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Understanding galactic cosmic rays

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ABSTRACT

The case is made for most cosmic rays having come from galactic sources. 'Structure', i.e. a lack of smoothness in the energy spectrum, is apparent, strengthening the view that most cosmic rays come from discrete sources, supernova remnants being most likely.

1. Introduction

Insofar as the present paper is a contribution to a Conference involved in the history of science it is appropriate to start by discussing the origin of the concept of 'the galaxy', i.e. the disc-like distribution of stars, with the solar system near its central plane (and 2/3 of the way from the centre). A further reason is that the initiator of the idea, Thomas Wright, was born near the home of one of the authors (AWW).

Fig. 1 shows the famous self-explanatory diagram from the book of Thomas Wright (1750). It seems that Immanuel Kant, the great German philosopher, saw a summary of the book (but not the book itself) and, since it accorded with his own ideas, he published it and Wright's fame was assured. It is perhaps as well that Kant did not dig more deeply because Wright believed the disc to be part of a spherical shell with God in the middle!

The scope of the article is to examine the role of the galaxy in explaining the origin of the Cosmic Rays (CRs) detected at Earth. Inevitably, attention is somewhat focused on the contributions of the authors, some of which are somewhat speculative. However, it is through speculation (e.g. Hess's idea that an extra-terrestrial radiation was responsible for his results) that eventual understanding arises.

2. Energy densities in the galaxy

The energy of any physical system is important, and 'cosmic rays' is no exception. Table 1 shows the relevant energy densities locally (the 'old-fashioned 'units', electron volts per cm^3, are used).

It is interesting to note their near equality and to appreciate the hazards involved in using 'equipartition' arguments as an aid to determining the mechanism by which CR are accelerated. Concerning the first basic question regarding CR origin: Galactic (G) or Extragalactic (EG) there is no guidance, in that there is a near-equality between the various galactic energy densities and the important EG density, that of the Cosmic Microwave Background (CMB), which is, of course, Universal; a factor two difference is hardly important, not least because the galactic values depend somewhat on Galactrocentric distance, and, of course, on distance from the galactic plane (z). Having said that, it is physically reasonable that the CR energy density should be close to that in magnetic fields, as it is, the field acting as a trapping mechanism and as a valve for CR escape.

In order to complete this discussion of energy densities, those for the Universe as a whole are given in Fig. 2. A wide spread is to be noted. The case for 'UHECR' being so low will be given later.

3. CR: galactic or extragalactic

An early controversy arose as to the origin of cosmic rays detected at Earth. Were they largely of galactic origin, or extragalactic? (see [23] for a detailed discussion). The answer came from gamma-ray astronomy, where most cosmic gamma rays result from the interactions between CR and gas (the inter-stellar medium, ISM, and the intergalactic medium, IGM). The history of the early studies has been given by Wolfendale [31] and will be summarised here.

1. Lack of EG gamma rays. If the CR were of EG (Universal) origin, as in Millikan's 'birth cries of the elements' and the CR intensity were the same everywhere in the Universe, the contribution to the universal gamma ray flux from CR interacting with the IGM would be considerable. As shown by Said et al. [28] expectation would exceed observation by a factor approaching 100.

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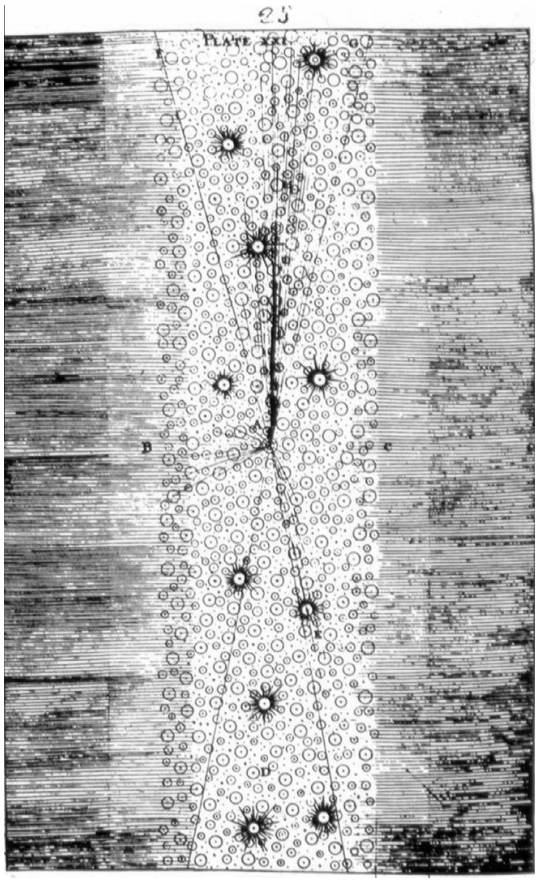

Fig. 1. Thomas Wright's 'galaxy', Wright (1750). The circles represent stars with those showing radiating lines being the brighter ones. The Sun is in the centre. The reason for the appearance of the 'Milky Way' is apparent: more stars will be seen on looking in the direction of the 'Plane', i.e. upwards and downwards.

Table 1
Energy densities in the galaxy. A comparison of that for cosmic rays with the others may have relevance to the origin of CR.

	eV cm^{-3}
Magnetic field ($B^2/8\pi$)	≃0.5
Gas motion ($\langle 1/2\ Mv^2 \rangle$)	≃0.5
Cosmic rays	≃0.5
Starlight	≃0.5
(Cosmic microwave background, 2.7 K)	≃0.5
But, most ≠ f(R)	≃0.24

2. Gradient of the CR Intensity. The work of Dodds et al. [14] showed the presence of a gradient of CR intensity in the galaxy such that the intensity in the outer galaxy is lower than that locally, in opposition to expectation for a Universal origin, where the CR intensity would be the same everywhere. Recent work by Erlykin and Wolfendale [18] describes the gradient problem, and its solution, in detail.
3. The Ginzburg test, viz an examination of the observed and expected gamma ray fluxes from the Magellanic Clouds, by Chi and Wolfendale [13] gives the same result, viz that the CR intensity in the Clouds is less than that locally.

The conclusion at this stage is that the bulk of the CR detected as the Earth come from galactic sources. EG sources provide only $\sim 10^{-5}$–10^{-6} of the energy content, mainly confined to particles above the 'ankle' at $E \sim 2$ EeV.

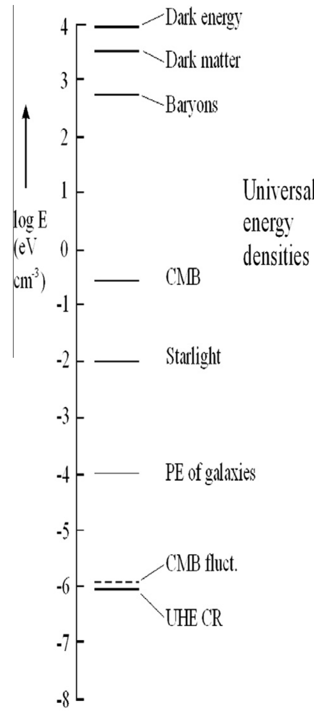

Fig. 2. Energy densities in the Universe. Most are self-explanatory. 'PE of Galaxies' is the potential energy of the material in Galaxies, the energy realised as kinetic energy when galaxies formed could, in principle, contribute to the universal CR budget. It is fascinating to note the wide range of energy densities involved in Cosmology – a range of a factor of 10^{10} from that of the Dark Energy to that in the ultrahigh energy (extra-galactic) cosmic rays.

4. Galactic sources: SNR

4.1. Evidence for supernova remnants as sources

The idea that supernovae are involved in CR acceleration stems from the work of Baade and Zwicky [8], Baade and Zwicky [9]. Initially it was thought that it was the SN themselves were the source but later work identified the supernova remnant (SNR) shocks as being responsible.

It is apparent [31] that other systems besides SN have enough total energy to be useful CR sources but SNR seem to be unique in providing individual particles with energy up into the PeV region, a key energy because this is where there is the 'knee', a sudden steepening in the energy spectrum, a feature that suggests the cessation of particles from a particular type of source.

The role of gamma ray astronomy in identifying SNR as CR sources has been described by Fazio [22], Bignami and Hermson [12] and Ramana Murthy and Wolfendale [27]. Gamma rays from specific SN and pulsars were described in the first two reviews and the evidence for extended SNR in the last-mentioned. An early example in the last-mentioned review is the work of Bhat et al. [11] in which an excess gamma ray intensity was claimed for the Loop 1 SNR.

Detailed studies of gamma rays from specific SNR is now the staple diet of modern satellite studies (e.g. Fermi-LAT) and the large Cerenkov detectors (H.E.S.S). It is possible that SNR provide the bulk of CR up to PeV energies, but it must be said that often there is ambiguity as to whether protons (nuclei) or electrons are responsible for the observed gamma rays.

4.2. Fine structure in CR spectra

That the CR energy spectrum is not smooth has been known for many decades, specifically, there is the 'knee' at about 3 PeV and