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The radial gradient of cosmic ray intensity in the Galaxy

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Abstract

The dependence of the cosmic ray intensity on Galactocentric distance is known to be much less rapid than that of the thought-to-be sources: supernova remnants. This is an old problem ('the radial gradient problem') which has led to a number of possible 'scenarios'. Here, we use recent data on the supernova remnant's radial distribution and correlate it with the measured HII electron temperature (T). We examined two models of cosmic ray injection and acceleration and in both of them the injection efficiency increases with increasing ambient temperature T. The increase is expected to vary as a high power of T in view of the strong temperature-dependence of the tail of the Maxwell–Boltzmann distribution of particle energies. Writing the efficiency as proportional to T^n we find $n \approx 8.4$. There is thus, yet another possible explanation of the radial gradient problem.

Keywords: Cosmic rays; Radial gradient; Ambient temperature

1. Introduction

The manner in which cosmic ray (CR) particles are accelerated in the Galaxy and how they propagate is still the subject of argument although it is generally agreed that up to a few PeV or so supernova remnants (SNR) play an important role, as does the diffusion in the interstellar medium (ISM) (Ginzburg and Syrovatskii, 1964). However, there are a few problems of detail among which one is the following:

why, when the surface density of SNR in the Galaxy falls so rapidly with Galactocentric radius, R, for $R > 3$ kpc (Case and Bhattacharya, 1998; Green, 2015), does the CR intensity fall so slowly (Erlykin et al., 1996; Strong (on behalf of the Fermi LAT collaboration), 2011).

In the recent past we have examined this question in some detail (Erlykin and Wolfendale, 2011), but here we study the problem again in the light of superior data on the radial gradient of SNR and the appreciation that in some models of particle injection into SN shocks the temperature of the ambient ISM has relevance (Berezhko et al., 1996; Kang et al., 2002).

2. The input data for the analysis

2.1. The radial gradient of SNR

The determination of the radial gradient is a matter of some difficulty on account of obscuration by dust and attenuation of the radio signals, by which distances are measured. Two, rather extreme, estimates have been made, by Case and Bhattacharya (1998) and Green (2015). The first (Case and Bhattacharya, 1998) peaks at $R \sim 4$ kpc and drops to 40% of its peak value by ~ 10 kpc whereas the second (Green, 2015) peaks at $R \sim 3$ kpc and falls to

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15% by 10 kpc. Insofar as the analysis in Green (2015) is later and, (Erlykin and Wolfendale, 2011) points to shortcomings in the analysis of Case and Bhattacharya (1998) we adopt the results from Green (2015). A representative surface density of SNR from Green (2015) is given in Fig. 1, denoted SNR.

2.2. The radial distribution of CR

The analysis of the gamma-ray emissivity in the Galactic Disk derived from the COS-B data by Bhat et al. (1986) and Bloemen et al. (1986) showed a flatter distribution of CRs than that of their presumed sources (SNR) as derived even from Case and Bhattacharya (1998). Later work by Bloemen et al. (1993), Digel et al. (1996), Strong et al. (1988) and Strong and Mattox (1996) as well as the emissivity from the Fermi-LAT (Ackermann et al., 2011a; Tibaldo (on behalf of the Fermi LAT collaboration), 2013) came to the same conclusion (see also for a review of the history of the 'radial gradient' of the CR intensity (Dogiel and Uryson, 1988). Here we use an amalgam and present the result in Fig. 2. It can be remarked that the problem of the difference between the radial gradient (i.e. the dependence of CR density on the Galactocentric radius *R*) of CR and sources is a live one. It seemed that a natural explanation would be an effective spatial mixing of CRs due to the diffusion which produces a more or less uniform distribution of CRs in different parts of the Galactic Disk if it is surrounded by a giant halo. However, numerical calculations of Dogiel and Uryson (1988) and Bloemen et al. (1993) for the free escape boundaries have shown, that even in the most favorable case of an extended halo, the diffusion model is unable to remove the signature of the source distribution even for the relatively smooth SNR distribution of Case and Bhattacharya (1998). The problem is even more aggravated for the sharper SNR distribution of Green (2015). One of the explanations was suggested by Breitschwerdt et al. (2002) who assumed that CRs leave the disk faster from the regions of a higher concentration of SNRs and that smoothes the CR distribution in the Disk in comparison with that of SNRs. Here, we suggest an alternative explanation of this effect.

2.3. The radial distribution of HII electron temperature

It is well known that there is a radial increase of the measured electron temperature in HII regions with the mean temperature from about 6600 K at $R = 2$ kpc to about 10,000 K at $R = 14$ kpc (Quiresa et al. (2006) and Fig. 1). This fact arises from the 'Galactic Metallicity Gradient' – the fall in metallicity (e.g. Fe/H) with increasing *R* due to the reduced surface density of SNR there (e.g. Fig. 1). The 'metals' act as cooling agents.

The data on the mean temperature comes from measurements on HII regions and the resulting 'warm gas' occupies on average some 30% of the available volume (Mushtotsky, 2012). However, SN are frequently to be found in regions of OB-associations – and nearby HII 'objects' - so that most SNR will accelerate background electrons (and protons) having 'high' temperatures. In what follows we assume that the CR all come from SN exploding in regions where the temperature is similar to that in the HII-temperature regions or, at least, the similarity is not radially dependent.

3. The relevance of rising temperature of ISM to the radial distribution of CR intensity

3.1. General consideration

The relevance of rising temperature of the ISM with increasing Galactocentric radius is that, as mentioned in §1, in some CR acceleration models, two of which we examine below, the temperature of the ions in the ambient ISM is related to the injection efficiency for the ions to take

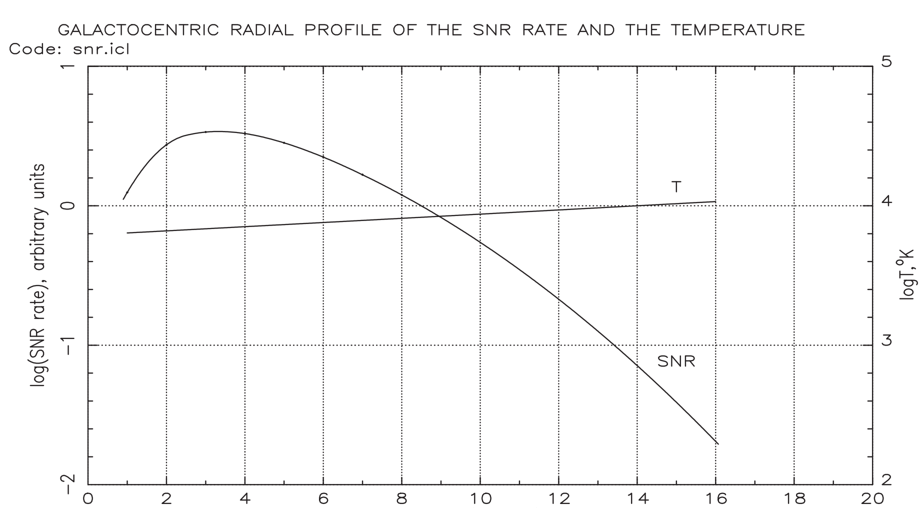

Fig. 1. Surface density of SNR vs. Galactocentric radius, *R*, (from Green (2015) Fig. 4) (arbitrary scale of ordinate) and electron temperature, *T* vs *R* from (Quiresa et al. (2006), [Fig. 5]).