Cosmic Accelerators

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Abstract

A status report is given on our knowledge about the cosmic radiation, with particular reference to particles above 10^{18} eV. It is pointed out that there is strong evidence for the presence of iron nuclei - of Galactic origin - at energies to 10^{19} eV but that at higher energies extragalactic particles seem to be necessary. Despite strenuous efforts the manner in which the particles are accelerated - and where - is quite unclear.

1 INTRODUCTION

Cosmic rays were discovered by Viktor Hess in 1912 but the problem of their origin has proved to be a very difficult one to solve. The difficulty stems from the fact that the Galaxy possesses a rather tangled (and uncertain) magnetic field so that for the bulk of the particles their deflections destroy any knowledge about their starting points. It is only if the particles are protons (which do indeed predominate at 'low' energies - below about 10^{14} eV) that the deflections are small enough, for energies above about 10^{19} eV, so that Galactic sources might be identified. Specifically, using the well known equation pc = 300 Bρ, with pc in eV, B in Gauss and ρ in cm, we have a deflection of about 10° for a proton of energy 1.6 x 10^{19} eV in a typical Galactic field of 3 x 10^{-6} G from a source 1 kpc away.

In what follows, a brief description will be given of searches at low energies (E < 10^{10} eV) before turning to energies above 10^{18} eV.

2 ENERGIES BELOW 10^{10} EV

It is in this energy region where gamma ray astronomy comes to the rescue by giving information about average cosmic ray intensities along various lines of sight. The method is (deceptively) simple: the measured gamma ray intensity is divided by the column density of gas, the argument being that the bulk of the gamma rays are produced by cosmic rays interacting with the gas in the interstellar medium. Although there are difficulties, associated with discrete sources, the actual gas components (principally H, H_2, H^+ and He), and the division between electrons and protons (see [1]) it is generally agreed that the particles responsible for the gamma rays detected by satellite-borne spark chambers, are produced in the Galaxy. The gamma rays have energies in the range 3 x 10^7 to about 10^9 eV and the initiating particles are principally electrons to about 10^9 eV and protons (and heavier nuclei) to about 10^{10} eV. The Galactic, rather than Extragalactic, origin identification comes from an inferred gradient of intensity, viz a reduction in intensity with increasing Galactocentric distance. [2, 3, 4].

The nature of the actual sources is less clear although supernova remnants are favoured by many. It is certainly true that there is considerable theoretical support for the idea of SNR shocks accelerating particles in the ISM (eg. [5, 6, 7]) but experimental evidence is hard to come by. The best almost certainly comes from gamma ray astronomy, again. The early claims [8, 9] seem to have been confirmed by recent observations of the prominent Loop I SNR. Figure 1 shows the most recent results using data from the Comption Gamma Ray Observatory [10]; the 'γ-ray' contours (actually the mean cosmic ray intensity along the lines of sight derived from the γ-ray intensities and gas column densities) bear some resemblance to the excesses identified in the radio and X-ray maps (see [10] for reference).

Many calculations have shown that the energetics of SNR are adequate to provide the ambient cosmic ray flux to some 10^{14} eV.

3 ENERGIES ABOVE 10^{18} EV

3.1 *The search for sources*

There is no consensus about the existence of Galactic sources but the present author's view is represented in Figure 2. This shows the results [11] of a detailed study some three years ago of the world's data on the arrival directions of extensive air showers generated by particles of estimated energy above 10^{19} eV. The study endeavoured to identify likely source directions from an analysis of the clustering properties of the showers. None of the 'sources' can be claimed to be statistically significant but two points should be made: (i) only 2 or 3 such 'sources' would be expected by chance, (ii) the excess along the Galactic Plane is heartening - there is no know technical reason for this result.

Two very recent observations have strengthened claims to have identified specific sources; these are the very big showers recorded by the Fly's Eye array ([12], energy 3.2 x 10^{20} eV) and the Akeno array ([13], energy 2 x 10^{20} eV). Both are indicated in Figure 2 and it will be seen that they are close to our previously claimed 'sources'. The mass of neither primary particle is know and, as will now be demonstrated, it is the problem of mass (or, rather,

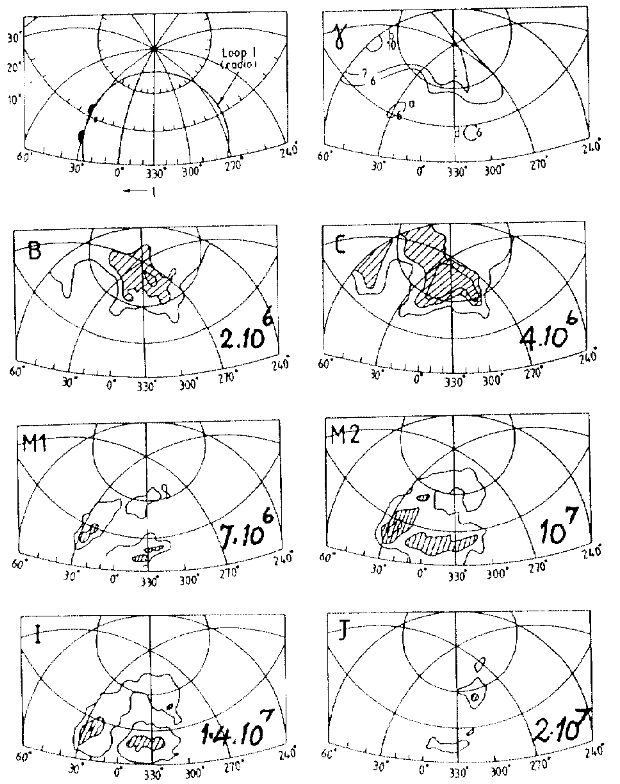

Figure 1: A comparison of the mean cosmic ray intensity derived from gamma rays, denoted γ, with the radio and X-ray maps which delineate the Loop I supernova remnant. The mean emission temperature associated with the X-ray maps are indicated (after [10]).

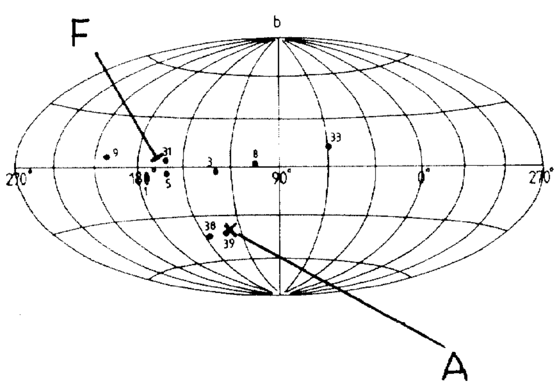

Figure 2: Map showing 'best-estimate' source directions from an anaysis of the world's EAS data at energies above 10^{19} eV prior to 1992 [11]. Also indicated are two very recent ultra-energetic showers: from Fly's Eye, at 3 x 10^{20} eV [12] and Akeno, at 2 x 10^{20} eV [13] , denoted ' F' and ' A' respectively.

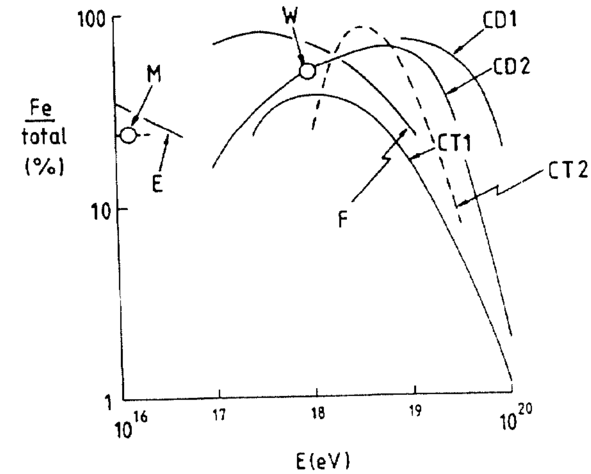

Figure 3: Estimates of the ratio of the flux of heavy nuclei (iron) to the total flux of cosmic rays from a variety of different techniques. [14]

charge) identification that causes the main difficulty with origin determination.

3.2 The mass composition at very high energies

Although mass identification is very difficult - and only possible on a statistical basis - there has been some progress. Figure 3 gives the result of a recent survey [14]. It is apparent that there is a considerable flux of heavy nuclei (probably iron) in the region of 10^{18} eV and the origin problem can be laid at their door; the deflections here are some 26 times greater than for protons and are thus too great to allow directional studies to have much value for the bulk of the particles (we must conclude that the ' sources' of Figure 2 represent the few light nuclei or nearby sources of heavier nuclei).

Figure 4 gives one possible interpretation of the high energy data. In it, the bulk of the particles above 10^{19} eV, which have little detectable anisotropy, are assumed to be Extragalactic protons. (It would be possible to retain a Galactic origin for these particles if the Galaxy had a truly enormous halo - some 100's of kpc, with a regular magnetic field of $\approx 1\ \mu$G [15] - but there is no evidence for such a halo.) It is with the origin of these Extragalactic particles that we will be concerned next.

3.3 Possible Extragalactic Sources

It is obvious that it is possible to invoke dramatic phenomena in distant galaxies on an ad hoc basis but there are some limits that can be placed on these phenomena. The first concerns the energetics of the processes - considerable energy outputs are involved. The second concerns energy losses by interaction with the cosmic microwave background; these losses become severe above about 5 x 10^{19} eV over cosmological dimensions. Thirdly, there is the common difficulty of suppressing the attendant emission of

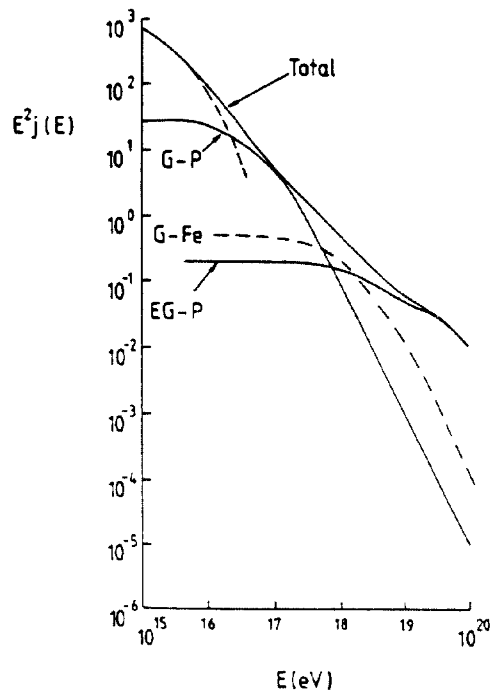

Figure 4: A possible interpretation of extensive air showers - their anisotropies, estimated energies and propagation characteristics in terms of Galactic and extragalactic components. [14]

gamma rays which then cascade through the universe [16] and can easily cause problems in the range 10^8 - 10^9 eV where the flux of so-called diffuse Extragalactic gamma rays is quite well known.

The present author's list of candidates contains the following:

(i) Galaxy - galaxy collision (spiral galaxies) where the magnetic fields undergo ' re- connection'.

(ii) Galaxy - intergalactic medium bow-shocks (in similar fashion to the earth's bow shock in the interplanetary medium).

(iii) Active-galactic nuclei.

Until recently, cosmic strings would have been included. Such strings intersecting will, in principle provide cosmic rays of energy up to 10^{24} eV [17], but very recent work [Gill and Kibble, private communication] indicates that the likely fluxes are too low by many orders of magnitude - at least for the more favoured string models.

The hunt for the origin of ultra-high energy cosmic rays goes on.

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