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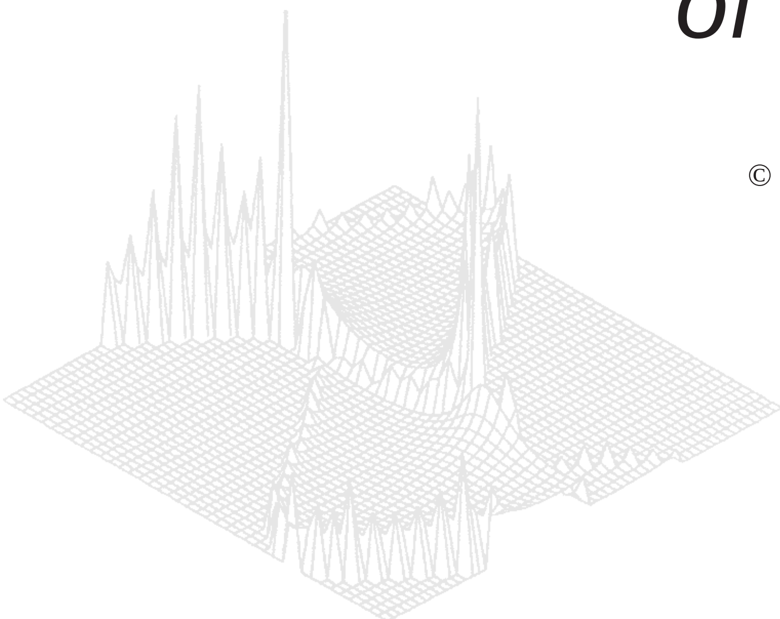

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Physics and the Cosmos: The Origin of Cosmic Rays of 'Low' and 'Very High' Energies*

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Abstract

The subject of 'cosmic rays' is one that embraces a vast range of particle and photon energies and is an ideal one for examining 'Physics and the Cosmos'. In the present work we examine the twin problems of the origin of cosmic rays of both low and very high energies and find that they are related by studies of the Magellanic Clouds. This remarkable result comes from the hypothesis that there is a Giant Halo surrounding the Galaxy, support coming from Magellanic Cloud observations. Also examined is the flux of extragalactic gamma rays and its relevance to the question of the asymmetry between matter and anti-matter in the Universe.

1. Introduction

Our knowledge about 'the Cosmos' comes to us by way of radiation—at all wavelengths—and through samples of matter. The radiation provides information back to a time, some 300,000 years after the Big Bang, when atoms formed and the physics of much of the period between 300,000 years and now appears to be understood fairly well. The matter comprises meteorites (and samples of lunar material) and cosmic ray particles. Of these two, despite many decades of effort, 'cosmic rays' are still not understood over most of their energy range and it is quite possible that 'new physics' is involved here; certainly the acceleration mechanisms must involve previously unknown processes.

It is not surprising that the most energetic photons—gamma rays—are linked to the most energetic particles—cosmic rays—and gamma-ray astronomy acts as a useful base from which to examine old, and new, physical processes.

It is fascinating that the work to be reported centres around those prominent objects of the Southern Sky, the Magellanic Clouds. Thus, they relate to the demonstration that the bulk of the low energy cosmic rays are of Galactic origin and to the determination of the diffuse extragalactic gamma-ray intensity, which is important in searches for anti-matter—one of the grand problems of astrophysics. The Magellanic Clouds also relate to the existence, or otherwise, of a Giant Halo around the Galaxy and this is where the diffuse gamma-ray flux becomes relevant, as will be demonstrated. If such a Great Halo does exist it

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will also have profound importance for the trapping of cosmic rays of the highest energies known and thus give a clue to the origin of these enigmatic particles.

2. Gamma Rays and the Magellanic Clouds

Cosmic rays (CR) were discovered by Viktor Hess in 1912 but there is still argument about their source, or sources. The reason is that the bulk of the 'rays' comprise charged particles, principally protons and electrons, and over most of their energy domain the irregular magnetic field in the Galaxy is strong enough to render their arrival directions virtually isotropic. Thus, there is essentially no connection between the arrival direction of a particle and the direction to its source.

Until comparatively recently there was even argument as to whether the majority, proton, component came from Galactic or extragalactic sources. Although the energy requirements would be large there would be no objection to having CR protons filling the Universe quite uniformly. The same cannot be said for electrons because EG ones are absorbed by inverse Compton (IC) interactions on the cosmic microwave background (CMB).

The Durham group (Dodds *et al.* 1984, 1986) claimed the identification of a radial gradient of CR protons in the Galaxy (a fall-off in intensity with increasing galactocentric distance) using the 'Gamma-ray Technique'. The principle of the method is to divide the measured gamma-ray intensity along a particular line of sight by the column density of gas along that line. Insofar as many of the gamma rays come from interactions of the CR protons with the gas, the result of the division is the average CR proton intensity along the line. After initial scepticism most contemporary workers now agree with the conclusion (e.g. Strong and Mattox 1996).

Another method was suggested by Ginzburg (1972), this being to determine the average proton intensity in the Large Magellanic Cloud (LMC) by the gamma-ray technique and to compare it with the local CR intensity. Equality would indicate an EG origin but if the LMC intensity were much lower a Galactic origin for the local CR protons would follow.

Until recently, satellite data of sufficient sensitivity were not available but with the advent of the Compton Gamma Ray Observatory, or more particularly the EGRET instrument on the CGRO (Fichel 1982, and later papers), the test can now be made. The first study by Sreekumar *et al.* (1992) gave equality for the Galaxy and the LMC, but Chi and Wolfendale (1993) found a clear difference, the LMC proton intensity being much less than locally. The reason for the discrepancy is not fully understood. It is a relief, however, that both groups agree that the SMC cosmic ray intensity is much lower than locally. A Galactic origin for most cosmic rays is therefore assured. Our most recent analysis gives the results shown in Fig. 1. Studies are being made at present of the generation of the cosmic-ray particles themselves in both the LMC and SMC. An interesting result (Fig. 2) is that in the LMC, where the fluxes are higher and details can be seen, the peak of the gamma-ray distribution moves systematically with increasing energy, from the region close to the centroid of the gas to the centroid of the starlight. We interpret this as being due to enhanced production of gamma rays via IC interactions of the electrons generated within the Cloud. Such a result is of considerable interest to us because it confirms our view (a view not held by all) that the IC process is an important one for gamma-ray production.

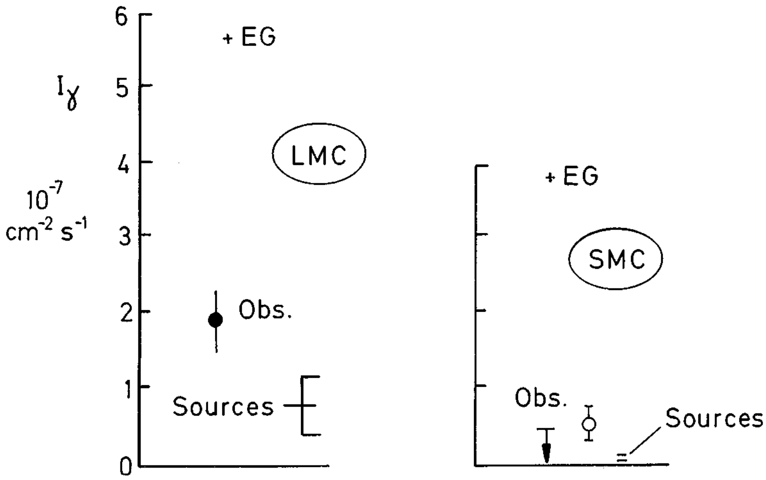

Fig. 1. Gamma-ray flux from the Magellanic Clouds above 100 MeV. The data are from the EGRET instrument on the Compton Gamma Ray Observatory (see references) as analysed by the Durham group (Chi and Wolfendale 1993; Smialkowski *et al.* 1996). EG denotes the flux that would be expected if the CR detected at the Earth were of Universal origin. There is some doubt as to the flux expected from discrete sources, as indicated. For the SMC Smailkowski *et al.* could only detect gamma rays above 300 MeV—the flux indicated in the figure assumes that the differential spectrum has exponent 2·0 and that no flux was actually detected above 100 MeV because of the larger PSF there, coupled with poor statistics.

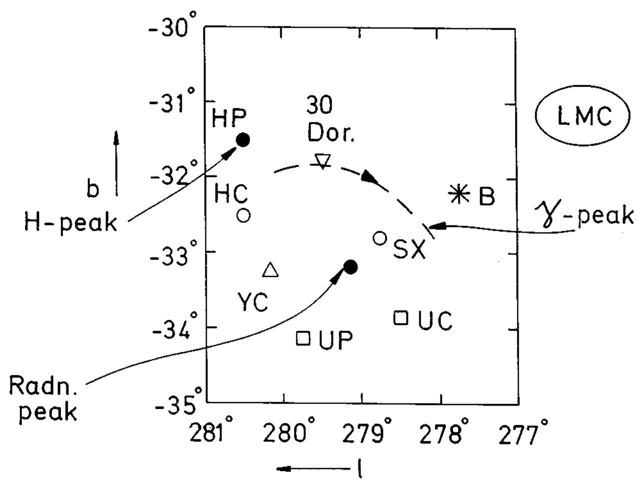

Fig. 2. Position of the peak of the gamma-ray contours as a function of gamma-ray energy for the Large Magellanic Cloud (Al-Dargazelli *et al.* 1996). The peak moves from being near that of the gas contours to that for radiation as the energy increases, a result that suggests that inverse Compton collisions are important. The symbols refer to the various LMC parameters: HP (hydrogen peak), HC (hydrogen centroid), ^{30}Dor (^{30}Doradus region of intense activity), B (bright stars), YC (yellow light centroid), UP (UV peak), UC (UV centroid) and SX (strong X-ray sources).

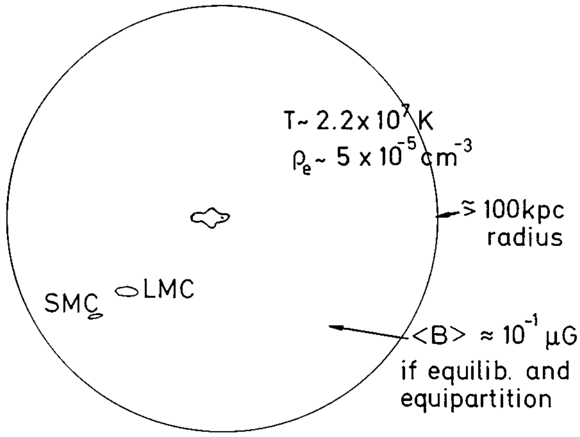

Fig. 3. Schematic diagram of the Giant Galactic Halo.

It is of particular interest—and relevance—that there is this spatial separation of gas and starlight—a feature which presumably relates to the history of the LMC, namely its 'collision' with the Galaxy and SMC some 10^8 years ago. Even more interesting, from the point of view of the present work, is the likelihood that the 'Halo' of the Galaxy extends to the Magellanic Clouds, and beyond; this extension causes ram pressure to be exerted on the LMC gas (Moore and Davies 1994). The effect of the ram pressure is clearly seen in the rapid fall in HI column density and synchroton radiation intensity on one side of the Cloud.

Fig. 3 shows the Giant Halo referred to above; its presence is inferred by ram pressure arguments and by arguments relating to Hα measurements (Weiner and Williams 1996) and to soft X-rays, these X-rays being generated in the Halo and absorbed, in part, by colder material nearby in the Galaxy.

To return to the CR intensity within the Clouds, we argue that it is less than about 20% of that locally in the Galaxy, thus confirming our contention that most of the local CR are of Galactic origin. Mechanisms for cosmic-ray production in the Clouds, and the precise contribution from gamma-ray sources therein, are currently under study.

3. Diffuse EG Gamma-ray Flux

The existence of a diffuse EG gamma-ray flux was inferred by Fichel *et al.* (1978) from an analysis of SAS II data. A number of estimates have been made of the flux and we (Smialkowski *et al.* 1996) have also made a new one. Fig. 4 shows the results. The flux is lower than hitherto because of small changes to the basic data, and the adoption by us of a larger IC flux than in our previous work (which was by Osborne *et al.* 1994). We regard the LMC results (see Section 2) as confirming the general correctness of our IC analysis. The result of accepting our new flux estimates is that it is possible to draw a smooth spectrum for EG X-rays and gamma rays all the way from 1 keV to several GeV.

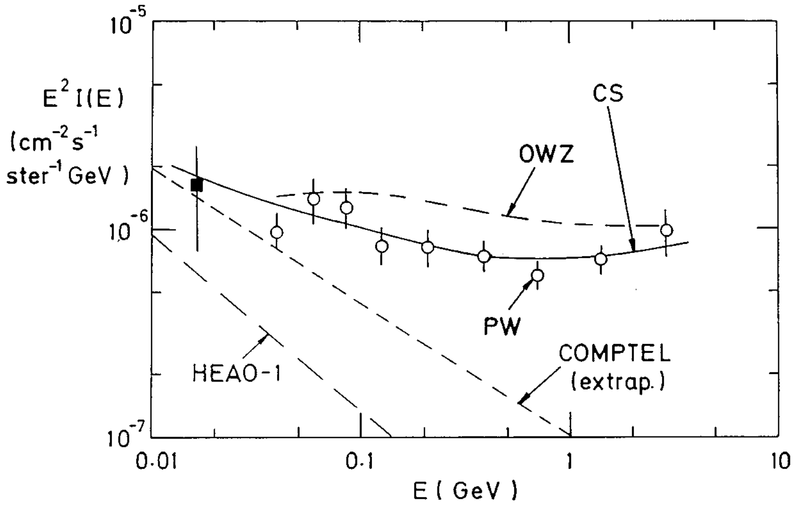

Fig. 4. Energy spectrum of diffuse EG gamma rays. OWZ is the earlier spectrum of Osborne *et al.* (1994).

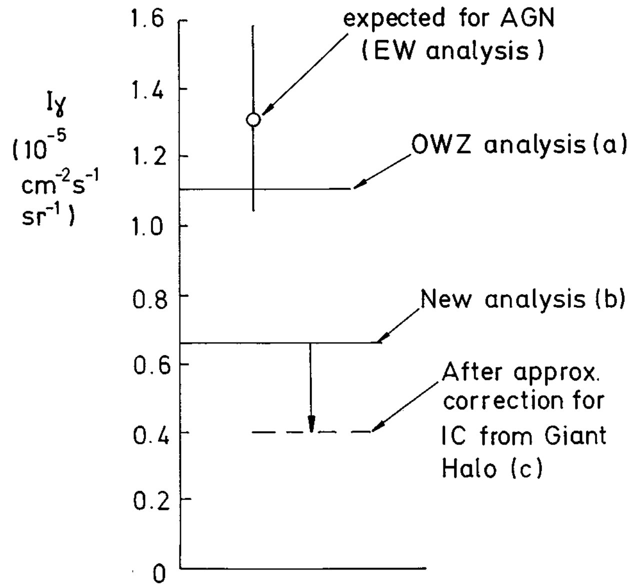

Fig. 5. Estimates of the diffuse EG intensity above 100 MeV as derived from the EGRET analysis and from a model in which it is assumed that unresolved AGN are responsible (EW denotes Erlykin and Wolfendale 1995). Clearly the model is inadequate. The dashed line is an approximate estimate of the 'true' EG diffuse intensity when allowance is made for IC scattering from the assumed Giant Halo.

The relevance of the Giant Halo is that if indeed it does exist the IC correction to the diffuse EG gamma-ray flux will be even larger. An accurate calculation has not yet been made, and in fact it will not be possible until more data are available about the Halo, but a rough estimate can be made using the analysis of Chi and Wolfendale (1989) which relates to the EG gamma rays produced by electrons escaping from 'normal' galaxies. It is virtually certain that none of the electron component produced in the Galaxy will escape from the Halo, in which case the true EG diffuse flux will be depressed still further. Fig. 5 shows the resulting flux.

Inspection of Fig. 5 shows a marked discrepancy between the observed EG diffuse flux and that expected from unresolved AGN (radio loud, flat spectra sources) using the calculations of Erlykin and Wolfendale (1995). Clearly it will be necessary to look again at the AGN analysis. One possibility is that raised by Chi and Young (1996, personal communication) that superluminal effects are responsible. The result would need to be that the effect of superluminal motion on gamma-ray emission from AGN differs from that on radio emission.

In the same spirit we can draw attention to the fact that there may be a difference between the cosmological parameter β [emissivity $\propto(1+z)^{\beta}$] for radio; specifically, Chi and Young (1996) quote $\beta \sim 3\cdot5$–$3\cdot8$ for radio and $\beta \sim 2\cdot6^{+0\cdot2}_{-0\cdot6}$ for gamma rays. Such a difference would be adequate to explain the shortfalls in Fig. 5.

4. Asymmetry of Matter and Anti-matter

EG gamma rays provide an important tool for searching for anti-matter in the Universe. The principle of the method is to use the fact that $M\overline{M}$ annihilation leads, via neutral pions, to gamma rays, which are, in principle, detectable. The work of Steigman (1976) showed that there is certainly no symmetry of M and $\overline{M}$ on scales up to, and including, cluster of galaxies. Dudarewicz and Wolfendale (1994) went the final 'distance' and showed that there could be no symmetry on the Supercluster scale either. Specifically, symmetry at the Supercluster level would lead to an excess of EG gamma-ray intensity over observation (Osborne *et al.* 1994) by at least 100. Using the most recent EG gamma-ray intensity and including a conservative estimate for the AGN contribution yields a value ∼500; the conclusion is thus strengthened.

5. Cosmic Rays of the Highest Energies

The problem here is well known; the detected anisotropies of arrival directions are small and indeed there is argument as to their validity. A common claim (e.g. by Bird *et al.* 1993) is that most of those above about $3{\times}10^{18}$ eV are EG protons, but we differ. Instead, whilst allowing a small EG contribution from colliding galaxies (Al-Dargazelli *et al.* 1996), the particles being protons, we can use the Giant Halo hypothesis to allow a containment of galactically-produced iron nuclei.

It can be remarked that progress in this field will depend on a number of factors, including:

(1) improved data, of higher statistical accuracy; and
(2) a more detailed study of the possibility of there being a Galactic Halo and the determination of its properties.

6. Conclusions

An illustration has been given of 'Physics in the Cosmos' by way of an analysis of the origin of cosmic rays and the implications of the measured intensity of diffuse gamma rays. Of particular relevance has been the demonstration of the importance of phenomena associated with the Magellanic Clouds—astronomical objects of great beauty as seen from the country (Australia) where this paper was presented.

Acknowledgment

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