PROCEEDINGS OF SCIENCE

The radial gradient of cosmic ray intensity in the Galaxy

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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 three models of cosmic ray injection and acceleration and in all 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.

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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) [1]. 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 [2, 3], does the CR intensity fall so slowly [4, 5] ?

2. The input data for the analysis

(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 [2] and [3]. The first [2] peaks at $R \sim 4$kpc and drops to 40% of its peak value by $\sim$ 10kpc whereas the second [3] peaks at $R \sim 3$kpc and falls to 15% by 10kpc. Insofar as the analysis in [3] is later and, [6] points to shortcomings in the analysis of [2] we adopt the results from [3]. A representative surface density of SNR from [3] is given in Figure 1, denoted SNR.

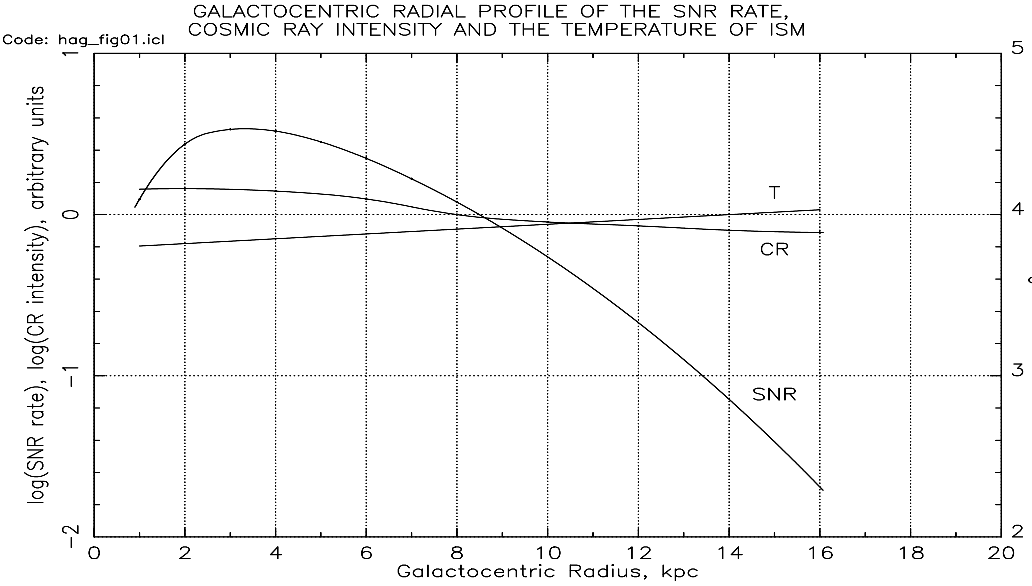

Figure 1: Surface density of SNR vs. Galactocentric radius, R, [from [3], Figure 4] (arbitrary scale of ordinate), cosmic ray intensity (CR) and electron temperature, T vs R [from [9], Figure 5]

(2) *The radial distribution of CR*
The analysis of the gamma-ray emissivity in the Galactic Disk derived from the COS-B data by [10] and [11] showed a flatter distribution of CRs than that of their presumed sources (SNR) as derived even from [2]. Later work by [12, 13, 14, 15] as well as the emissivity from the Fermi-LAT

[16, 17] came to the same conclusion (see also for a review of the history of the 'radial gradient' of the CR intensity [18]). Here we use an amalgam and present the result in Figure 1.

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 [18, 12] 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 [2]. The problem is even more aggravated for the sharper SNR distribution of [3]. One of the explanations was suggested by [19] 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.

(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 $R = 2kpc$ to about 10000°K at $R = 14kpc$ ([9] and Figure 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. Figure 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 [20] . 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 part in the acceleration process.The argument is that the particles in the high energy tail of the Maxwell-Boltzmann distribution above some 'high' threshold energy ε_{thr} have a number which rises rapidly with temperature when the mean energy $< \varepsilon >$ is much less than ε_{thr}. Figure 3 illustrates the situation.

The inferred CR intensity is proportional to the product of the surface density of SNR, $\sigma_{SNR}(R)$, and the efficiency factor $\Delta(R)$, where we assume that Δ is a function of the electron temperature and is the fraction of the ionized gas having sufficiently high energy to enter the SNR shock, i.e. the fraction with energy greater than ε_{thr}. The problem is to find the necessary values of ε_{thr} and Δ.

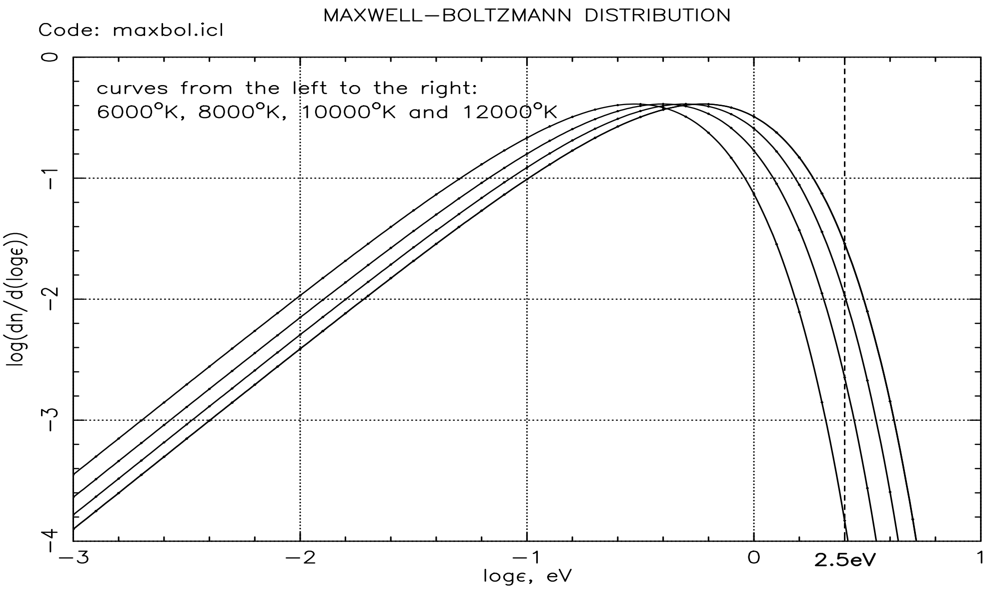

Figure 2: Maxwell-Boltzmann distribution for atomic particles

In Figure 4 we give f versus T for various values of ε_{thr}. Indicated above the abscissa are the limiting values of R: 2 and 14kpc to which the analysis refers (the data are too sparse beyond 14kpc and there are complications within 2kpc due to black hole effects).

Examining Figures 1 and 2 we see that an increase in efficiency of about a factor 30 is needed between $R = 2$ and $R = 14kpc$. Figure 5 shows the ratio of Δ vs. ε_{thr} for $R = 14kpc$ and $2kpc$; it shows that a factor of 30 results from $\varepsilon_{thr} = 2.5eV$. The corresponding Δ-values are 10^{-4} and $10^{-2.5}$, and, writing $f \propto T^n$, we have $n \sim 8.4$. It means that the fraction of interstellar plasma injected into the acceleration process can rise rapidly with the rising temperature.

3.2 The process of stochastic CR acceleration from a background plasma and acceleration by SNR shocks

We have applied this idea to the known mechanisms of CR production in the Galaxy: the stochastic Fermi acceleration and acceleration by SNR shocks. The results for the former mechanism can be found in [21, 22] and are shown in Figure 3 by the dash-dotted line.

The results forthe latter mechanism of the particle acceleration by the SNR shock are given in [23] and presented in Figure 3 by the dashed line. Both mechanisms give rise of the fraction of injected and accelerated particles with the rising temperature of the ISM.

4. Discussion and conclusions

We see that both in our general consideration and in more sophisticated models the fraction of background particles injected into the acceleration process rises with the ambient ISM temperature. In first order, the values of $\varepsilon_{thr} = 2.5eV$ and $10^{-4}/10^{-2.5}$ for the fractions appear 'reasonable' but there are a number of uncertainties. The most important concerns the extent to which the gas

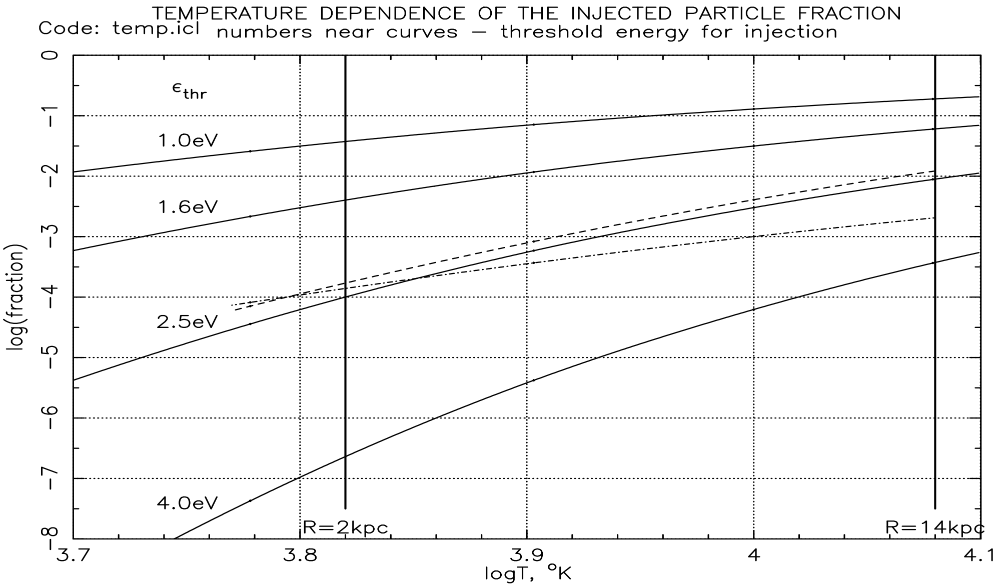

Figure 3: Temperature dependence of the injected particle fraction. ε_{thr} is the threshold energy for injection. The temperatures at $R = 2kpc$ and $14kpc$ from [9] are indicated. Fractions of particles injected from the background plasma and accelerated by the process of the stochastic Fermi acceleration or by the SNR shocks are shown by dash-dotted and dashed lines respectively.

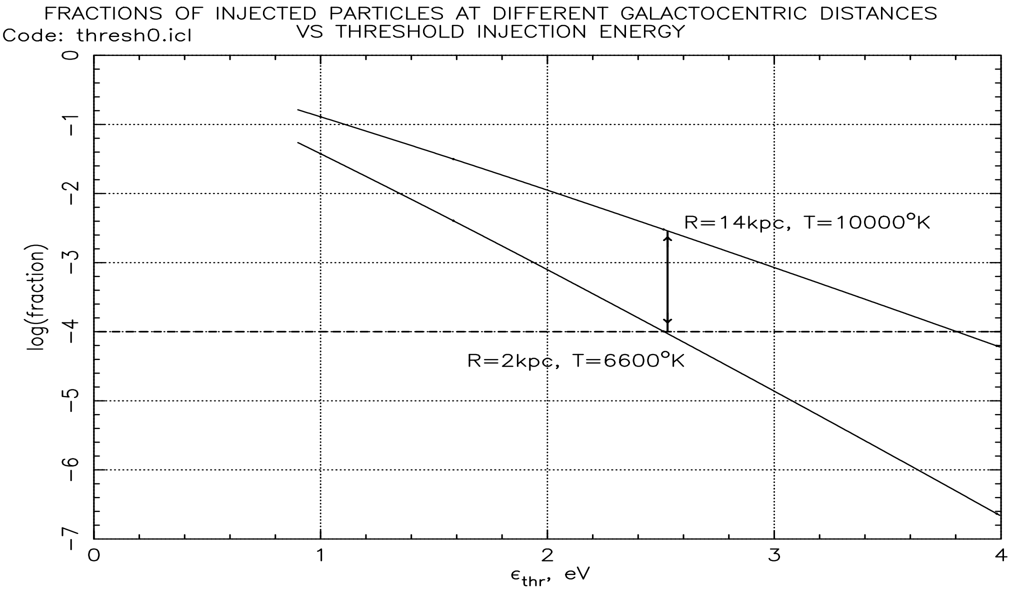

Figure 4: Fractions at $R = 2kpc$ and $14kpc$ vs. ε_{thr}. The value of ε_{thr} where the ratio of the fractions for $R = 2$ and $14kpc$ is the necessary 30 is indicated

densities in the regions in which CR are accelerated are proportional to the total gas densities in those regions and the temperatures likewise. If they are then the value of ε_{thr} will be appropriate and the Δ-values can be regarded as injection efficiencies and can be compared with the values commonly adopted; for example, the values adopted as examples in [7] range from 10^{-2} to 10^{-4}, i.e. in our range. Writing $\Delta \propto T^n$ we have $n = 8.4 \pm 3.2$. Such a value may seem large, but it can be pointed out that $n \approx 25$ in the case of the flux of neutrinos emitted by the Sun from fusion interactions in the solar core, where T_c is the temperature therein.

In conclusion, we have presented a model in which the gradient of electron temperatures in the Galaxy can make a contribution, at least, to solving the cosmic ray gradient problem.

Acknowledgements

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References

[1] V.L. Ginzburg and S.I. Syrovatskii, *The Origin of Cosmic Rays*, Pergamon Press, Oxford, 1964

[2] G.L. Case and D. Bhattacharya, *A new Σ-D relation and its application to the galactic supernova remnant distribution, ApJ* **504** (1998) 761

[3] D.A. Green, A catalogue of Galactic supernova remnants, Bull. Astr. Soc. of India, **42** (2014) 47

[4] A.D. Erlykin et al., *The gradient of cosmic rays in the Outer Galaxy, Astron. and Astrophys. Suppl. Ser.,* **120** (1996) 397

[5] A.W. Strong et al., *Interstellar gamma rays and cosmic rays: new insights from Fermi-LAT and INTEGRAL, Proc. ICATPP conference 'Cosmic rays for particle and astroparticle physics'*, World Scientific, (2011) ISBN-13 978-981-4329-02-6, p. 473 [arxiv:1101.1381]

[6] A.D. Erlykin and A.W. Wolfendale, *The cosmic ray gradient in the Galaxy, Proc. 2nd Int. Cosm. Ray Workshop 'Aragats 2011'*, (2011) 16

[7] E.G. Berezhko, V.K. Elshin and L.T. Ksenofontov, *JETP* **82** (1996) 1

[8] H. Kang, T.W. Jones and U.D. Gieseler, *Numerical studies of cosmic ray injection and acceleration, ApJ* **579** (2002) 337

[9] C. Quireza et al., *The electron temperature gradient in the Galactic Disk, ApJ,* **653** (2006) 1226

[10] C.L. Bhat et al., *The acceleration of cosmic rays in supernova remnants. II. Large scale intensity variations, J.Phys.G* **12** (1986) 1087

[11] J.B.G.M. Bloemen et al., *The radial distribution of galactic gamma rays. III-The distribution of cosmic rays in the Galaxy and the CO-H2 calibration,* A&A **154** (1986) 25

[12] J.B.G.M. Bloemen et al., *Galactic diffusion and wind models of cosmic ray transport. I-insight from the cosmic ray composition studies and gamma-ray observations, A&A,* **267** (1993) 372

[13] S.W. Digel et al., *Diffuse high energy gamma ray emission beyond the solar cycle: the Cepheus and Polaris flares and the Perseus Arm, ApJ,* **463** (1996) 609

[14] A.W. Strong et al., *The radial distribution of galactic gamma rays. IV. The whole Galaxy, A&A*, **207** (1988) 1

[15] A.W. Strong and J.R. Mattox, *Gradient model analysis of EGRET diffuse galactic gamma-ray emission, A&A* **308**(1996) L21

[16] M. Ackermann et al., *Fermi-LAT observation of the diffuse gamma-ray emission: implications for the cosmic rays and the interstellar medium, ApJ*, **750** (2012) 3

[17] L. Tibaldo et al., *A tale of cosmic rays narrated in gamma rays by Fermi, Brazilian Journ. of Phys.* **44/5** (2014) 600 [arXiv:1311.2896]

[18] V.A. Dogiel and A.V. Uryson, *Cosmic ray spectra and galactic diffuse gamma-ray emission, A&A*, **197** (1988) 335

[19] D. Breitschwerdt, V.A. Dogiel and H.J. Völk, *The gradient of diffuse gamma-ray emission, A&A*, **385** (2002) 216

[20] C.F. McKee and J.P. Ostriker, *A theory of the interstellar medium, ApJ*, **218** (1977) 148

[21] V.A. Dogiel *On the thermal origin of the hard X-ray emission from the Coma cluster, A&A*, **357** (200) 66

[22] D. Chernyshov, V.A. Dogiel and C.M. Ko, *Stochastic particle acceleration and the problem of background plasma overheating, ApJ*, **759** (2012) 113

[23] S.V. Bulanov and V.A. Dogiel, *The influence of energy losses on the acceleration of cosmic ray particles at a shock front, Soviet. Astron. Lett.* **5** (1979) 278