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Anisotropies and the Power Requirements for Galactic Cosmic Rays

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Abstract: Measurements of cosmic ray directional properties at about 10^{15} eV in both northern and southern hemispheres confirm that those particles have a unidirectional anisotropy and are flowing along the direction of our spiral arm from the inner Galactic regions. On the basis of diffusive cosmic ray flow along the Galactic arms, the power required for the Galaxy to maintain this flow is below 10^{30} W.

Keywords: ISM: cosmic rays

1. Introduction

Cosmic rays have a remarkably uniform distribution over the sky. The deviation from isotropy (the anisotropy) is typically below 1% and can be as low as 0·03% (e.g. Clay & Smith 1996; Smith & Clay 1997). Recent compilations of data have shown that measurements of this anisotropy give a coherent picture in the energy range from about 10^{14} eV up to almost 10^{18} eV (Clay et al. 1997a,b). That is, in the lower half of that range the relatively plentiful northern data show a peak of cosmic ray intensity from the spiral arm inward direction. At about 10^{16} eV, this changes dramatically to a more complex picture which is nevertheless consistent in phase over the next decade and a half of energy.

Cosmic rays in the lower energy range have gyro radii of about 1 pc or less in typical Galactic magnetic fields (a proton with an energy of 10^{15} eV would have a gyro radius of 1 pc in a one microgauss field). In order to have a low anisotropy such as is observed, we must assume that their propagation is diffusive in some way (see e.g. Allan 1972). It is likely that this diffusion is broadly along magnetic field lines which are in tubes of dimensions greater than the gyro radii. The direction of the peak of the anisotropy would then indicate the direction back towards the cosmic ray source, and the amplitude of the anisotropy would give information on the scattering process involved in the diffusion. In particular, an estimate of the mean free path might be obtained.

The exact nature of the flow of the cosmic rays has been unclear but can be greatly clarified if observations can be made in both the northern and southern hemispheres at the same energies. We will examine the limited southern data at energies in the half decade above 10^{15} eV and confirm that the northern anisotropies do indeed correspond to a general diffusive flow past the solar system. We can then estimate the power requirement for the Galaxy to produce its cosmic rays.

2 Southern Cosmic Ray Anisotropies

Compared to northern hemisphere data, the quantity of anisotropy information in the south is very sparse. It is only in the half decade energy range above 10^{15} eV that the total data set is large enough to be useful for comparison with that from the north. We have taken those southern data (Farley & Storey 1954; Chapman & Ryder 1957; Farley & Storey 1957; Escobar, Nerurkar & Weil 1960; Bird, Clay & Edwards 1989) and derived combined first and second harmonic anisotropies in the same way that we did for the north (Clay et al. 1997a,b). This gives us values of amplitude and phase of (0·33%, 19·7 hr) for the first harmonic and (0·09%, 1·2 hr) for the second harmonic (see Table 1). We can then estimate how the cosmic ray intensity varies over the southern sky in right ascension by combining these data as shown in Figure 1. It is important to include the second harmonic, even though its data are of limited statistical significance, since it defines the difference in flow between the north and the south which is not possible with the first harmonic alone. The latter would be the same in both the north and the south for simple diffusive flow. Figure 1 also shows the corresponding result that we found for the northern data (Clay et al. 1997b).

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3 Discussion

An examination of Figure 1 shows that, in the north, the anisotropy has a peak at about 21 hours in right ascension. The southern anisotropy shows a dip at about 7 hours right ascension. Given the uncertainties of the data of one to two hours due to limited statistics and the combination of only first and second harmonics, these data are remarkably consistent in the sense that the peak is in almost an opposite direction on the sky to the trough. Such a situation is that which would be expected for a unidirectional anisotropy due to net cosmic ray streaming (e.g. Jacklyn 1986). That is, the cosmic rays have a diffusive flow from the direction of greatest intensity and show a minimum in intensity in the opposite direction. An ideal unidirectional anisotropy would have a cosinusoidal variation with the angle from maximum intensity. The case shown in Figure 1 deviates from this but retains an intensity peak in the forward direction and a trough behind. We are not able to identify the diffusion process with such confidence from northern data alone.

The majority of both the northern and southern data are at mid-latitudes, and we can identify the direction of the cosmic ray flow as from the spiral arm inwards direction, which is at about 20 hr in right ascension and 35° in declination (Jacklyn 1986). Studies of the Galactic magnetic field identify the spiral arm as the local direction of the overall Galactic magnetic field, which has a broad-scale value of a few microgauss.

The amplitude of the anisotropy is of the order of 0·2%. Simple diffusion ideas (see e.g. Allan 1972) suggest that this value would be roughly equal to the ratio of the scattering mean free path to a characteristic dimension of the containment region (perhaps the central Galactic region, with a scale of 10 kpc). In this case, a plausible mean free path of about 20 pc is found—perhaps 20 gyro radii. Alternatively, one could take cosmic ray lifetimes of about 10^7 yr and estimate the size of the containment region as the product of the anisotropy and the lifetime. That lifetime has been measured at low energies through studies of radioactive nuclei. As energies increase, it still appears to apply up to 10^{15}eV, based on a number of propagation calculations as discussed by Clay & Smith (1996). A containment dimension of the order of 10 kpc is thus found, which is a consistent, albeit crude, check of our ideas.

It is possible that there may be a local source of cosmic rays, perhaps associated with the local bubble (Clay & Smith 1997; Erlykin & Wolfendale 1997).

Table 1. First and second harmonics of the cosmic ray anisotropy in the energy range 1–3×10^{15} eV, derived by combining all available data

Latitudes	First harmonic		Second harmonic	
	Amplitude (%)	Phase (hr)	Amplitude (%)	Phase (hr)
Northern	0·171±0·054	21·1±1·2	0·108±0·054	09·4±1·9
Southern	0·325±0·058	19·7±0·7	0·093±0·068	01·2±2·8

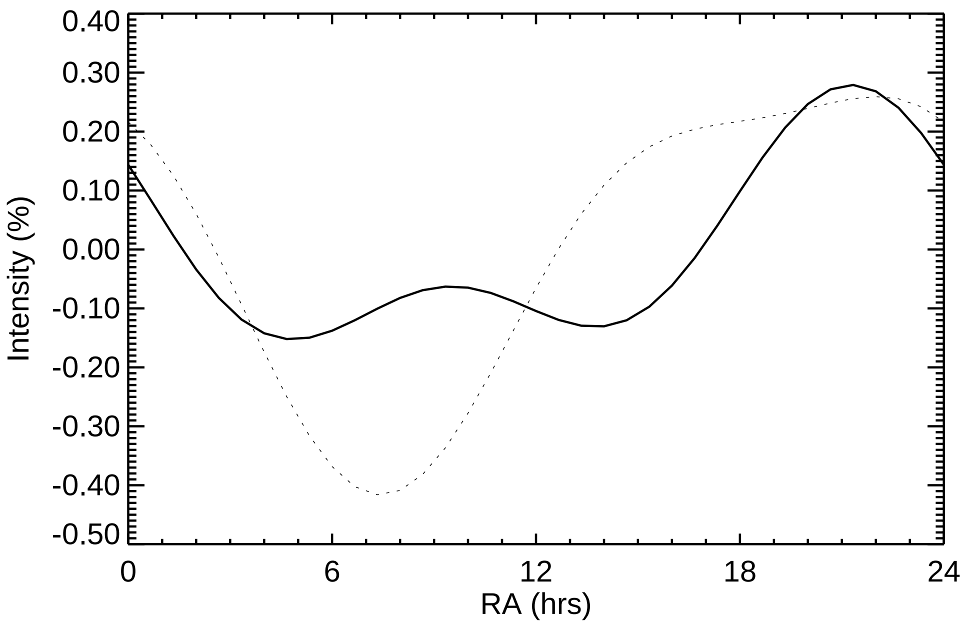

Figure 1—Intensity distribution obtained by combining the first and second harmonics of the anisotropy from Table 1. The solid line is the result for the northern hemisphere data and the broken line is the result for the southern hemisphere data.

The direction of any anisotropy associated with such a bubble is proposed by Clay & Smith (1997) and is not compatible with the observations presented here. The data presented by Erlykin & Wolfendale (1997) for a local single source are not a good fit to observations at the energy discussed in this paper.

A knowledge of the amplitude of the anisotropy and the suggestion that it is associated with streaming along the spiral arm allow one to estimate the rate of energy injection into Galactic cosmic rays. It is assumed that the outward cosmic ray flow is dominated by streaming along the spiral arm. This is supported by the anisotropy data for, if there was poor containment and the Galactic central regions were the source of the cosmic rays, there would be some suggestion in the data of flow from those regions and this is not observed. If we take the spiral arm cross section as 1000 pc in the Galactic plane and 100 pc perpendicular, we can estimate the area through which the cosmic rays diffuse. The magnitude of the anisotropy gives us rather directly the speed of the diffusive drift (the speed of light multiplied by the amplitude of the anisotropy) and we can then use our knowledge of the local cosmic ray energy density for all cosmic ray particles ($1\,\mathrm{eV\,cm^{-3}}$ to the level of approximation which we are using) to derive the rate of cosmic ray energy flow past us. Since we observe the cosmic ray flow to be along the spiral arm, this rate of about $10^{38}\,\mathrm{erg\,s^{-1}}$ corresponds to the necessary rate of energy injection and is significantly less than that which we would have derived assuming diffusion through the whole Galactic surface.

The anisotropy at lower energies is less than at $10^{15}\,\mathrm{eV}$ (see e.g. Clay & Smith 1997; Speller, Thambyahpillai & Elliot 1972) and below about $10^{14}\,\mathrm{eV}$ it may be even smaller, being dominated by other effects such as the motion of the solar system through the Galaxy. This implies that, as would be expected, the diffusive flow is slower at lower energies where the gyro radii are smaller in the Galactic field and the particles follow the small-scale random field components more effectively. Our estimate of the power will thus be an upper limit, high by at least a factor of 10. We thus make our estimate of the power injection into Galactic cosmic rays as less than or of the order of $10^{37}\,\mathrm{erg\,s^{-1}}$ ($10^{30}\,\mathrm{W}$). This power requirement is modest compared to some in the literature and reflects the relative lack of high-energy activity in our Galaxy. It is not far above the estimate by Ginzburg (1969) of 10^{34} to $10^{36}\,\mathrm{erg\,s^{-1}}$ for the average power of cosmic rays only from stars like our Sun in the Galaxy. Such stars will not provide particles up to $10^{16}\,\mathrm{eV}$ but we can see that they might well contribute the bulk of the power requirements.

4 Conclusions

Anisotropy data have been combined for the half decade of energy above $10^{15}\,\mathrm{eV}$ from southern hemisphere experiments. When taken with northern data at similar energies, these data confirm a unidirectional cosmic ray flow outwards in the direction of the Galactic spiral arm. If this spiral arm flow is characteristic of the cosmic ray diffusion generally in the Galaxy, the power required for the maintenance of Galactic cosmic rays is below $10^{30}\,\mathrm{W}$.

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