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Galactic Structure and the Cosmic Ray Anisotropy at 10^{18} eV

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Abstract: Cosmic ray arrival directions at energies a little over 10^{18} eV have been reported to show an excess from directions close to that of the Galactic centre. That result was originally presented by the AGASA group and was later strengthened by an analysis of SUGAR cosmic ray data. We discuss here a second feature of the AGASA data, a deficit in roughly the Galactic anticentre direction. We interpret this as a result of cosmic ray diffusion past us. We find that the most straightforward interpretation of the data then requires that a strong magnetic field exists out of the plane of our Galaxy to distances of at least several kiloparsecs.

Keywords: cosmic rays — ISM: magnetic fields

1 Introduction

Data from the AGASA cosmic ray detector in Japan have recently been presented which show an excess of events from the general direction of the Galactic centre at energies a little above 10^{18} eV (Hayashida et al. 1999). The Galactic centre is just below the southern limit of the acceptance of the AGASA array and data from the southern SUGAR array were used to confirm the result (Bellido et al. 2001). Those data indicated that the source direction was probably several degrees from the actual direction of the Galactic centre and that there was a point source component (within the array angular resolution). The AGASA array data suggested the existence of a broader scale component around the Galactic centre direction and it may be possible to describe the phenomenon in terms of a two-component model with a neutral point source beam (possibly neutrons) together with a charged particle beam which scatters in the Galactic magnetic field (Clay 2000). The limited energy range over which the anisotropy and the point source are strongly detectable supports the idea of a neutron component from a source roughly at the distance of the Galactic centre since a time dilation threshold for such neutrons would be close to 10^{18} eV. Clay et al. (2000) have shown that conditions in the region of the Galactic centre might be suitable for cosmic ray acceleration to these energies; interactions in material close to the source could easily then produce a neutron beam.

There are two further features in the AGASA directional data. There is the suggestion of an excess towards our spiral arm inward direction, which might have a natural interpretation in terms of some propagation from inner Galactic regions guided by the large scale spiral arm magnetic field. There is also a strongly significant deficit close to the Galactic anticentre. The magnitude of this deficit is not so large as that of the Galactic centre excess, but is significant due to its declination, which is much better observed by AGASA.

The existence of an excess and a deficit of cosmic ray flux at opposite directions on the celestial sphere is strongly suggestive of a unidirectional anisotropy (e.g. Jacklyn 1986). In this case, either the observer moves through a frame of reference in which the cosmic ray flux is isotropic or the flux is diffusing past the observer. The solar velocity through the Galaxy is not sufficiently great to produce an anisotropy of the appropriate magnitude. Our interpretation of the AGASA data is that there is the diffusion of a cosmic ray component at 10^{18} eV past us from the inner Galactic regions.

2 Galactic Cosmic Rays

The overall cosmic ray beam is largely isotropic and the cosmic ray energy spectrum is a rather featureless power law. It is believed that cosmic rays at the lower energies (of the order of 10^{16} eV and below) originate in sources within our Galaxy and have their directions made isotropic in the Galactic magnetic fields. However, there are data at these energies which show deviations from isotropy. Some of these are significant and fit an overall pattern which is somewhat clouded by limited observational statistics (Clay & Smith 1996a). One of those deviations shows a form of unidirectional anisotropy. This is an outward flow along our Galactic spiral arm at energies of about 10^{15} eV (Clay et al. 1998). There is also a change in phase of the anisotropy at about the energy of a spectral feature (the knee) in the vicinity of 10^{16} eV. This may be associated with the beginning of the effect of an intergalactic cosmic ray component which is thought to dominate at the highest energies. It is thought that the extragalactic component completely dominates at energies above 10^{19} eV (see the spectrum in Takeda et al. 1998) where there is a second spectral feature (the ankle). The energy range between the knee and the ankle is probably associated (at least in part) with a progressive reduction in the ability of our Galaxy to contain particles and allow their flux to build. It is noteworthy that any interpretation similar to this model

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implies that our Galaxy is capable of accelerating particles at least up to the vicinity of 10^{19} eV, a point not often emphasised.

3 Diffusion and the AGASA Anisotropy

The AGASA anisotropy suggests that, at about 10^{18} eV, cosmic rays are diffusing past us from the direction of the central Galactic regions. That diffusion produces a flux component which has, in its simplest case, a cosinusoidal distribution with angle from the source direction. We expect this to be modified somewhat by any systematic Galactic magnetic fields. Clay (2000) has shown that the modelled magnitude of the anticipated flux at these energies is dependent on detail in the magnetic field model and that, at energies approaching 10^{19} eV, the diffusion model is likely to break down.

The excess in the Galactic centre direction may have a point source component due to neutral particles. We therefore take the magnitude of the deficit in the anticentre direction as a better measure of the magnitude of the unidirectional anisotropy. At the peak of the deficit that is of the order of 5–10% of the total flux. In terms of a total outflowing flux averaged over all directions, this reduces to 1–2%. As we saw, the total flux includes a significant extragalactic component at these energies, which means that the amplitude of the anisotropy in terms of the Galactic component alone is several times this value. Assuming that the resulting Galactic anisotropy has a value of the order of 10%, we can attempt to estimate the scattering mean free path in the plane of the Galaxy. If we consider simple diffusion, with scattering which typically occurs at a distance of about one mean free path, this implies a mean free path of the order of kiloparsecs to fit the anisotropy as observed at the Earth. This is comparable with results of our modelling (see below) for propagation in the turbulent Galactic plane magnetic fields which have strengths of a few microgauss. There are sufficiently large dimensions in the Galactic plane to allow such a process to occur. Thus, our interpretation of the AGASA deficit appears plausible.

The AGASA anisotropy (apart from the spiral arm excess) shows no other discernible features. There are, for instance, no other deficit directions. It may thus appear that the data support a simple unidirectional anisotropy model with simple diffusion as a first approximation. However, it is not clear how this might be so. At energies of about 10^{18} eV, we expect our Galaxy to become a poor cosmic ray container (Lee & Clay 1995; Clay & Smith 1996b). This is because of the flat and thin structure of the Galaxy. Cosmic rays are expected to readily leak away above and below the Galactic plane magnetic fields. This leakage would be expected to result in cosmic ray deficits from directions out of the Galactic plane. Such deficits are not observed, even though the minimum in the anticentre direction is clearly seen. We therefore wish to examine the scattering properties of turbulent Galactic magnetic fields at these energies. We will then be in a better position to understand the data and their implications for the Galactic magnetic field.

4 Propagation through Turbulent Magnetic Fields

We have examined the propagation of cosmic rays through turbulent magnetic fields as described by Lee & Clay (1995) and Clay (2000). We used a random magnetic field with a turbulent Kolmogorov spectrum and a maximum scale size of 100 pc. We wished to determine how far cosmic ray particles would propagate in such a field before their flux was significantly reduced by scattering. One might expect that the attenuation length would be related, in an order of magnitude way, to the gyroradius of particles in a simple field which had the strength of the random field under consideration. In propagating particles through a slab containing such a modelled field, it was found that the number passing completely through a certain thickness of slab reduces exponentially to e^{-1} over approximately six gyroradii. In other words, a diffusive propagation model would require containment dimensions greater than or of the order of 5–10 gyroradii in order that the diffusive process would operate without significant particle loss from the sides of the container. With a field strength of 3 μG, this distance would be several kiloparsecs at an energy of 2×10^{18} eV (0.7 kpc gyroradius for protons).

If one asks what thickness is required to obtain a particular magnitude of anisotropy, our modelling can be extended to observe how many particles pass the observer and then how many return, based on the distance of the observer to the far limit of the slab which acts as a sink. In this case, for a 10% anisotropy, the distance to the limit of the slab is required to be 1–2 gyroradii, in broad agreement with the argument discussed above.

5 Discussion

A unidirectional anisotropy appears to be a straightforward way of interpreting data from the AGASA cosmic ray array at energies of a little above 10^{18} eV. However, whilst the data are compatible with our understanding of the properties of the magnetic fields and spiral arm structure within the Galactic plane, the lack of a deficit out of the plane is disconcerting. As has been noted before (e.g. Berezinsky et al. 1991; Lee & Clay 1995), cosmic ray anisotropies are best fitted if there is a strong (several microgauss), turbulent, halo magnetic field which extends several (Lee & Clay (1995) suggest 15) kiloparsecs out of the Galactic plane. Those previous suggestions have had the weakness that they were based on unsubstantiated assumptions of a broad distribution of cosmic ray sources which, whilst plausible at lower energies, is probably not the case at 10^{18} eV. We now have a particular source to deal with, and we still find the same effect. These data seem to argue that there is the need to assume the existence of a strong halo field out to at least several kiloparsecs. The actual extent of such a field beyond those distances is not determined by the cosmic ray data.

We note in this context that we have only discussed one Galactic source component. The flux associated with the AGASA source alone is not well defined, due to the analysis procedures, but a comparison with the AGASA energy spectrum suggests that there are significant remaining Galactic sources at 10^{18} eV. The remaining directions show no clear anisotropy and we are left with the problem addressed by Lee & Clay (1995) in a rather stronger form. This is that, despite the likelihood that there are only a few active cosmic ray sources at 10^{18} eV, the Galactic cosmic ray anisotropy is very low. It is not clear how that remaining anisotropy can be explained by Galactic plane magnetic fields alone.

6 Conclusions

Cosmic ray direction measurements at energies a little above 10^{18} eV can be interpreted in terms of the diffusion of particles from a direction towards the Galactic centre. This interpretation is plausible in terms of our knowledge of the magnetic fields in the Galactic plane, but requires a similarly strong magnetic field in our Galactic halo, which extends at least several kiloparsecs above and below the plane.

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