extremely high energies, exceeding 10^{20} eV (refs 3–10). The filled circles in Figure 3, for example, represent the so-called UHE (i.e. with energy $E \geq 10^{18}$ eV) cosmic-ray spectrum as measured by one of the experiments, namely, the Fly's Eye experiment[7]. Similar spectra have been obtained by other experiments (see refs 3, 4 for more details). These experiments show that the cosmic-ray spectrum does indeed extend to such high energies (albeit with steeply falling intensity as energy increases) *without any indication of a upper cut-off in energy in the spectrum*, at least up to the highest energy ($E \sim 3 \times 10^{20}$ eV) detected so far for a cosmic-ray particle. This has important implications for possible sources and the underlying acceleration mechanisms responsible for producing these extremely high-energy particles, which we shall discuss in the next two sections. The composition of these extremely high-energy cosmic ray particles is also not well determined. However, recent results of one of the experiments, namely, the Fly's Eye experiment[7] indicate that the composition is dominated by heavy nuclei (most probably Fe) from energy $E \sim 10^{17}$ eV to $E \sim 5 \times 10^{18}$ eV at which there is a dip in the spectrum accompanied by a change of composition from 'heavy' to 'light' (probably proton, or, possibly even photon).

3. Origin of cosmic rays

The question of origin of cosmic rays consists of two distinct yet interrelated questions: (a) what powers the 'engine' that endows the cosmic-ray particles with the enormous energies that some of them evidently possess? (b) what is (are) the source(s) of these particles? The conventional view is that origin of cosmic rays is linked to some of the most energetic phenomena in the universe represented by active objects like supernova explosions, pulsars, quasars, active galactic nuclei, radio galaxies, and so on. The consensus seems to be that cosmic rays with energy at least up to $\sim 10^{15}$ eV are of galactic origin, i.e. their sources reside within our Galaxy. However, the charged cosmic-ray particles on their way to earth from a given source are repeatedly scattered and bent by the non-uniform magnetic field of our Galaxy. There is thus, in general, no simple relationship between the arrival direction of the particle at earth and the original direction in which it is ejected from the source. It is, therefore, not possible to trace the source(s) of these cosmic rays to any specific object(s) in the sky. Nevertheless, it is possible to gauge the nature of the potential sources from simple considerations of energetics: The power output of any candidate source must be larger than the power represented by the observed flux of cosmic rays, a rough estimate of the latter being $\sim 10^{34}$ W (see ref. 2 and the references therein). It is widely believed that cosmic rays up to an energy of $\sim 10^{15}$ eV are linked with supernova explosions. The arguments are as follows: A typical supernova explosion releases $\sim 10^{44}$ J of mechanical energy; on the average one supernova explosion occurs in a typical galaxy in about every 30 years (although none has occurred in our own Milky Way since Kepler's supernova of 1604!). Thus the power output in a typical supernova is $\sim 10^{35}$ W. Therefore, a supernova origin of the bulk of cosmic rays requires that roughly about 10% of the energy output of the supernova be used in some kind of acceleration process that boosts low-energy charged particles to the very high energies observed in cosmic rays.

How exactly the acceleration process might work is a subject of considerable complexity and is beyond the scope of this article. Very briefly, essentially all the acceleration mechanisms proposed in this context are variants of a basic idea originally due to Fermi[11]. In Fermi's original mechanism, charged particles are accelerated by repeated collisions with moving 'magnetized clouds'; the macroscopic kinetic energy stored in the moving clouds is transferred to the particles through their repeated encounters with the clouds. Fermi's basic idea, with some important modifications, has been applied to acceleration of particles in a variety of realistic astrophysical situations, such as acceleration of particles in passing through moving shock waves generated by supernova explosions, acceleration in active galactic nuclei (AGN), in radio galaxies, and so on. A particularly successful mechanism, that is currently favoured by most theoretical cosmic-ray physicists, is the so-called 'diffusive shock acceleration mechanism' (see Drury[2] for a review and references to original literature). A major characteristic feature of all 'Fermi mechanisms' and, in particular, of the diffusive shock acceleration mechanism (DSAM), is that particles emerge from the acceleration site with spectra that are power-law in energy, like the observed cosmic-ray spectrum. The power-law index (α) of the spectrum is related to basically two characteristic time-scales in the problem, namely the acceleration time scale and the escape time scale, and is, therefore, calculable. The typical values of α in DSAMs satisfy $\alpha \geq 2$.

The DSAM is typically a slow acceleration process; the average energy of any particle increases gradually as the particle crosses the shock region back and forth many times. The particles are confined within the shock region by the magnetic field which, therefore, plays an important role in all variants of the Fermi mechanism. However, for a given strength of the magnetic field and for a given size of the shock region, as a particle's energy increases it becomes increasingly difficult to prevent the particle from escaping from the shock region. This prevents further acceleration of the particle. The process is therefore, self-limiting: For a given strength of the magnetic field (B) and for a given maximum size of the acceleration site (R), there is, in general, a maximum energy, $E_{\max}$, to which a particle of a given charge and mass can be accelerated. This severely restricts the candidate acceleration sites for the most energetic cosmic rays.

Apart from the slow Fermi acceleration mechanism, several fast or 'one shot' acceleration mechanisms have also been proposed, the chief example of which is acceleration in the induced electric field due to strong rotating magnetic field around pulsars. There are typically two major drawbacks of these kinds of fast acceleration scenarios, viz. (a) a power-law spectrum is not a characteristic feature of these acceleration mechanisms, and (b) the accelerated particles generally lose a lot of their energy in collision with particles of the dense electron–photon plasma that typically surround the high magnetic field regions around objects like pulsars.

The general relationship between the strength of the magnetic field (B) and the characteristic linear dimension of the acceleration region (R) for a variety of astrophysical objects which are suspected to be potential sites of particle acceleration is shown schematically in Figure 2. It is seen that protons or iron nuclei can, in principle, be accelerated to $E \sim 10^{20}$ eV, the most favoured candidate site for acceleration to this energy being the lobes of radio galaxies[12], although active galactic nuclei are also possible sites. Acceleration to energies significantly beyond 10^{20} eV is difficult as we run out of possible known astrophysical objects that would have the right combination of magnetic fields and linear sizes.

When numbers for B, R and the characteristic shock velocity β are put in, it is found that energies up to the 'knee' (i.e. up to energy $\sim 10^{15}$ eV) can be reasonably well achieved by acceleration in shocks associated with supernova remnants (SNRs). For higher energies, SNRs fail, and other sources must be invoked for the rest of the spectrum. As already mentioned in §2, the spectrum beyond $\sim 10^{15}$ eV is steeper than the one below it; it is also dominated by 'heavies' (probably mostly iron nuclei) up to an energy $\sim 5 \times 10^{18}$ eV at which the spectrum becomes flatter and the composition changes to 'light' particles (probably mostly protons). The steep heavy component beyond the 'knee' and up to $\sim 5 \times 10^{18}$ eV is interpreted as a second galactic component whereas the flatter and 'lighter' component beyond $\sim 5 \times 10^{18}$ eV (i.e. the UHE spectrum) is thought to be of extragalactic origin for the reasons that the gyro-radii of these energetic particles in the galactic magnetic field would be much larger than the size of the Galaxy itself. The heavy galactic component between $\sim 10^{15}$ eV and $\sim 5 \times 10^{18}$ eV is thought to be associated with accelerations in pulsar magnetospheres. This may be because pulsars are thought to be formed in supernova explosions, and so the 'fine-tuning' problem of matching of the two components in terms of their 'amplitude' at the 'knee' may be explained in a natural way. However, the precise way this may come about remains uncertain.

The general view is that UHE component is of extragalactic origin. There are, however, stringent constraints on the distances of the possible sources of these UHE cosmic rays. A proton of energy above $\sim 5 \times 10^{17}$ eV is above the threshold for electron–positron pair creation in collision with photons of the universal 3 K thermal microwave background that is known to pervade the whole universe. Above an energy of $\sim 6 \times 10^{19}$ eV a proton in collision with a microwave background photon is even above the threshold for photo-pion production reaction. Both the above mentioned processes are significant energy-loss processes for any UHE proton propa-

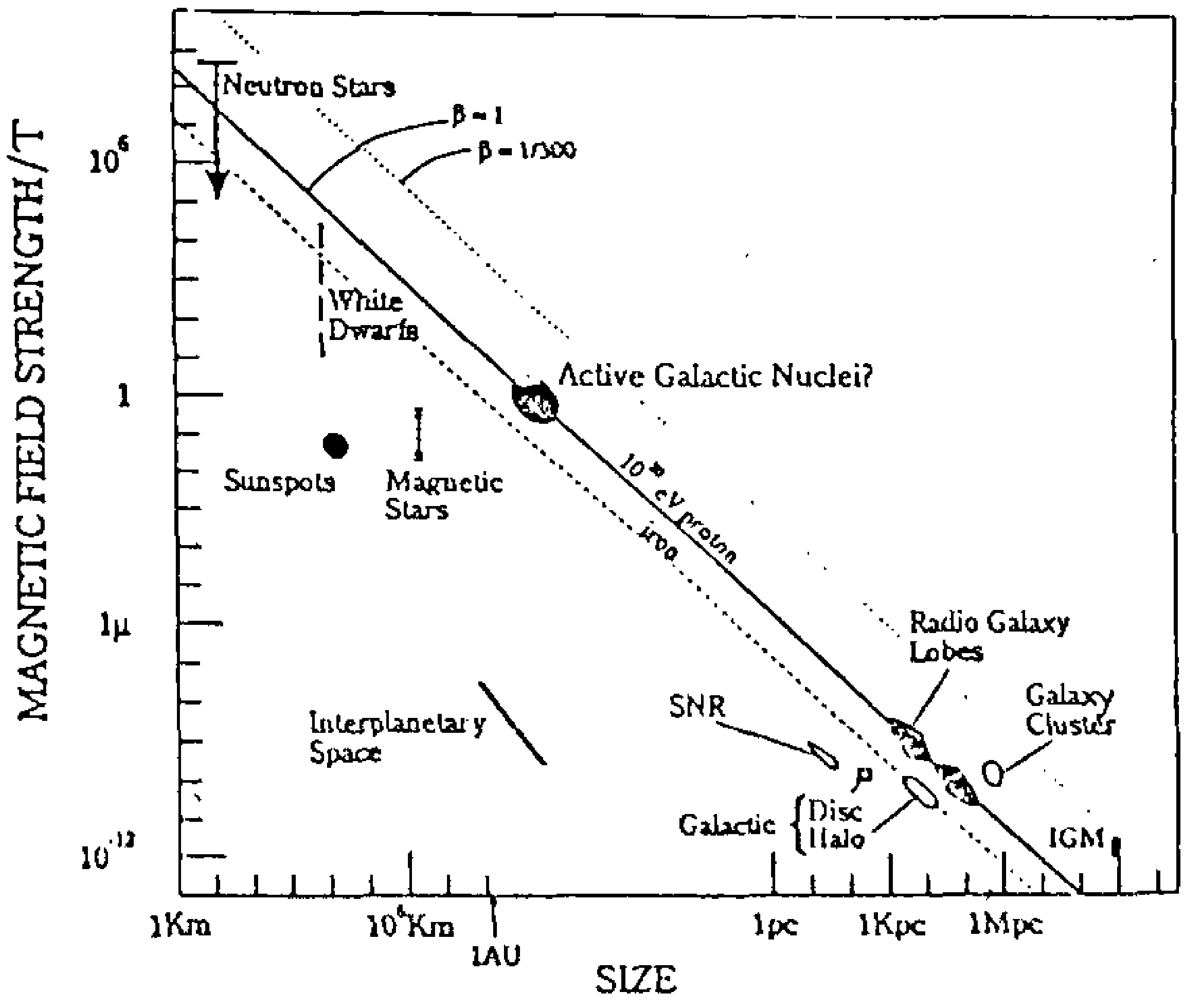

Figure 2. Magnetic field strengths and typical linear dimensions for various astronomical objects, some of which are potential sites for acceleration of cosmic rays. For illustration, the restrictions on the possible astronomical objects that can in principle accelerate protons to 10^{20} eV are indicated. Only objects on, or to the right of, the solid diagonal line can accelerate protons to 10^{20} eV for relativistic characteristic shock velocities ($\beta = 1$). The dotted line marked $\beta = 1/300$ indicates the limit if the shock velocities are only ~ 1000 km s^{-1}. The applicable restrictions on the possible astronomical objects that can accelerate iron nuclei to 10^{20} eV are also indicated (from Drury[4]).

gating from an extragalactic source to us. The photo-pion production process is in fact a rather drastic energy-loss process for extragalactic UHE protons; it puts an upper limit to the distance of any extragalactic source from which a proton of a given energy at source can reach us with a given remaining energy. Indeed, soon after the discovery of the 3 K thermal background radiation by Penzias and Wilson in 1965, Greisen, and independently Zatsepin and Kuz'min[13] suggested in 1966 that the UHE cosmic-ray spectrum, if it is truely extragalactic in origin, should show a cut-off at some high energy somewhere around 10^{20} eV. This predicted cut-off in the UHE cosmic-ray spectrum is now-a-days called the Greisen–Zatsepin–Kuz'min (GZK) cut-off. A similar cut-off is predicted if the UHE particles are heavy nuclei such as iron nuclei; there the relevant process is the photo-disintegration of the nuclei in collision with the 3 K photons.

Whether the measured UHE cosmic-ray spectrum indicates a true GZK cut-off remains unclear. The problem is accentuated by the recent detection of an event with $E \sim 3 \times 10^{20}$ eV by the Fly's Eye experiment[7,8] and an event with $E \sim 2 \times 10^{20}$ eV by the Akeno experiment[9,10]. The Haverah Park experiment[5] as well as the Yakutsk experiment[6] had also earlier reported events with energy $\sim 1 \times 10^{20}$ eV. It has been recently shown[14,15] that a proton detected with an energy $\sim 3 \times 10^{20}$ eV could not have come from a source at a distance of more than about 60 Mpc (1 Mpc $\simeq 3 \times 10^{24}$ cm). Moreover, at this energy, a charged particle should not be deflected by the intergalactic and the galactic magnetic fields by more than $\sim 10°$ (ref. 14). The implication is that the source of the 3×10^{20} eV event should essentially lie within a distance of about 60 Mpc from us and it should be within a cone of angular radius $\sim 10°$ centered around the measured arrival direction of the event. Yet, when a source-search for this event was made in the sky[14,15], no potential source such as any active galactic nucleus, radio galaxy, etc. satisfying the above restrictions on the distance and positional direction was found! The highest-energy cosmic ray event, therefore, constitutes a puzzle: Here we have a particle so energetic that its essentially undeflected trajectory should allow us to more or less directly trace its sources back in the sky (unlike the case for lower energy particles which suffer random deflections due to the magnetic fields enroute). However, no suitable source is found when the trajectory is traced back!

In the next section we discuss the possibility that the highest-energy cosmic rays (HECR), i.e. the cosmic rays with energies above 10^{20} eV constitute a new component perhaps of an entirely different origin. It is even possible that the HECR particles are not connected with any acceleration process associated with any known astrophysical object, an exciting possibility that has received a great deal of attention in recent years and to which we now turn.

4. The highest-energy cosmic rays: Possible non-acceleration origin

The existence of the HECR poses serious challenge for conventional DSAM that attempts to explain the origin of these particles in terms of accelerating them in special astrophysical situations, e.g. in relativistic shocks associated with AGNs, or in the lobes of radio galaxies. Acceleration in the latter is in principle capable of producing particles with energies as high as a few times 10^{20} eV although it requires the use of rather extreme (and perhaps somewhat unrealistic) values of parameters such as R, B, etc.

One alternative possibility is that the HECR particles have a more *fundamental* origin in the sense that they are *not accelerated* at all[14,16–18]. Instead, these particles may simply be the decay products of some sufficiently massive elementary particle species surviving from an early cosmological epoch. One attractive realization of this idea of *non-acceleration* origin[16,17] of HECR involves collapse and/or annihilation, in recent epochs, of cosmic topological defects (TDs)[19] such as magnetic monopoles, cosmic strings, domain walls, etc., which could be formed in the early universe during phase transitions associated with spontaneous breaking of symmetries implemented in unified models of elementary particle interactions such as in Grand Unified Theories (GUTs).

Owing to their topological stability, the TDs formed in the early universe can survive down to the present epoch. The TDs nevertheless are occasionally, and in certain circumstances, frequently, destroyed in physical processes like collapse or annihilation (see ref. 16 and references therein). When a TD is physically destroyed, the energy stored in the TD is released in the form of massive quanta of the fields that 'constitute' the TD, namely, the massive gauge and higgs fields (the 'X' particles) associated with the broken symmetry. The released X particles would then decay, essentially instantaneously, typically into fundamental particles like quarks and leptons. Hadronization of the quarks would then produce jets of hadrons containing mainly light mesons (pions) together with a small fraction ($\sim 3\%$) of nucleons (protons and neutrons). The γ-rays and neutrinos from the decay of the neutral and charged pions, respectively, would thus be the most abundant particles in the final decay products of the massive X particles. If the TDs under consideration were originally formed at a GUT energy scale, the mass m_x of X particles released from the TDs can be $\sim 10^{25}$ eV. The decay of the X particles released from the TDs can thus give rise to protons, neutrons, γ-rays and neutrinos with energies up to $\sim m_x$, very much higher than what can be achieved by astrophysical shock acceleration mechanisms. The cosmic ray particles can thus be produced directly in this scenario (referred to as 'TD model'), and no acceleration mechanism is needed.

The release of X particles from TDs may occur continually at all cosmological epochs after the formation of the TDs under consideration in the early universe. However, only the X particles released in relatively recent epochs are likely, if at all, to contribute to the present-day flux of UHE protons and γ-rays, because those released in the earlier epochs would have to traverse greater distances through the cosmic background radiation fields to reach us and would, therefore, lose significant fractions of their energy in collision with the photons of the background radiation. However, neutrinos can come from relatively earlier cosmological epochs because they suffer little energy loss as a consequence of their small cross section of interaction with the relevant particles of the background medium.

In the TD model, the shapes of the energy spectra of protons, γ-rays and neutrinos at production (i.e. the injection spectra) at any time are determined primarily by the physics of fragmentation of quarks into hadrons and not by any astrophysical parameters. At any given time, the injection spectra are, therefore, also independent of the specific kind of TDs responsible for release of X particles. Different kinds of TDs, however, evolve in different ways. Therefore, the absolute magnitude and the rate of production of the various particles, and so also the final evolved spectra, will be different for different kinds of TDs. However, in the highest energy regions, the shapes of the proton as well as γ-ray spectra become insensitive to the kind of TDs producing them, because to survive at these energies, the protons and photons must originate at relatively close (i.e. non-cosmological) distances for which the cosmological evolution is immaterial. The shape of the neutrino spectrum will, however, remain sensitive to the kind of TDs producing them and their cosmological evolution because neutrinos can propagate over large (cosmological) distance scales without much attenuation.

The injection spectra of nucleons, γ-rays, and neutrinos in the TD model have been calculated[16,17,20] by extrapolating the available models of hadronization of quarks as described by the theory of Quantum Chromo-Dynamics (QCD) to extremely high energies. This gives approximately power-law differential injection spectra for nucleons, γ-rays and neutrinos all with a power-law index $\alpha \sim 1.3$. However, there is a great deal of uncertainty involved in extrapolating the low-energy QCD-based models of hadronization of quarks to extremely high energies involved in the present situation. It is also possible that the value of α for nucleons may be somewhat different from that for, say, γ-rays. The main point, however, is that the injection spectra of cosmic ray particles in the TD model can, in principle, be considerably *flatter* than in the standard shock acceleration scenarios which, by and large, produce differential injection spectra with $\alpha \geq 2$.

The typical shapes of the final proton, γ-ray and neutrino spectra, including the effects due to propagation through the extragalactic medium, are shown in Figure 3. This figure was obtained for a specific TD model, namely, that involving annihilation of magnetic monopole–antimonopole pairs[21]; however, as explained above, the spectra have more or less a universal shape independent of the specific kind of TD-process one considers, especially at the highest energies, and hence the spectra shown in Figure 3 are representative of the particle spectra expected in TD models in general. One major uncertainty in this scenario is the absolute magnitude of the cosmic ray flux produced by TDs, i.e. the 'normalization' of the predicted flux. This clearly depends on the specific process of particle production involving specific kind of TDs. The normalization of the particle fluxes in Figure 3 implies a monopole abundance that is well below the stringent astrophysical

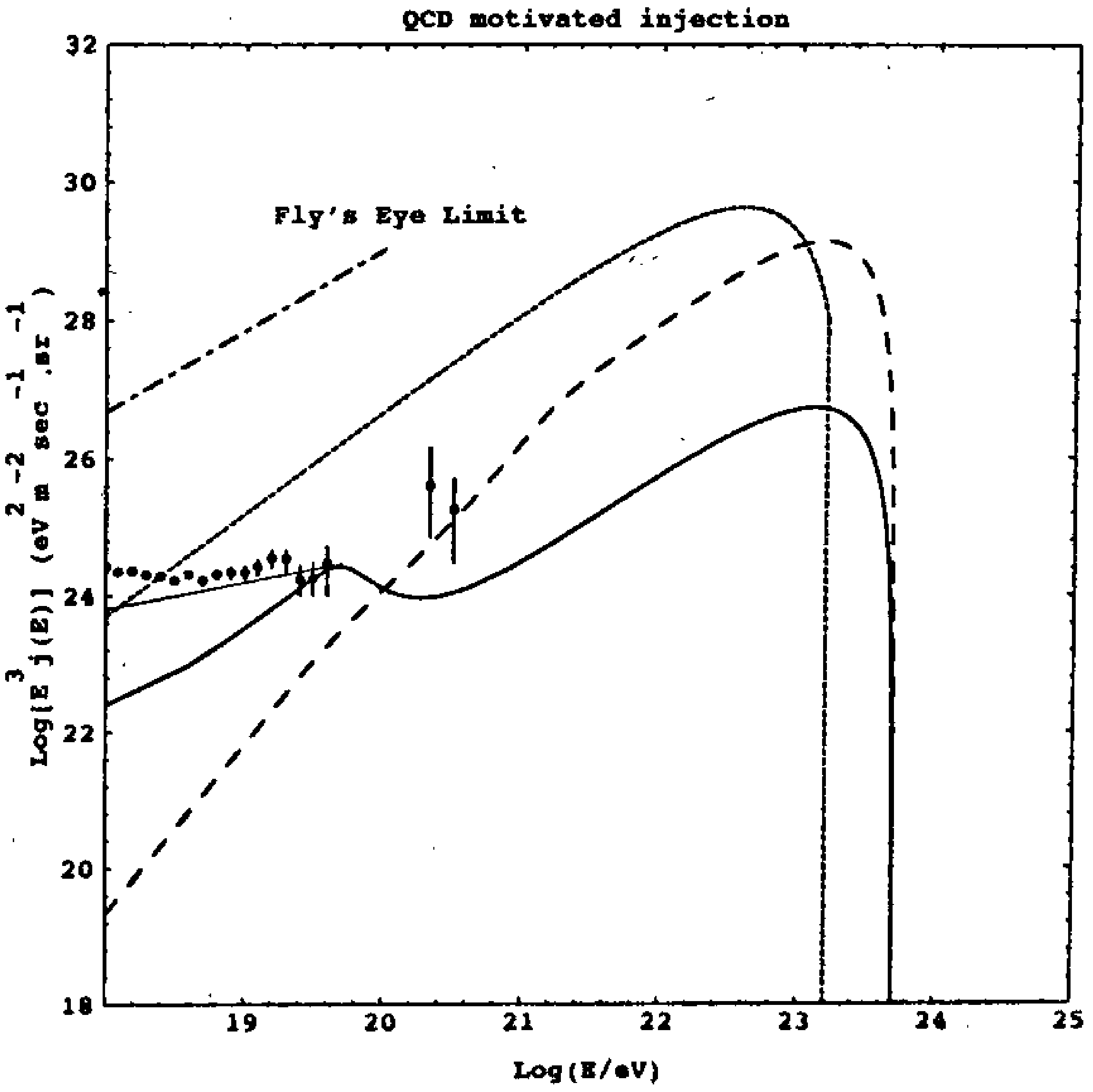

Figure 3. The proton (solid line), γ-ray (long-dashed line) and the neutrino (short-dashed line) spectra in the TD model including the effect of propagation through the cosmic background medium. The X particle mass is taken to be 10^{15} GeV and an extrapolation of QCD-based hadronization spectrum to the relevant high energies has been used to obtain the injection spectra. The combined proton and gamma ray flux has been normalized at $10^{19.7}$ eV to the 'extragalactic flux component' (thin solid line) (see ref. 7) fitted to the data from the Fly's Eye experiment (filled circles with error bars)[7]. Also shown (dash-dotted line) is an approximate limit on the neutrino flux determined from non-detection of deeply penetrating particles by the Fly's Eye detector.

upper limit on the monopole abundance – the so-called 'Parker limit' (see ref. 22) – and is, therefore, quite plausible.

From Figure 3 we see that TD models are probably not relevant for cosmic rays below about 5×10^{19} eV; it is only at energies above this energy that TD models become a viable option. It is to be mentioned here that the shape of the proton spectra in the acceleration models (not shown in Figure 3), which typically yield power-law injection spectra with index $\alpha \geq 2$, would correspond to a sharply falling curve at energies beyond $\sim 10^{20}$ eV, and so would be unable to explain the two highest energy events indicated in the figure. The 'dip' of the proton curve of Figure 3 beginning at $\sim 10^{20}$ eV and its subsequent 'recovery' at $\sim 10^{21}$ eV are characteristic features induced by the propagation effects (the GZK effect discussed in §3). The 'recovery' after the 'GZK cut-off' of the proton spectrum in Figure 3 is, however, a feature that is not shared by the proton spectra one gets in standard acceleration models, which as mentioned above, do not 'recover' after the GZK cut-off. (For detailed understanding of this point see, e.g. figure 1 of ref. 17.) The recovery in the present case is essentially due to flatter nature of the proton injection spectrum in the TD model compared to that in the acceleration models. Note also from Figure 3 that the two highest-energy events are naturally explained in the TD model only if these are γ-ray events, and not protons. Experimentally, it is hard to determine the composition of the events at these energies with full certainty. Although, the traditionally favoured composition for these events are protons, a γ-ray composition is certainly not ruled out[8].

Figure 3 also indicates a peculiar feature of the present HECR data: There is an apparent 'gap' in the spectrum; the two highest-energy events are separated from the rest of the data by almost half a decade in energy. Possible implications of this apparent 'gap' in the spectrum for theories of origin of HECR have recently been analysed[18] where it is concluded that although an acceleration origin of the HECR cannot be entirely ruled out with the current data statistics, the persistence of the apparent gap in the existing data at a quadrupled total exposure of the detector (as might be expected to be achieved within the coming few years) would rule out many acceleration models at more than 99% confidence level. In that case, one may have to take recourse to some kind of non-acceleration scenario for the origin of HECR like the TD model described above.

Besides the characteristic shapes of the HECR spectra, the TD models of HECR origin have two definitive predictions. Firstly, the HECR should consist of only 'fundamental' particles like protons, neutrons, γ-rays, neutrinos, electrons, positrons, and so on (and perhaps their antiparticles too), but definitely *no nuclei* such as ^{4}He or Fe. (There is no way hadronization of quarks would directly give rise to nuclei!) Secondly, the HECR should be highly rich in γ-rays and neutrinos. These predictions can be used as crucial tests of the TD model in future HECR experiments with large-area detector coverage, such as the proposed Pierre Auger project[23]. More details on the subject of topological defect scenario of origin of HECR can be found in refs 24, 25.

5. Summary and conclusions

We have discussed rather sketchily the present status of the subject of cosmic rays, the origin of which is one of the major unsolved problems in physics and astrophysics. There are reasons to believe that cosmic rays with energy up to the 'knee' region of the spectrum corresponding to the energy $\sim 10^{15}$ eV are produced by some kind of acceleration process operating in the relativistic shocks associated with supernovae, and those from about 10^{15} eV up to the 'ankle' region at $\sim 5 \times 10^{18}$ eV are produced by acceleration processes in pulsar magnetospheres. The sources of these components are thought to lie within our Milky Way Galaxy, although the highly tangled nature of the trajectories of these particles (caused by the non-uniform galactic magnetic field) prevents direct identification of these sources with the known supernova remnants and pulsars. The component beyond $\sim 5 \times 10^{18}$ eV is thought to be of extragalactic origin. As far as the highest-energy cosmic rays (i.e. those with energy above $\sim 10^{20}$ eV) are concerned, the known acceleration processes are found to be inadequate from the point of view of energetics. We have discussed a possible alternative *non-acceleration* scenario for the origin of this HECR component. This scenario involves new physics; in particular, it involves formation and destruction of cosmic topological defects in the form of cosmic strings, monopoles, etc. that are predicted in theories of early universe that bring together modern ideas of high-energy particle physics and the big-bang model of cosmology. The highest-energy end of the cosmic ray spectrum thus offers a probing ground for testing some of these new ideas.

We have skipped many issues that have important bearings on the question of origin of cosmic rays in general, such as the issue of isotropy of the observed cosmic rays, the possible important roles of γ-ray astronomy as well as neutrino astronomy in unravelling the mystery of cosmic rays, and so on. It is hoped, however, that the reader will get a general flavour of the outstanding open issues in modern cosmic ray physics, issues which undoubtedly constitute one of the most exciting areas of current research in contemporary physics, astronomy and astrophysics.

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1. Pomerantz, M. A., *Cosmic Rays*, Van Nostrand Reinhold, New York, 1971.

2. Drury, L. O'C., *Contemp. Phys.*, 1994, **35**, 231.
3. Nagano, M. and Takahara, F. (eds), *Astrophysical Aspects of the Most Energetic Cosmic Rays*, World Scientific, Singapore, 1991.
4. Proceedings of Tokyo Workshop on Techniques for the Study of Extremely High Energy Cosmic Rays, ICRR, Univ. of Tokyo, 1993.
5. Lawrence, M. A., Reid, R. J. O. and Watson, A. A., *J. Phys. G: Nucl. Part. Phys.*, 1991, **17**, 733; Watson, A. A., in ref. 3, p. 2.
6. Efimov, N. N. *et al.*, in ref. 3, p. 20; Egorov, T. A., in ref. 4, p. 35.
7. Bird, D. J. *et al.*, *Phys. Rev. Lett.*, 1993, **71**, 3401; *Astrophys. J.*, 1994, **424**, 491.
8. Bird, D. J. *et al.*, *Astrophys. J.*, 1995, **441**, 144.
9. Yoshida, S. *et al.*, *Astropart. Phys.*, 1995, **3**, 105.
10. Hayashida, N. *et al.*, *Phys. Rev. Lett.*, 1994, **73**, 3491.
11. Fermi, E., *Phys. Rev.*, 1949, **75**, 1169 (also Collected Papers, vol. II, pp. 655–666).
12. Biermann, P. L. and Strittmatter, P. A., *Astrophys. J.*, 1987, **322**, 643; Rachen, J. P. and Biermann, P. L., *Astron. Astrophys.*, 1993, **272**, 161.
13. Greisen, K., *Phys. Rev. Lett.*, 1966, **16**, 748; Zatsepin, G. T. and Kuz'min, V. A., *JETP Lett.*, 1966, **4**, 78.
14. Sigl, G., Schramm, D. N. and Bhattacharjee, P., *Astropart. Phys.*, 1994, **2**, 401.
15. Elbert, J. W. and Sommers, P., *Astrophys. J.*, 1995, **441**, 151.
16. Bhattacharjee, P., in ref. 3, p. 382.
17. Bhattacharjee, P., Hill, C. T. and Schramm, D. N., *Phys. Rev. Lett.*, 1992, **69**, 567.
18. Sigl, G., Lee, S., Schramm, D. N. and Bhattacharjee, P., *Science*, 1995, **270**, 1977.
19. Kibble, T. W. B., *J. Phys.*, 1976, **A9**, 1387; *Phys. Rep.*, 1980, **67**, 183; Vilenkin, A., *Phys. Rep.*, 1985, **121**, 263.
20. Aharonian, F. A., Bhattacharjee, P. and Schramm, D. N., *Phys. Rev.*, 1992, **D46**, 4188.
21. Bhattacharjee, P. and Sigl, G., *Phys. Rev.*, 1995, **D51**, 4079.
22. Kolb, E. W. and Turner, M. S., *The Early Universe*, Addison–Wesley, Redwood City, California, 1990.
23. Boratov, M. *et al.* (eds), *Cosmic Rays above 10^{19} eV, Nucl. Phys. (Proc. Suppl.)*, 1992, **B28**.
24. Bhattacharjee, P., in *Astrophysics and Cosmology* (eds Sinha, B. and Moitra, R. K.), Proceedings of International Conference on Astrophysics and Cosmology, Commemorating the birth centenary of Prof. M. N. Saha, Saha Inst. of Nuclear Physics, Calcutta, India, December 1993, Narosa, New Delhi, 1995, pp. 144–167.
25. Bhattacharjee, P., in *Non-Accelerator Particle Physics* (ed. Cowsik, R.), Proceedings of International Conference on Non-Accelerator Particle Physics, Bangalore, India, January 1994, World Scientific, 1995.

Is the Hubble flow a result of inverse cascade?*

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A few general characteristics of nonlinear open systems are described. A turbulent fluid is one such system which exhibits order by supporting structures in an otherwise random medium through the transfer of energy from small spatial scales to large spatial scales. The spatial distribution of energy so derived is found to account well for two disparate situations like the solar granulation and the rotation curves of galaxies. Encouraged by these successes, one wonders if the spatial distribution of energy at the largest scales, i.e. $V(L) \propto L$ has anything to do with the Hubble flow.

COHERENT structures, correlated motions and well-defined patterns are observed on a variety of spatial as well as temporal scales. Organized states of matter and motion can be seen in a convection cell, cloud complexes, a tornado, a cyclone, zonal flows on planetary surfaces, the Red Spot of Jupiter, convective flows on stellar surfaces, spiral patterns in galaxies, clusters of galaxies and perhaps ourselves. Figure 1 *a–c* represents distribution of clouds in the earth's atmosphere, of convective motions on the solar surface and of galaxies in clusters of galaxies. Could you tell one from the other? Figure 2 *a, b* represents the velocity vectors in a cluster of galaxies and on the solar photosphere. Both show converging and diverging flows. The usual interpretation for clusters of galaxies is infall of matter in the strong gravitational field of the unseen dark matter, whereas the solar photosphere acquires the same pattern due to the formation of fluid vortices. Can the vortices account for the flow patterns in clusters of galaxies? Is the invisible matter indispensable? In other words, do these organized states of matter and motion arise under equilibrium or non-equilibrium conditions? Is it substance and or style? Are these dissipative structures?

Our proposal[1-6] is that apparently disparate phenomena of (i) non-equilibrium motions on stellar surfaces, (ii) the large scale organization of matter, motion and magnetic field or in general the large scale structure of the universe have their origin in the inverse cascade of energy leading to self-organization in an otherwise nonlinear turbulent medium.

Novelties of non-equilibrium systems

Near equilibrium, a system, when perturbed, comes back

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