Stochastic Effects on the Electron Spectrum above TeV Energies

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Abstract

High energy electrons in cosmic rays lose energy predominantly by the radiative processes of synchrotron radiation in the galactic magnetic fields and inverse compton scattering on the ambient photon field. It is well known that these effects are expected to produce a finite lifetime for electrons above TeV energies that is as short as 30,000 years at 10 TeV. The population of electrons above 10 TeV is therefore highly dependent on the age and location of nearby supernovae, assuming these are the sources of cosmic rays. We shall examine how the detection of a flux of electrons at sufficiently high energy could call into question our current paradigm of the origin of cosmic rays in supernovae.

1. Introduction

Several authors have pointed out that the strong energy dependence of electron radiative losses in the galactic magnetic field and photon environment produces a limiting effect on the lifetime of electrons at energies above ∼1 TeV [1,2]. The time taken for an electron of energy E to lose half of its energy is $\propto 1/E$. For realistic values of the electron diffusion coefficient in the magnetic fields of our Galaxy this provides a strong argument that electrons at GeV energies observed in cosmic rays must be galactic in origin. Electrons at these energies cannot diffuse much further than ∼10 kpc before they undergo significant energy loss. Under the assumption that the diffusion coefficient is more or less constant, this process can be scaled in a naive fashion to energies near 10 TeV where the maximum diffusion distance should be ~ 100 pc. This becomes comparable to the distances between the objects which are the current paradigm for accelerators of the bulk of the cosmic rays, supernovae remnants (SNR) with ages less than $\sim 10,000$ years. A version of this has been discussed by Nishimura and collaborators, (see e.g. [1]), which results in an expected 'cutoff' in the electron spectrum above these energies. The nature of this feature strongly depends on the distribution and potency of the local cosmic-ray-producing sources. The purpose of this paper is to investigate numerically the expected variations of this cutoff across the Galaxy and to identify some maximum energies expected at Earth, based on known nearby SNR.

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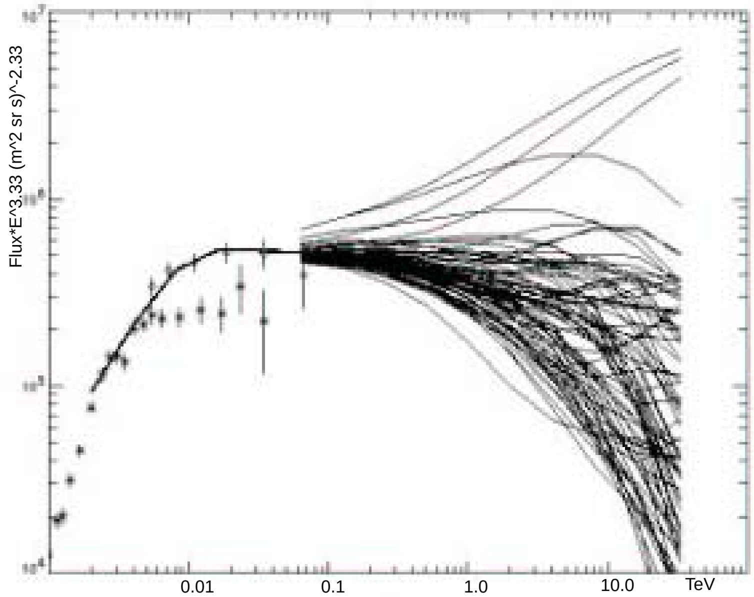

Fig. 1. High energy electron spectra observed in a numerical model of the Galaxy at a ring distant 8kpc from the Galactic center - described in text.

2. Simulations

We have used the Galactic simulation code GALPROP (C++ v0.41) developed by Strong and Moskalenko [3] to study these effects on high energy electrons. The simulation is run in full 3D mode with stochastic supernovae (SN) explosions. The SN rate was adjusted to give, on average, one event every 30 years and have a lifetime for accelerating cosmic rays of 10,000 years. At any given instant ∼300 SNR are actively producing cosmic rays. All the sources produce electrons with the same energy spectra where $dN/dE \propto E^{-2.5}$. The simulation is run for an effective history of 10 million years. To investigate the variations which might be expected to be characteristic at Earth, Figure 1 shows a snapshot of various electron spectra above 60 GeV generated by the model at 30 equally spaced locations on a ring of radius 8.5 kpc around the Galactic center. Also shown are some data from recent experiments (see [4] for a review of these)and a standard 'steady state' solution which is the thick solid line below 60 GeV. The fluxes are multiplied by $E^{3.33}$ to emphasize differences in the spectra. There is wide variation by over an order of magnitude in the fluxes above 10 TeV depending on the history of nearby SNR. Some locations even show an increase in fluxes above the average trend - corresponding to recent, nearby SN events where radiative losses have yet to dominate.

3. The Local SNR Environment

The standard paradigm for the generation of Galactic cosmic rays revolves around diffusive shock acceleration in shell-type SNR which must be considered as the most likely sources of high energy cosmic-ray electrons. The most complete catalog of these objects has been produced in the radio by Green[5]. We have used this catalog to try to establish how close these might be to contemporary Earth, spatially and temporally, and derive some limits on the maximum energy of electrons which might be detected.

Under the simple assumption that the radiative loss cross sections are energy independent, we can quantify the time an electron takes to lose half of its energy. We can make a further simplification that the diffusion constant is energy independent and calculate how far this electron might diffuse in this time. The effects of these limits are shown in Figure 2 where distances and ages are plotted for nearby SNR. Shell-type remnants are plotted as circles, plerion-type objects are shown as diamonds. For the shell-type SNR, in several cases the ages are estimated from the size of the remnant and an assumed average expansion parameters during the Sedov phase. The line boxes on this plot are an estimate of the maximum energy electrons which might be observed from a source. For example, if electrons of energy in excess of 10 TeV are expected to reach Earth an object must lie inside the lower left region bounded by the dashed lines with the label '10 TeV'. It is fairly clear from this plot that assuming SNR are the sources of cosmic-ray electrons implies there should be no primary electrons detectable at Earth at 100 TeV and most likely none above 30 TeV. It is probably also worth pointing out that the bulk of the cosmic-rays are expected to be produced by shell-type SNR, so that although, in principle, plerions might produce particles at these energies they are far less likely to be the source of most of the electrons observed at Earth.

4. Conclusions

The radiative energy losses of electrons provides the opportunity to make a unique test of the SNR origin paradigm of cosmic rays. Simply put: If electrons are detected above 50 TeV it is difficult to see how they can have originated in SNR. There are some caveats here; there are certainly some electrons at these energies because of secondary production by hadronic cosmic rays in collisions in the interstellar medium. However calculations show these secondary fluxes should be nearly two orders of magnitude below a simple extrapolation of the low energy fluxes shown in Figure 1. The measurement of an electron cut-off in the energy region 10-100 TeV would place the SNR origin of cosmic rays on a much firmer observational footing. Conversely, the absence of a cutoff would be a major discovery. To make these measurements an electron detector with an

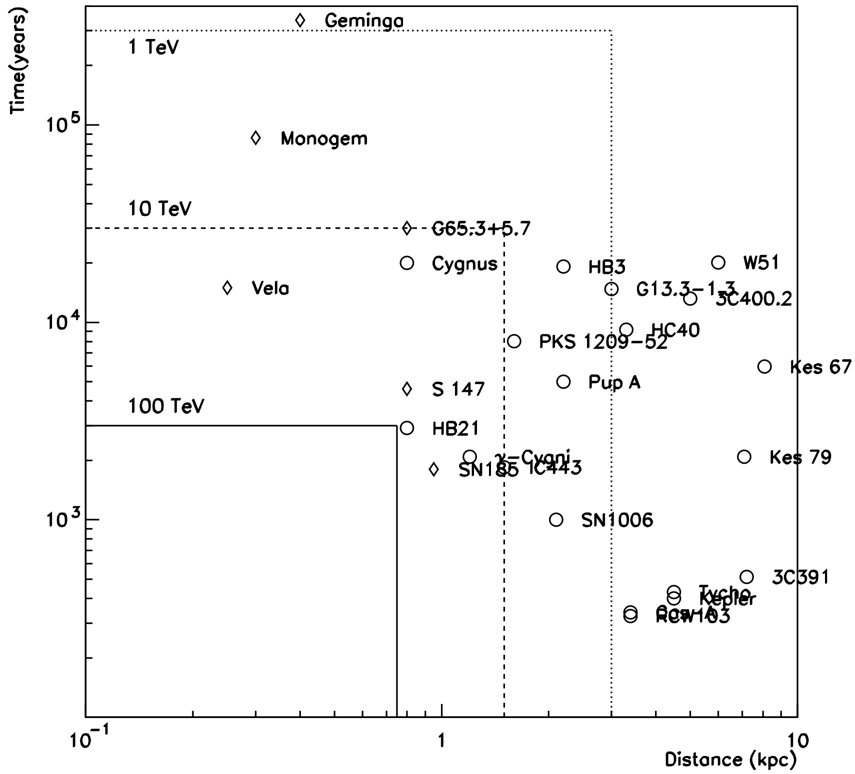

Fig. 2. Compilation of nearby shell-type and plerion SNR distances and ages. Line boxes represent limiting energies for electrons to reach Earth - see text.

effective collecting power larger than 1000 m^2sr days is needed.

5. Acknowledgements

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6. References

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