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Cosmic rays from SNR, III: The electron component

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Abstract. The Monte Carlo analysis of CR from SNR has been used to predict the energy spectrum of electrons (and positrons) incident on the earth. The measured electron spectrum is consistent with there having been a local, recent SN. The reason for a possible positron excess above 5 GeV is discussed.

1 Introduction

The importance of electrons in astronomy and astrophysics cannot be overemphasised — most of our information about the Universe comes from the movement of electrons which generate radiation from radio right through to gamma ray energies.

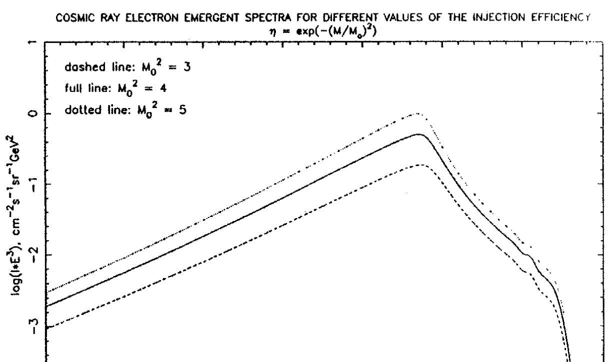

Fig. 1. Emergent energy spectrum of electrons for different values of the injection efficiency: $\eta = \exp-(M/M_0)^2$, where M is the Mach number and M_0 is a constant.

Direct measurements of the energy spectrum of electrons (and positrons) exist only for those impinging on the earth's atmosphere and even here there are problems. Thus, at low energies — say below 5 GeV — uncertain solar modulation effects are important, and at high energies — say above 500 GeV — energy losses caused by interactions with photons and magnetic fields give rise to uncertain cut-offs.

In the present work we address a number of problems: the reason for e/p being only $\sim 1\%$, the relevance of our SNR acceleration model (e.g. Erlykin and Wolfendale, 2001a, these Proceedings; from now on Erlykin and Wolfendale will be referred to as EW) to understanding the spectral shape and to providing evidence for or against our contention (e.g. EW, 1998) that a single recent supernova is contributing significantly to a prominent feature in the energy spectrum of nuclei. Also examined, briefly, will be the relevance of some of our very recent work to the situation in the jets from Active Galactic Nuclei.

2 The electron injection problem

At first sight, the fact that the ratio of electrons to protons at (say) 10 GeV is only 1%, when the ambient interstellar medium which gives rise to these particles has virtually equal numbers of e and p, is surprising. The problem is an old one and many (e.g. Ellison and Reynolds, 1991) have put forward as the reason the fact that the gyroradii of thermal electrons and protons are very different. Specifically, the radii are such that $r_e/r_p = \sqrt{m_e/m_p} = 43^{-1}$ in the non-relativistic region. The relevance of this to injection into the SNR shocks, which we consider to be the source of most cosmic rays below several PeV, is that the particles must couple to the plasma waves in the shock and these have a smaller density for small linear dimensions (gyroradii). We concur with this view and we have gone on (EW, 2001b) to endeavour to quantify this effect using results from solar plasma studies (Denskat et al., 1983; Dröge, 2000) and adopting an empirical model of the type used by Berezhko et al. (1996) for protons and heavier nuclei.

We have gone on further and postulated that the 'injection

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efficiency', usually taken to be an adjustable constant (e.g. $10^{-3} \sim 10^{-4}$ depending on the characteristics of the interstellar medium, ISM), is not constant for a particular SNR but depends on the Mach numbers of the shock at the point of acceleration. The manner of variation has modest theoretical justification and is different for protons and electrons, the effect for electrons being much bigger, i.e. the injection efficiency is smaller for electrons than for protons. The difference comes from the plasma wave phenomenon referred to earlier, specifically that the short wavelengths take time to build up and the fact that the important kinetic temperatures for e and p are different (see EW, 2001b), T_p/T_e being greater than 1 and increasing with Mach number.

Calculations using our model give the spectra emerging from an SNR in the Hot ISM of radius 100 pc (at which the particles break out) shown in Figure 1. The steepening introduced by $\eta = f(M)$ and the reduction in e/p are apparent.

Figure 2 shows the emergent spectrum at the end of the expansion for the preferred value of M_0 and its constituents from equal intervals of time during the expansion.

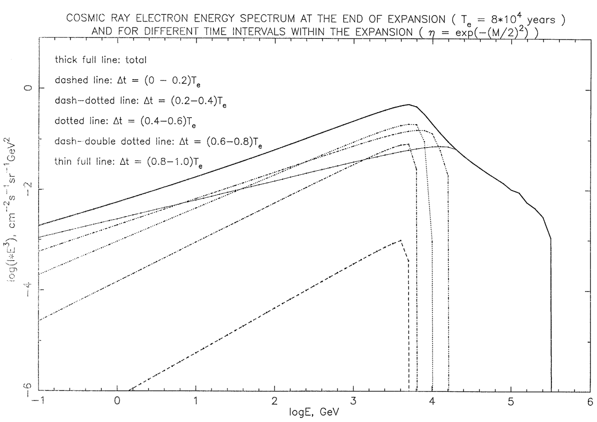

Fig. 2. Electron energy spectrum at the end of the expansion ($T = 8 \times 10^4$ y) and the constituents for subsequent time intervals after the SN explosion. The gradual steepening of the spectra with time can be seen.

3 The expected electron spectrum at earth

The Monte Carlo model of EW (2001a), which has SN of random ages and positions in the Galaxy, has been used to give the spectra shown in Figure 3. A mean line through the measured spectrum (summarised by Kobayashi et al., 1999) is also indicated. It is apparent that the 'average' spectrum predicted has a similar shape to that observed. The difference in absolute intensity can easily be corrected by including

(a) a higher SN energy fraction going into the CR component than normally assumed, which is 10%.

(b) re-entrant particles from the Galactic Halo.

(c) the known higher rate of SN in the local region of the Galaxy over the past 10^6 years (Grenier and Perrot, 1999) than the standard 10^{-2}/Galaxy/year adopted here.

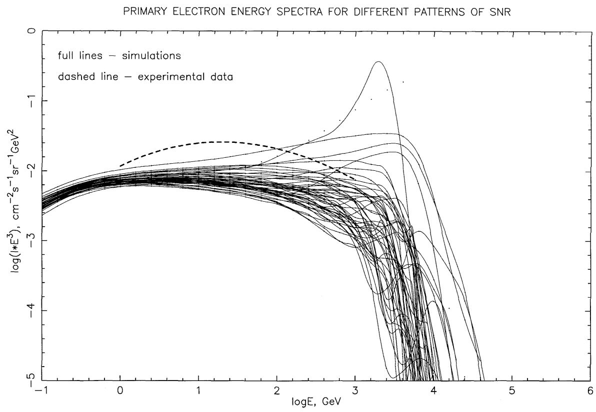

Fig. 3. Primary electron spectra for different patterns of SNR. Those spectra showing a peak at high energy are such that there was a singularly close/recent SN. The dashed line represents the experimental spectrum from the summary by Kobayashi et al. (1999).

Figure 4 shows the calculated spectra for both the electron and the proton components for several values of the parameters. Starting with $\eta = 1$, the spectra relate to equal injection and acceleration efficiencies for electrons and protons and an energy input into CR of 10^{50} erg. It is assumed that the acceleration process involves rigidity rather than energy, and this is why there is a cross-over at low energies.

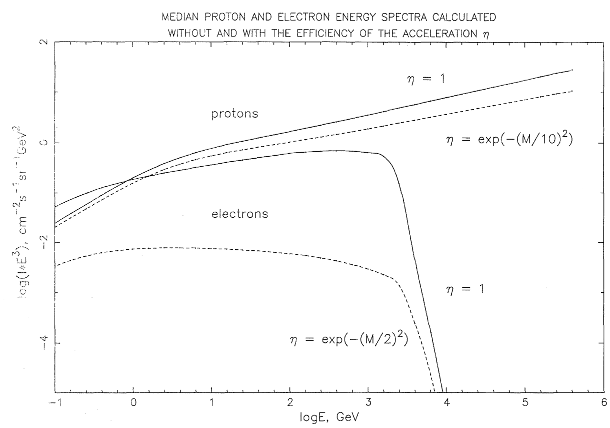

Fig. 4. Median proton and electron spectra calculated for various values of the injection efficiency parameter, η. See the text for details.

Elsewhere (EW, 2001b) we have made the case for a slight fall of injection efficiency for protons, too, at high Mach numbers. The situation for $M_0 = 10$ is shown in the Figure. It will be noted that the result is a slight increase in the predicted proton spectral exponent: $\Delta\gamma_p = 0.06$.

Our preferred situation for electrons is for $\eta = \exp -(M/2)^2$ and this is also shown in Figure 4. The reduction in intensity by about two orders of magnitude is apparent, as is the increase in slope over the situation for $\eta = 1$ ($\Delta\gamma_e \simeq 0.3$).

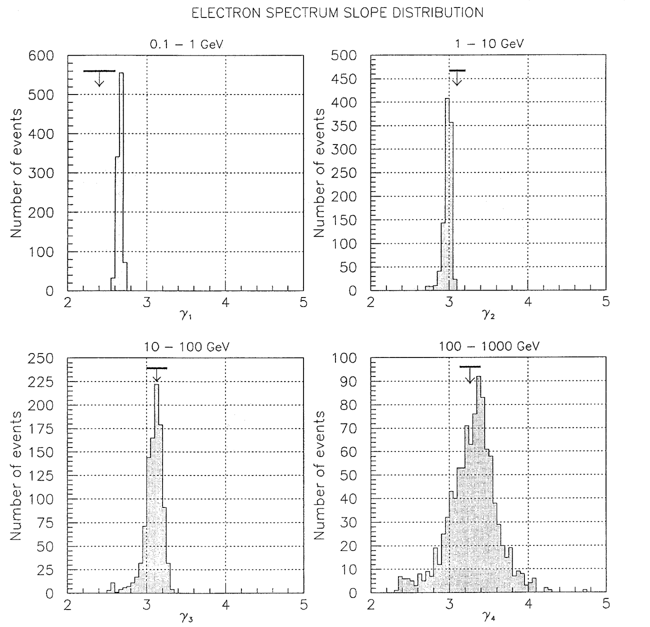

Fig. 5. Frequency distribution of spectral slopes from our calculations, in comparison with observation, arrows and bars. It will be noted that agreement is good except for the lowest energy band; the reason here may be associated with the indirect manner in which the spectrum is determined in this band.

Figure 5 shows the computed spectral components from Figure 3 for different energy bands. The agreement with observation is good, except for the lowest energy band where observational problems cause difficulties; specifically that one must use radio techniques with consequent problems due to absorption of low frequency radiation by ionised gas.

A comment can be made here about the work of Pohl and Esposito (1998). These workers adopt an emergent electron spectrum of the form E^{-2} and make a similar Monte Carlo study to ours. Likewise, they find a spread of predicted spectral shapes at earth. Although they incline to the view that the spread is wide enough to bracket the observed spectrum this seems to us not to be — the range of predicted spectra is, in fact, too narrow and the spectra are all, understandably, too flat. As Figure 5 indicates, for the important range 10-100 GeV, the dispersion of slopes is not great, specifically the half-width-at-half-maximum is only $\Delta\gamma_e = 0.10$; a steeper spectrum than E^{-2} at emergence is certainly needed (as Kobayashi et al. (1999) have noted; they use an emergent spectrum with $\gamma_e = 2.40$, close to our 2.49).

4 Evidence for or against the EW Single Source Model

Figure 6 shows results for both 'protons' and electrons from a (not uncommon) configuration of SN which gives a quite large contribution to the 'proton' component. It is of considerable interest to note that there is a predicted feature in the electron spectrum in the region of 1000 GeV, just where the contemporary measurements cease. There is certainly no inconsistency with the existence of a SSM contribution. Indeed, Kobayashi et al. (1999) have estimated spectral intensities in the region above 100 GeV from known SN, or more accurately, from the pulsars associated with the SN. It is generally agreed that the region of energy above 100 GeV for electrons is sensitive to local, recent SN; by the same token, Figure 6 shows that the spectrum of 'protons' should be likewise.

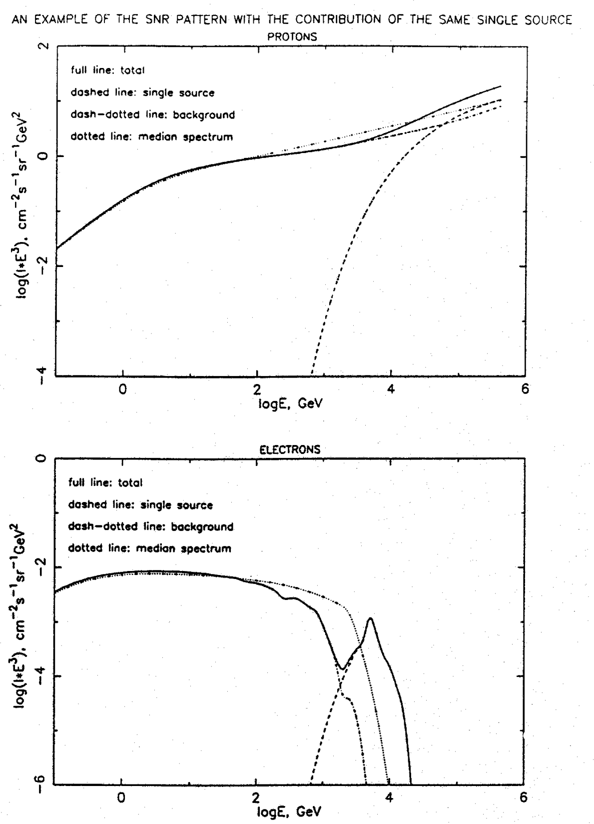

Fig. 6. An example of an SNR pattern with a local/recent SN showing the features visible in both 'protons' and electrons.

5 Contributions from 'known sources'

Our own version of the Kobayashi et al. plot of spectra from specific, known, sources is given in Figure 7. As usual, it is assumed that SNR (not the pulsars) are responsible and that the energy per SN going into CR is 10^{50} erg, and that the particles diffuse with 'our' diffusion coefficient.

Inspection of Figure 7 shows that (as was the case with the calculations of Kobayashi et al.) the discrete sources are starting to affect the predicted total electron intensity, i.e. there should certainly be structure in the electron spectrum.

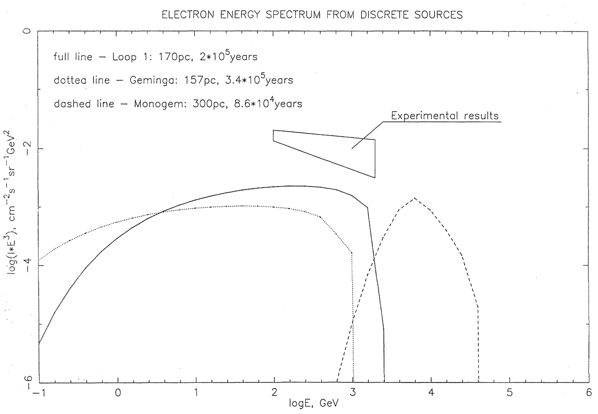

Fig. 7. Electron spectra from the specific discrete sources indicated.

6 The Positron Component

The general view is that positrons in the primary cosmic radiation arise as secondaries from CR — ISM collisions but, of course, there is always the possibility that there are some also from exotic particles, for example, from the decay of mini-black holes. Interestingly, there is some evidence for an excess over conventional expectation (see the summary by Boezio et al., 1999). The excess seems to grow with energy above about 5 GeV. A possible explanation that can be put forward, in the spirit of what has been described already, is in terms of relativistic positrons from radioactive nuclei. It is well known that about 0.07 $M_\odot$ of ^{56}Ni are produced in SN explosions and this undergoes K-capture with a lifetime of 6 days to yield ^{56}Co. The ^{56}Co, in turn, is unstable and decays with a lifetime of 77d by emission of a positron of maximum energy 1.5 MeV. It is commonly argued that the SN light curve, which has a lifetime of $\sim$77d, is governed by this decay. If more than some 10's of percent of the positrons survive the early stages of expansion and are accelerated (with high efficiency since they are already relativistic) then the apparent excess positron flux can be accounted for.

7 Relevance to electrons in Extragalactic situations

As is well known, only very rarely is it possible to infer the electron to proton ratio in Extragalactic 'objects' such as galaxies, the jets from Active Galactic Nuclei (AGN) etc. Often it is assumed that the local value (1%) is relevant in these objects too. Thus, when the electron energy content is determined this is multiplied by a factor of 100 in order to find the total energy. Such a situation is clearly highly undesirable — and could lead to an overestimate by two orders of magnitude in high energy particles in the Universe if, in fact, e/p is more nearly unity. Our model in which the injection efficiency for e and p is dependent on a variety of factors, most notably the Mach number of the accelerating shock, appears to have relevance to the problem.

An example is afforded by jets from AGN (and there is an analogy in the much closer case of the Crab nebula; Robson, 1996), where X-rays are observed at considerable distances from the 'central engine'. The magnetic fields are such that the energetic electrons ($10^{12} - 10^{13}$ eV) would have lost all their energies en route. How, then, are they accelerated? We postulate that weak shocks, which in our model have injection efficiencies close to that for protons, are responsible. A case in point is the very recent work by Leahy et al. (2001) in which measurements of extended X-ray emission around 3C 388 and radio data were used to study the relationship between the inferred CR electron pressure with that of the thermal environment. The required pressure is about a factor ten greater than the electron pressure and Leahy et al. postulate relativistic protons $(e/p = 10\%)$ or electrons emitting below 10 MHz (or both). Thus, the required e/p is not 1% but 10%, nearer to the prediction of our model. In fact, the 10% may well be a lower limit if, as appears to be the case in our Galaxy, very low energy electrons are considerably overabundant (Chi and Wolfendale, 1991) in comparison with the usual extrapolation of the electron spectrum to lower energies.

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