New Journal of Physics
The open access journal at the forefront of physics

Deutsche Physikalische Gesellschaft DPG IOP Institute of Physics

A universal origin for cosmic rays above 10^7 GeV?

To cite this article: A D Erlykin *et al* 2001 *New J. Phys.* **3** 18

New Journal of Physics
An Institute of Physics and Deutsche Physikalische Gesellschaft Journal

A universal origin for cosmic rays above 10^7 GeV?

A D Erlykin[1,2], T Wibig[3] and A W Wolfendale[1]
[1] Department of Physics, University of Durham, South Road, Durham, DH1 3LE, UK
[2] P N Lebedev Physics Institute, Leninsky Prospekt, Moscow, Russia
[3] Experimental Physics Department, University of Lodz, Pomorska 149/153, Lodz, Poland
E-mail: a.w.wolfendale@durham.ac.uk

New Journal of Physics **3** (2001) 18.1–18.14 (http://www.njp.org/)
Received 24 August 2001
Published 12 November 2001

Abstract. An analysis is made of the origin of cosmic rays above about 10^7 GeV. Two models are considered, involving 'super supernovae' and pulsars. In both cases the fluctuations in spectral intensity and shape, for the important iron component, are very great from one pattern of sources to another; the situation is expected to be the same for the other mass components too. There is also 'structure' in the predicted spectra, particularly for pulsars. The experimentally observed spectrum is easily considered as a downward fluctuation on the mean. Adoption of the mean output per galaxy, together with an estimate (in depth) of the volume density of (equivalent-to-ours) galaxies in the Universe leads to an expected extragalactic spectrum not far from observation.

The meaning of the above is that it may be possible to explain all cosmic rays, above 10^7 GeV in terms of Galactic and extragalactic sources involving the same mechanism.

1. Introduction

It is generally agreed that the vast majority of cosmic rays are Galactic in origin and only at the very highest energies, above the 'ankle' at $\log E = 9.5$—with E in GeV—are they extragalactic (EG). These EG particles are usually regarded as coming from 'exotic sources', either via the 'up–down' or by the 'down–up' mechanisms. An example of the former (up–down) would be the decay of dark-matter particles or topological defects and of the latter (down–up) would be the acceleration in dramatic active Galactic nuclei (AGN).

1367-2630/01/000018+14$30.00

In the present paper we examine an alternative scenario: that the EG sources are essentially of the same type as the Galactic ones, specifically what we call 'super supernovae' (SSN) and pulsars. We have described the former in a little detail already (Erlykin and Wolfendale 2001a, hereafter denoted EWI)—and this will be elaborated on; the description of the pulsar work is new.

The essence of the treatment is to use our Monte Carlo treatment of the production and propagation of cosmic rays from sources distributed randomly in space and time (Erlykin and Wolfendale 2001b, hereafter denoted EWII) with SSN or pulsars and to determine the energy spectrum at Earth for each configuration. The mean spectrum is also found. The fundamental point now is that the Galactic spectrum expected is just *one* of those calculated, whereas the EG spectrum will be related to the mean of very many. The latter follows from the fact that many sources contribute (in our model). The model will be a possible one if the predicted EG spectrum is of the order of that observed.

2. Super supernovae

There has been much discussion about the nature of sources above the knee; here we present a model involving a 'special' variety of SN—which we denote as 'super supernovae' (SSN). By SSNR we mean, essentially, sources which produce particles of energy above the PeV region which is commonly regarded as the maximum energy for particles from conventional SNR. A specific possibility is type 1c SN 1998 (Dermer 2001a), and there are others, as described later. As another possibility, we consider pulsars, with these objects being relevant at the very highest energies.

A number of general remarks can be made.

(i) Unless the rate of occurrence of the birth of the sources is much greater than that of conventional SN (10^{-2} per year within the Galaxy of the relevant type II SN)—surely, an unexpected situation—and the lifetime of particles within the Galaxy increasing with energy—another most unlikely situation—the fluctuations in the predicted intensity will be large. By 'fluctuations' we mean the divergence between the outcome from one particular configuration of SN and another. Thus, the usual 'leaky box' model prediction, with an *a priori* smooth distribution of SN, can be grossly in error.

(ii) At rigidities above $\sim 3 \times 10^7$ GV (10^9 GeV for iron) rectilinear propagation will become increasingly important. The fluctuations here are even more serious, although if the actual sources are known the situation is clearly eased.

Our so-called SSNR can be taken to include other, comparatively rare, sources of the type considered by Dermer (2001a): relativistic shocks with second-order Fermi acceleration which can easily achieve 10^{20} eV and beyond. In addition to the 'mildly relativistic' outflows for the type 1c SN 1998 associated with an actual gamma ray burst: GRB 980425 (Weiler *et al* 2000, 2001), GRB involving fireballs with strongly relativistic shocks have also been invoked (Meszaros and Rees 1993, Chiang and Dermer 1999). However, none appears, as yet, to have been observed.

Turning to specific rates of SSNR we adopt the standard rate of 10^{-2} y^{-1} although, as remarked already, we are appreciative of the fact that it could be much less—for example, Dermer (2001b) quotes $\sim 10^{-3}$ y^{-1} for 'his' sources. As will be seen later, we normalize the predicted intensity to observation; this (downward) displacement is equivalent to a reduced rate of

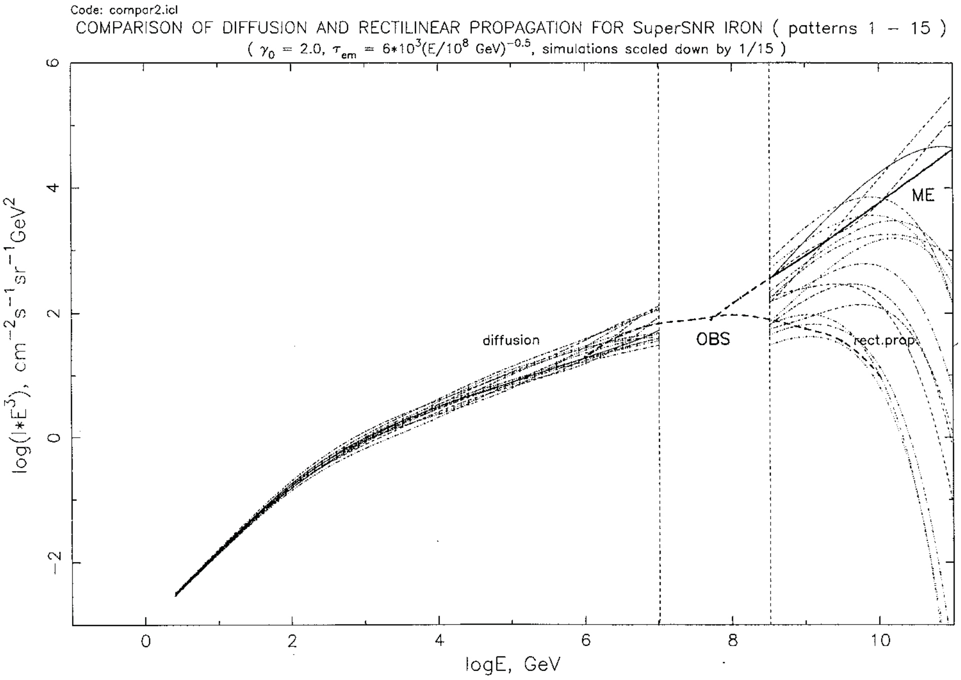


Figure 1. A set of 15 spectra, each for an independent, random collection of SSNR. The results refer to iron nuclei with an energy spectrum on production of the form E^{-2}. Below $\log E = 7$ the propagation is of diffusion type and above $\log E = 8.5$, recti-linear propagation is assumed. 'ME' denotes the mean intensity versus energy above $\log E = 8.5$. 'OBS' relates to the observed Galactic iron spectrum (after Chi *et al* 1994, Wibig and Wolfendale 1999). The power of SSNR in the Galaxy is 10^{50} erg ($\times 10^{-2}$ y^{-1}($\times 1/15$)).

appearance of sources but, although the mean predicted spectrum will be correct, the fluctuations will be even bigger than derived.

Another model for a SSNR is based on that put forward by Lucek and Bell (2000). Here, there is strong coupling of CR to the shock and the result is the production of very high magnetic fields.

For SSN with very high initial shock velocities ($\sim 10^4$ km s^{-1}) it should be possible to just reach 10^{11} GeV for iron nuclei and, as remarked earlier, with relativistic shocks the energy can be higher still. For our calculations, we assume that acceleration in the SSN shock creates particles with rigidities distributed from 10^{-1} to 10^{11} GV. We postulate that the very high energy particles of concern to us are not trapped but escape rather quickly after acceleration (the situation is therefore different from that for 'conventional' SNR). A 'reasonable' dependence of the time interval for emission, $\tau_{\rm em}(E)$, on energy is $\tau_{\rm em}(E) = 6 \times 10^3$ $(E/10^8$ GeV$)^{-0.5}$ y.

This expression comes from an analysis of the acceleration time for very strong shocks (by analogy with the SNR case).

It is necessary, now, to consider the Galactic particle spectrum for which the calculations will be made. It is generally agreed that up to 3×10^9 GeV the bulk of the CR are of Galactic origin and that the particles towards the upper limit, at least, are mainly iron nuclei. That iron nuclei predominate comes from two classes of observations: depth of maximum of the showers and the very low anisotropy. The latter is less model dependent; essentially, calculations with a rather straightforward Galactic magnetic field model and sources distributed in the Galactic Plane give the measured small 'Galactic Plane enhancement' anisotropy only if iron nuclei predominate (see, for example, Chi *et al* 1994, Wibig and Wolfendale 1999, Szabelski *et al* 2001). The authors quoted show that the fraction of the Galactic particles which are 'heavy nuclei' (i.e. most likely iron) is $\sim 90\%$ at 10^9 GeV, rising to $\sim 97\%$ at 3×10^9 GeV. The exponent of the differential spectrum of all Galactic particles is estimated as ~ 3.1 at 10^8 GeV, ~ 3.6 at 10^9 GeV and ~ 4.0 at 3×10^9 GeV.

The adopted iron spectrum is shown in figure 1.

Returning to the model, in view of the comparatively rapid escape of particles from the shock, the emergent spectrum was taken to be of the straightforward E^{-2} form. The energy required for each SSNR was taken such that there was an approximate fit between the mean of the spectra derived using our Monte Carlo calculations and the 'observed' iron spectrum just described. The normalization energy was chosen as $\log E = 6$ and the required energy per SSNR is 10^{50} erg $\times 15^{-1}$. The factor 15^{-1} is not unreasonable for the fraction of total energy given to the iron component—at lower energies, in the SNR region, the factor is $\sim 10^{-1}$. Also the rate of SSNR might be lower than the 10^{-2} y^{-1} for SNR.

Figure 1 shows the result of our Monte Carlo calculations for the situation just described. The gap is the transition region where neither the diffusion mechanism nor rectilinear propagation is appropriate. Results are given for a set of 15 SSNR patterns.

It is seen that the 'observed' spectrum can be easily achieved in some of the possible SNR and SSNR space–time configurations.

3. Pulsars

3.1. Energetics

A number of workers have evaluated the likely maximum potential drop available from pulsars, the source of the energy being the rotating magnetic field. A typical result is that given by Giller and Lipski (2001):

$$\phi = 6.6B/P^2, \tag{1}$$

where ϕ is the maximum potential drop in volts, B is the field strength in Gauss and P is the period, in seconds. The rate of energy loss is given by

$$\dot{E}_{\mathrm{tot}} = \frac{E_0}{T\,(1+t/T)^2}, \tag{2}$$

where E_0 is the initial rotation energy, T is the pulsar 'starting' age, equal to $P_0/(2\dot{P}_0)$, P_0 and $\dot{P}_0$ are the initial period and its time derivative and t is the current time. The result is that over the life of a pulsar the emitted spectrum is of the form $1/E$.

If the particles are mainly iron, then the maximum energy is

$$E_{\mathrm{Fe,max}} \simeq 2.6 \times 10^{-8}\,\phi\,\mathrm{GeV} \rightarrow 10^{12}\,\mathrm{GeV}, \tag{3}$$

for B equal to a few $\times 10^{13}$ G and $P \sim 1$ ms. That iron is a very likely nucleus to be emitted by a pulsar comes from the fact that it is likely from astrophysical reasons that iron should predominate on the pulsar surface.

The situation with respect to the 'concentration' of millisecond pulsars is not clear—a fact that stems from their very short lifetime (e.g. 1 y at 10^{11} GeV). The smallest periods for non-binary pulsars so far recorded (in the Galaxy) seems to be those of $2322 + 2057$ (4.81 ms) and $2124-3358$ (4.93 ms), with a 3 ms pulsar (B1821-24) in M28. Theoretical work on the 'evolution of rotating massive stars' includes that of Heger *et al* (2000); these authors make the point that there should be many millisecond pulsars coming from the collapse of rapidly rotating massive stars. The problem thus resolves itself into 'how many such rapidly rotating stars are there?'. There are many factors which determine this number, but some general remarks can be made. It is likely that regions of dense star formation (e.g. OB associations) will have a high fraction of such stars for reasons of angular momentum transfer in the collisions of the pre-cursor clouds. Particularly important here is the likelihood of some EG systems having an enhanced density of short-period pulsars; the ensuing high rate of star formation in galaxies under collision is a likely source of high angular momentum precursors as well as a high rate of SN.

Turning to energetics, it is of interest to compare the total energy involved in a pulsar ($\frac{1}{2}I\omega^2$) with that for a 'standard SN', i.e. 10^{53} erg, including neutrinos, of which 10^{51} ergs is, in principle, available for CR acceleration and acceleration and heating of the ISM gas. With the standard value for the moment of inertia of a neutron star, $I = 10^{45}$ g cm^{-2} and what is probably the shortest allowable period (1 ms), the total energy, $\frac{1}{2}I\omega^2$, would be 2×10^{52} erg. In fact, 'our' initial period is 5 ms, a value that seems more typical and one which, in fact, gives equality with the available energy for SNR: $\sim 10^{51}$ erg. The equality with the available energy for SNR is interesting and, in a sense, useful insofar as it means that pulsars and SNR (and presumably SSNR) are similar contenders for the sources of the highest energy particles; indeed, *both* may contribute.

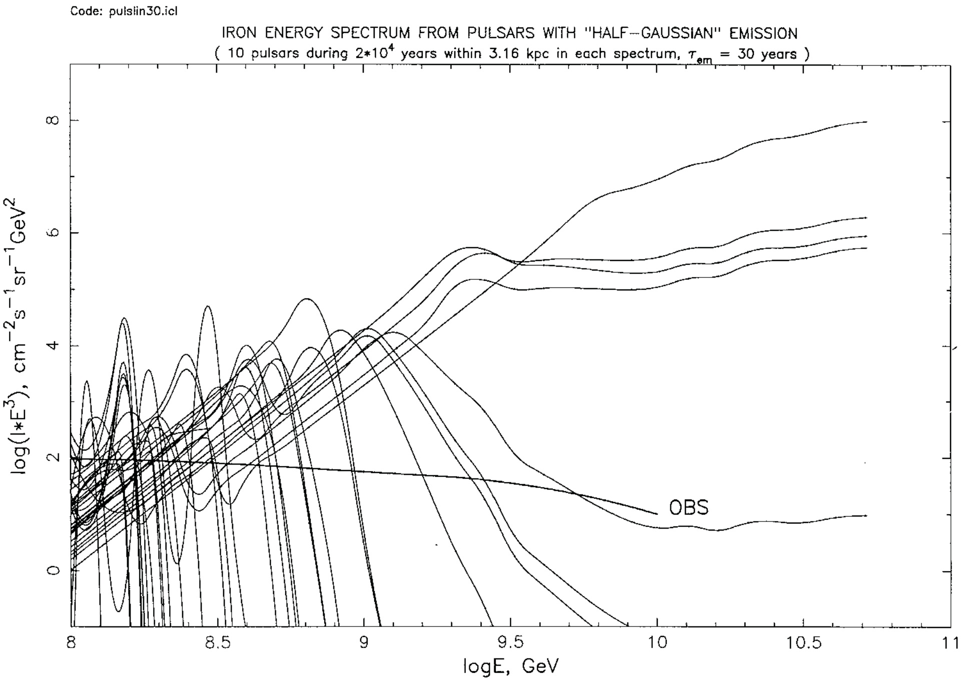
Presumably the equality is more an accident than a fact of fundamental physical importance insofar as the pulsar rotational energy is dependent on the angular rotation of the precursor star and this is selected from quite a high range.

The extent to which the energy released as the pulsar slows down is, in fact, converted into cosmic rays is not clear; that taken off by gravitational radiation in the important early stages is particularly debatable. Here, we perform most calculations assuming that the 'efficiency' for CR acceleration is energy-independent.

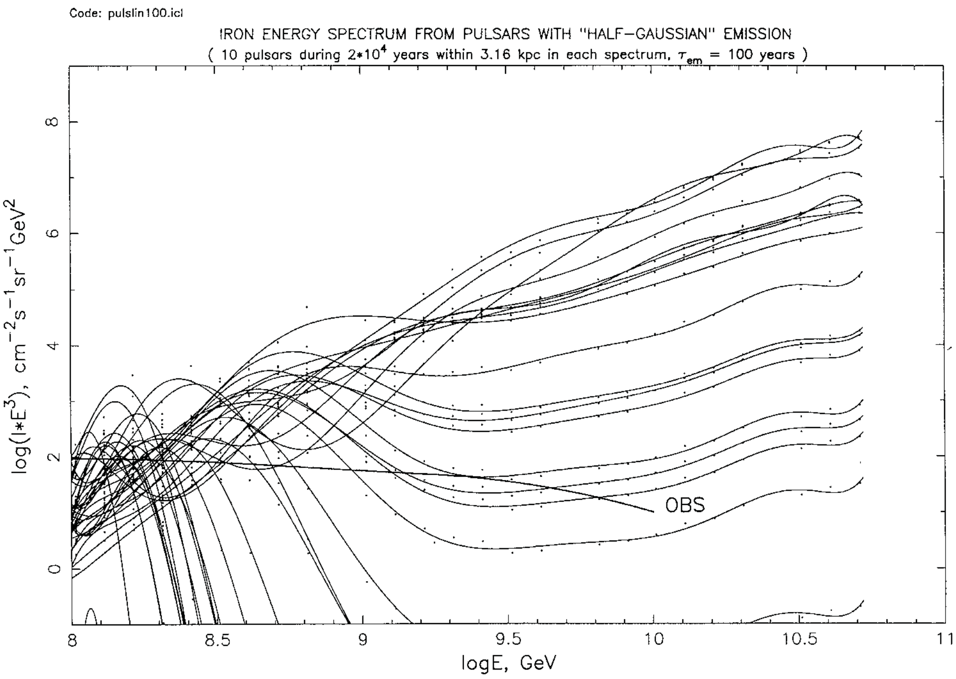
3.2. The emission model

Taken literally, the models predict the emission of particles of a unique energy at a particular time but this is clearly unphysical. Here, we allow for the distribution of the potential drop for different directions of the emission to give a saw-tooth shape spectrum up to the maximum energy. The energy content of this spectrum was equal to that maximum energy. This form is adopted; to some extent it allows for a variety of smoothing effects.

Of greater significance is the time interval over which the particles of a particular energy can be considered to be emitted. Presumably there are diffusion-like effects in the pulsar atmosphere which can be important. We adopt a semi-Gaussian fall for this time distribution and assume that its standard deviation, τ_{em}, is independent of energy. Calculations have been made for three values of τ_{em}: 30, 100 and 300 years. This emission time can be considered to also include the residual differences of transit time between emission and arrival at Earth, such differences arising from the effect of the regular and irregular magnetic field, which distorts the rectilinear propagation that was adopted above rigidities of $\sim 3 \times 10^7$ GV, similar to the case of cosmic rays from SSN.

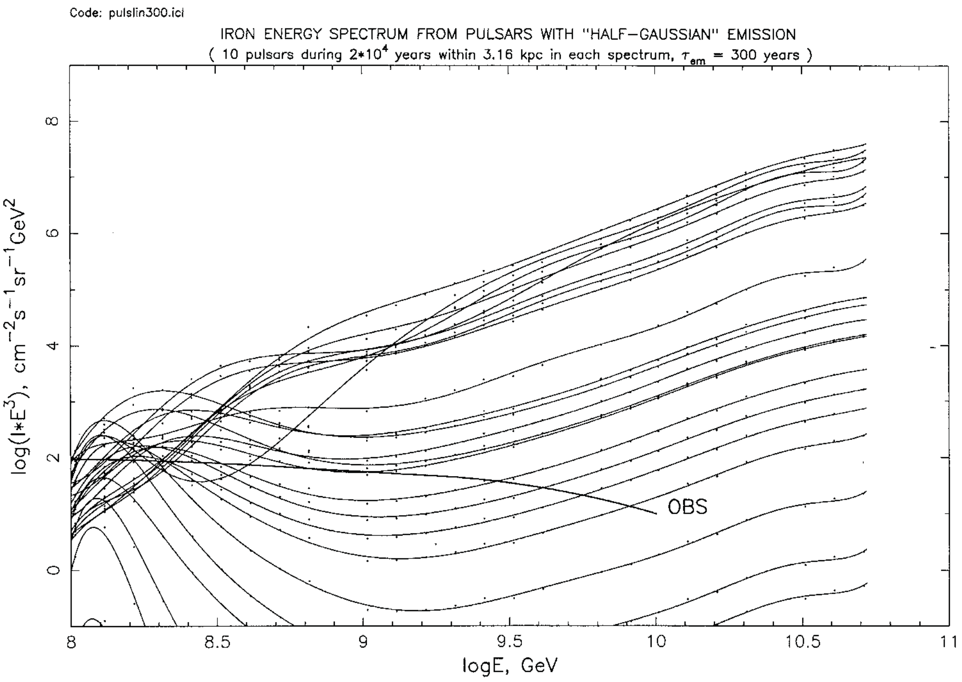


(a)



(b)

Figure 2. Sets of 50 spectra, each for an independent random collection of pulsars. The mean emission time, independent of energy, is, successively, 30, 100 and 300 years. The form of the emission profile is a 'half-Gaussian'. The observed Galactic iron spectrum is indicated. The energy content per pulsar is 10^{50} erg and their rate in the Galaxy is 10^{-2} y^{-1}. The small undulations in predicted intensity above $\log E = 9.5$ are technical artifacts.



(c)

Figure 2. Continued.

3.3. The Monte Carlo calculations

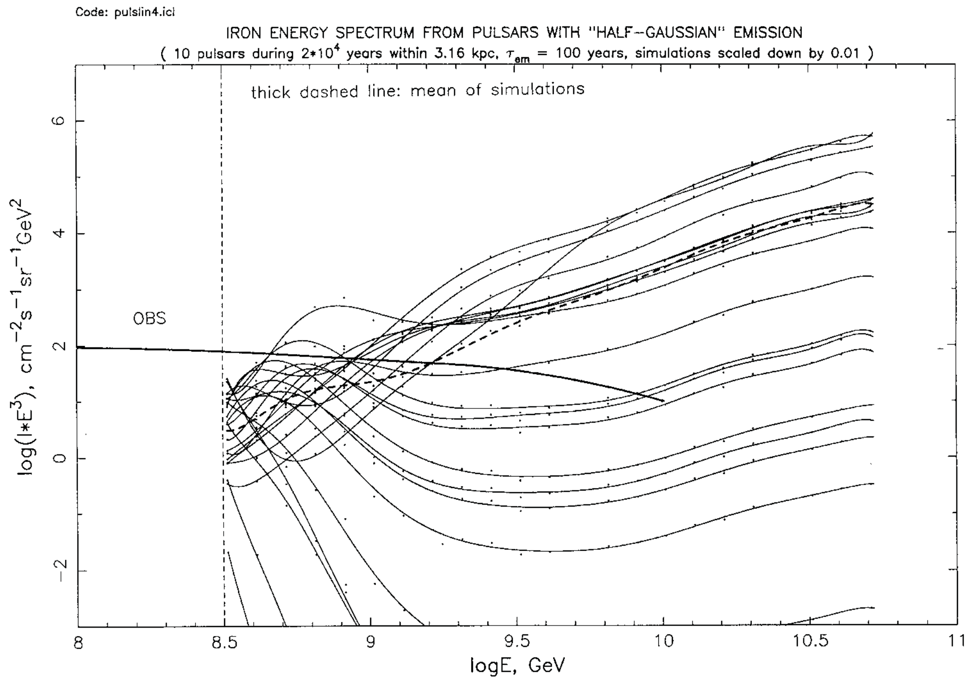
The calculations are of the same form as for SNR, indeed the same random distribution of sources (pulsars) is taken in each case. The details are given in II. In this particular application of the pulsar model we choose $P_0 = 5$ ms and $B = 1.4 \times 10^{13}$ G. The maximum energy (for iron) is near 10^{11} GeV and the initial energy content is 8×10^{50} erg. We adopt, as usual, an efficiency factor of $\sim 10\%$, in the first instance at least.

Figure 2 gives the results for the situation where the emission time is 30, 100 and 300 years. A 'half-Gaussian' distribution is adopted to characterize the emission. Of the times, the 'best' is $\tau_{\mathrm{em}} = 10^2$ y and figure 3(a) gives the corresponding spectra for this situation. Remarkably, the results are sensitive to the tail of the Gaussian, and figure 3(b) shows the effect of terminating the tail at 3σ. In order to achieve a reasonable fit to the absolute intensity in the region of $\log E = 9$, the intensities from figure 2(b) have been multiplied by 0.01. The region below $\log E = 8.5$ has been omitted, as previously (figure 1), because of problems with magnetic deflections. Also shown is our estimate of the Galactic iron energy spectrum (after Chi *et al* 1994, Wibig and Wolfendale 1999).

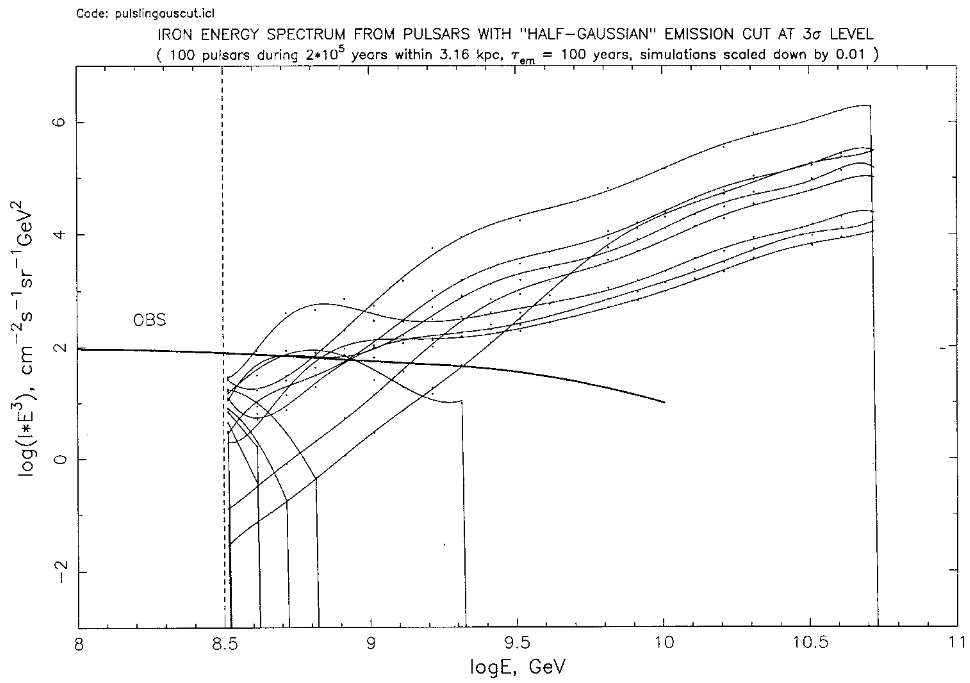
3.4. Comparison of observations and expectation

A number of remarks can be made, as follows.

(i) If the rate of pulsar birth is the same as that of SNR, i.e. 10^{-2} y^{-1} in our Galaxy, a predicted energy spectrum of the form observed (or an approximation to it) can be achieved with a pulsar model in which the energy per pulsar going into UHECR is $\sim 10^{48}$ erg, i.e. only 1% of the canonical *total* energy for SNR. Such a fraction is not unreasonable.



(a)



(b)

Figure 3. (a) As for figure 2(b) but with the ordinate reduced by 100 in order to fit the experimental data. 'OBS' is, as before, the Galactic iron spectrum. (b) As for (a) but with the half-Gaussian truncated at the 3σ level. The effect of the Gaussian tail is seen to be large—cutting off the tail usually cuts off the highest energy particles. Clearly the sharp cut-off in intensity is not physical.

(ii) Inevitably, the overall mean spectrum is very flat (E^{-1}) so that it can be invoked only above about $\log E = 8$.

(iii) The fluctuations in spectra, 'run-to-run', are very large. The observed spectrum looks to be about average—it is not unusual.

(iv) There is considerable 'structure' in the predicted spectra and, interestingly, there are peaks in the range $\log E$: 8.5–9.0, which is where inspection of the data (e.g. in the summary by Szabelski *et al* 2001) shows some evidence for such structure.

4. The extragalactic component

4.1. General remarks

As remarked already, the idea under examination is that the EG particles, detected at Earth, are produced by the same type of source (SSNR or pulsar; here we just use the term SSNR but include, within it, pulsars as an alternative) as are most of the Galactic particles above the knee.

What is needed is the volume density of such sources in the Universe and an estimate of its spatial, and perhaps temporal, variation. A number of factors need to be considered, as follows:

(i) the situation in our Galaxy, in terms of likely production rate of SSNR, energy spectrum, and frequency per unit mass and unit luminosity.

(ii) the volume density of galaxies in terms of equivalent Milky Way galaxies from the standpoint of luminosity and mass, to be denoted ρ_0.

(iii) the effect of galaxy type on (ii) in connection with a dependence of SSN rate on type.

(iv) spatial variations, most notably the effect of our being inside the VIRGO supercluster.

(v) temporal effects—the significance of starburst galaxies and active galactic nuclei (AGN).

(vi) cosmological effects.

4.2. Galactic properties

As remarked already, we take the rate of the important type II SN as 10^{-2} y^{-1}. We take this as a datum frequency for SSN too—presumably the actual rate is less than that of 'ordinary' SN although if SSN are to be found in OB associations, as mentioned in section 2 the rate may not be much less. For example, Bykov and Toptygin (1997) quote $\sim 10^{-5}$–10^{-6} y^{-1} as the typical SN rate in the OB associations and 'several thousand' associations in the Galaxy. Adopting 3×10^{-6} y^{-1} and 3000, respectively, the average rate is, in fact, $\sim 10^{-2}$ y^{-1}. As mentioned already, Dermer (2001a, 2001b) prefers 10^{-3} y^{-1}.

Surprisingly, there is some doubt about the 'type' of our Galaxy, with opinion divided between S_b and S_{bc}; this is a matter of importance because of the dependence of SN rate on type.

Concerning Galactic mass, that in baryons is $\sim 1.2 \times 10^{11}$ $M_\odot$ and the luminosity is $M_V = -20.5$.

4.3. Universal averages of mass and luminosity

The average baryonic mass in the form of 'visible matter' in the Universe as a whole is commonly taken as about $\Omega_B = 0.024$, of which $\frac{2}{3}$ is in cluster gas and $\frac{1}{3}$ is associated directly with stars, i.e. of immediate relevance to the Galaxy. Taking $\Omega_B^* = 0.008$ and a closure density of 1.1×10^{-29} g cm^{-3}, with a Galactic mass of $1.2 \times 10^{11}\ M_\odot$ leads to a density of Milky Way-style galaxies of

$$\rho_G \simeq 1.0 \times 10^{-2}\,\mathrm{Mpc}^{-3}. \tag{4}$$

In fact, the cluster gas has relevance, for the following reason: an interesting consequence of the presence of large amounts of gas in galaxy clusters is the presence of 'cooling flows' (e.g. Fabian 1994); some of the energy is used to compress the magnetic field in the large cluster galaxies, and this immediately has consequences. The main one is to enhance the 'efficiency' of SSNR regions for the production of ultra high energy particles. Interestingly, Fabian reports that compression of magnetic fields can cause $B \simeq 30\ \mu$G, with a reversal length of ~ 10 kpc. Such B, ℓ values lead to rigidities of order 3×10^{10} GeV; corresponding to $\sim 8 \times 10^{11}$ GeV for iron nuclei. A further fact is that the hot intercluster medium, with temperature 10^7–10^8 K, is very likely to be an environment where the injection efficiency for cosmic rays is high.

Including the effect of cluster gas in the mass analysis leads us to write an enhanced 'density':

$$\rho_G' \sim 2 \times 10^{-2}\,\mathrm{Mpc}^{-3}. \tag{5}$$

Turning to luminosity, insofar as the mass to light ratio does not seem to vary much from one galaxy to another (e.g. Binggeli *et al* 1988) luminosity arguments add nothing to the mass analysis as such.

4.4. Variations of SN rates

The first correction relates to the need to allow for the ratio of the SN rate in the 'average' galaxy to that in our own Galaxy.

The main aspect here is the dependence of SN rate on galaxy type, not least for the important SNII component; the underlying factor being the frequency of the very massive precursor stars. Such stars are also of considerable importance for the production of rapidly rotating neutron stars, such rapid rotation being a prerequisite for ultra high energy particle acceleration (see section 3.1).

It is generally agreed that the SN rate depends on galactic properties. Van den Bergh and Tamman (1991), in their summary, give results for the dependence of SN rate on galaxy type and luminosity. Concerning the former, the results are

$$ESO(0.98); SO/a, S_a(0.70); S_{ab}, S_b(2.11); S_{bc} - S_d(5.19) \quad \text{and} \quad S_{dm} - I_m(5.6), \tag{6}$$

the number in the brackets being the relative SN rate. Type II SN have a preference for the last three galaxy types.

It is interesting to note that there is discussion as to which type our own Galaxy belongs. Schmidt-Kaler and Schlosser (1973) designated it as type S_{bc} but more recent work favours it being intermediate between S_b and S_{bc}. What is needed is the mean value for the SN rate weighted over the *a priori* frequency distribution of galaxy types. Using the distribution, weighted by brightness, given by Voigt (1974) (e.g. $S_a(8\%), S_b(18\%)$ and $S_c(33\%)$) and assuming that the Galaxy is midway between S_b and S_{bc} the ratio of the mean rate to that of the Galaxy is $\simeq 1.6$. The value of the effective density of galaxies therefore rises by 1.6 to $\rho_G' = 3.2 \times 10^{-2}$ Mpc^{-3}.

4.5. Spatial variations

The most important situation here is, presumably, that we are not at an 'average' position in the Universe but on the outskirts of the VIRGO supercluster and thereby in a region of higher than average galaxy density.

Inevitably, there are problems in determining the effect of this situation on the value of ρ_G, these problems stemming from a lack of knowledge of the magnetic field topography between VIRGO and the Sun, and the exact details of the distribution of matter within the central VIRGO cluster, and its environment.

For the situation where magnetic fields are ignored, the calculations of Tkaczyk *et al* (1975) give guidance. For the case where the initial particles are iron nuclei, the intensity is enhanced by (in logarithmic units): 0.38 at 10^{11} GeV, 0.26 at 3×10^{10} GeV, no change at 10^{10} GeV and (a reduction) -0.0045 at 10^9 GeV. Insofar as we are interested, mainly, in the energy range 10^{10} to 10^{11} GeV, the average value for the enhancement to take is ~ 0.32 (in logarithmic units), i.e. a ratio of ~ 2.

The 'final' value is thus $2 \times \rho'_G$, i.e.

$$\rho''_G = 6.4 \times 10^{-2}\,\mathrm{Mpc}^{-3}. \tag{7}$$

This is the value that will be used in the calculations.

The whole question of propagation in EG space is taken up separately in section 5.

4.6. Starburst galaxies (SBG) and AGN

Insofar as both SBG and AGN involve (or may involve) SN, their incidence in the Universe is of importance. It seems that many AGN were formed by colliding galaxies and that starbursts are caused when the galaxies are gas rich. AGN are important because of their comparatively high frequency: $\sim 10\%$ of bright galaxies, of which quasars comprise $\sim 1\%$ (Maeder and Conti 1994).

The relevance of all this to the present problem is not completely clear because not only are SN involved as energy sources: black holes are often invoked, as is well known. However, a very interesting—and relevant—mechanism has been proposed for the lower luminosity AGN, involving starbursts and type II SNR (see Robson 1996 for details). Specifically, shock velocities as high as 2×10^4 km s^{-1} have been invoked and this is just the sort of magnitude that is needed for the UHE acceleration model referred to in section 2.

Nevertheless, we do not increase ρ''_G for this effect.

4.7. Cosmological effects

Many of the phenomena discussed so far become even more important in the early Universe, not least because the probability of galaxy–galaxy collisions is greater there. The factor by which one should increase ρ''_G could be quite significant. Some work by Chi and Wolfendale (1989) is relevant here. These workers examined the various radiation fields from the standpoint of comparing the actual EG intensity with what would be expected if there were 10^{-2} galaxies Mpc^{-3} of the same luminosity as our own. In the analysis, a modest cosmological increase in output was allowed, to the extent of just integrating back to $z_{\max} = 4$; the value of H_0 was 100 km s^{-1}Mpc^{-1}. The so-called 'background radiation enhancement factor' F was found to be, for each radiation field: Radio (8); FIR (9); V (0.5); UV (8), x-rays (25); γ-rays (10). It is of interest to note that only in the case of visible light is the ratio less than one. It cannot be claimed that the effective density factor, ρ, is, correspondingly, of order $10 \times 1 \times 10^{-2}$ for our purpose (SNR/pulsars) because most of the radiation is generated by other mechanisms. However, some of these mechanisms are related to SNR (conventional SNR at least). For example, 'radio' and 'gamma rays' both have sizeable contributions from electrons accelerated by SNR.

Insofar as we already have an increase in density by a factor 6.4, the residual factor is less than 2. Presumably if, as is likely, much of the factor 2 comes from cosmological effects—i.e. an increased luminosity at high z—then UHE particles produced would be attenuated very severely in their passage to Earth. The attenuation is due to both the CMB radiation and the undoubted presence of magnetic fields in the intergalactic medium, fields which slow down the particle propagation and lead to many particles never arriving at the Earth in the Hubble time; thus a further factor of 2 increase in ρ_G'' may not be justified.

4.8. The expected EG spectrum from Universal SSNR and from pulsars

The expected EG spectrum follows simply from ρ_G'', assuming, as we have maintained, that all HECR—above the knee—come from the same type of source.

The value of ρ to be adopted, after allowance for the factors enumerated in sections 4.2–4.5, is 6.4×10^{-2} Mpc^{-3}.

The expected EG spectrum is as shown in figure 4. EG(0), the spectrum to be expected, in the absence of any EG attenuation, follows directly from the Galactic mean spectrum (ME), using the value of ρ_0 just referred to. Application of the reduction factors adopted by Szabelski *et al* (2001) for the case of iron nuclei at source gives EG(pred.)—not far from the observed EG spectrum (OBS).

The spectrum for SSN is not far off, in shape, the spectrum for pulsars (EG(P)) is not as good. In fact, it is not inconceivable that SSNR and pulsars *both* contribute to the flux. Adding the two would give a spectrum rather close (within a factor 2) to the observed spectrum.

5. Conclusions

Most workers in the field would probably agree with our contention that conventional SNR are prominent sources of CR at energies below the knee. At higher energies, although there is no consensus as to origin, most would agree that iron nuclei become increasingly prominent as one approaches 3×10^9 GeV, above which EG particles rapidly 'come in'. The mass of the EG particles is uncertain, although we prefer a mixture, such as would come from largely iron nuclei accelerated at their sources. We draw attention to the fact that, because it is the Lorentz factor, E/Z, that is important in interactions with the CMB, rather than the energy itself, very heavy nuclei are less fragile than protons in their passage through the Universe.

Concerning Galactic particles above the knee, whatever the sources, fluctuations in intensity are expected over long periods (10^5 y or so) and the 'Leaky Box' model is invalid. We have put forward here, for the first time, a model in which there is only one dominant type of source (pulsar?, super SNR?, ...?) for the particles, both Galactic and EG. Our 'measured' Galactic spectrum, with its steepening shape above 10^9 GeV (see section 2), is simply the result of a not-uncommon downward fluctuation in intensity, namely, by chance, there has been

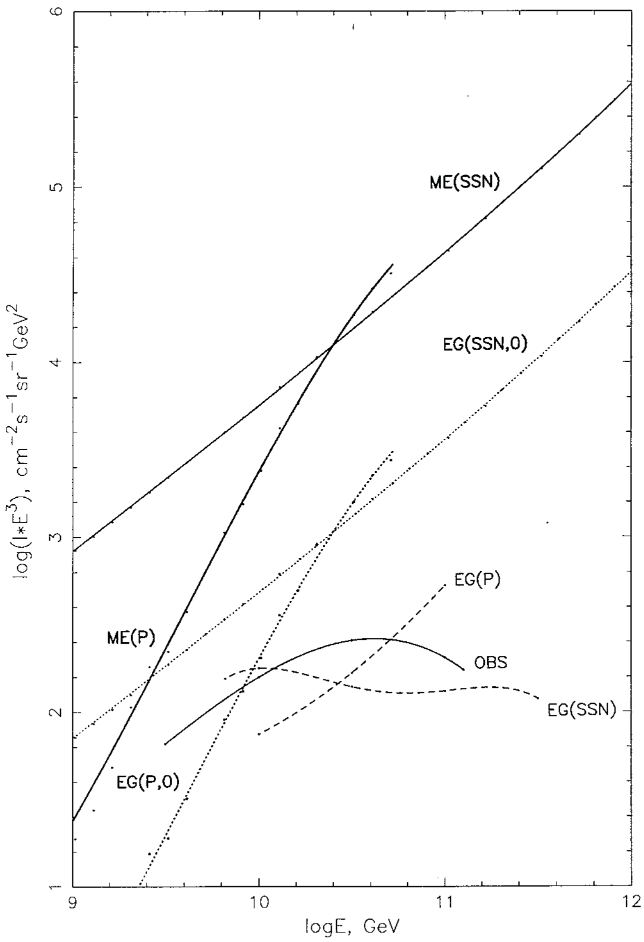


Figure 4. The predicted EG spectrum for the case where there is only one type of source of UHECR in the Universe. EG(0) is without CMB losses and EG(pred.) includes them. 'OBS' is the 'observed' EG spectrum from the World-Summary of Szabelski *et al* (2001). 'ME' relates to the mean of the spectrum for the SSNR situation (figure 1). The sum of EG(SSN) and EG(P) would be an acceptable fit to observation.

no recent nearby Galactic source at these energies—a situation which is the opposite of the likely situation for the origin of the knee, but not an inconsistent one since the sources are different.

The resulting EG spectra (for iron), for SSNR and pulsars, are not identical with that implied by observations of shower depth of maximum and anisotropy, but not far off, particularly for the SSN model, the maximum discrepancy in spectral intensity being only a factor 3. Furthermore, if both SSNR *and* pulsars contribute, their sum will be within a factor of 2 of observation.

It is not obvious as to how one might confirm, or disprove, the fluctuation hypothesis, which is perhaps the most important aspect considered in this paper. The best that we can offer at present is a search for rare energetic cores of radiation-damaged material on the lunar surface; such cores would result from the very considerable concentrated energy deposition caused by the impact of the occasional 10^9–10^{10} GeV iron nucleus.

Acknowledgments

The authors are grateful to The Royal Society and PPARC (both in the UK) for financial support.

References

Binggeli B *et al* 1988 *Ann. Rev. Astron. Astrophys.* **26** 509
Bykov A M and Toptygin I N 1997 *Proc 25th Int. Cosmic Ray Conf., Durban* **4** 365
Chi X and Wolfendale A W 1989 *J. Phys. G: Nucl. Part. Phys.* **15** 1509
Chi X *et al* 1994 *J. Phys. G: Nucl. Part. Phys.* **20** 673
Chiang J and Dermer C D 1999 *Astrophys. J.* **512** 699
Dermer C D 2001a *Proc. 27th Int. Cosmic Ray Conf., Hamburg* **6** 2039
—— 2001b *Proc. 27th Int. Cosmic Ray Conf., Hamburg* Rapp. Vol.
Erlykin A D and Wolfendale A W 2001a *Europhys. News* accepted for publication
—— 2001b *J. Phys. G: Nucl. Part. Phys.* **27** 941
Fabian A C 1994 *Ann. Rev. Astron. Astrophys.* **32** 277
Giller M and Lipski M 2001 *Proc. 27th Int. Cosmic Ray Conf., Hamburg* **6** 2092
Heger A, Langer N and Woosley S E 2000 *Astrophys. J.* **528** 368
Lucek S G and Bell A R 2000 *Mon. Not. R. Astron. Soc.* **314** 65
Maeder A and Conti P S 1994 *Ann. Rev. Astron. Astrophys.* **32** 227
Meszaros P and Rees M J 1993 *Astrophys. J.* **405** 278
Robson I 1996 *Active Galactic Nuclei* (New York: Wiley)
Schmidt-Kaler Th and Schlosser W 1973 *Astron. Astrophys.* **29** 409
Szabelski Y, Wibig T and Wolfendale A W 2001 *Astropart. Phys.* at press
Tkaczyk W, Wdowczyk J and Wolfendale A W 1975 *J. Phys. A: Math. Gen.* **8** 1518
van den Bergh S and Tamman G A 1991 *Ann. Rev. Astron. Astrophys.* **29** 363
Voigt H H 1974 *Outline of Astronomy II* (Groningen: Noordhoff)
Weiler K W *et al* 2000 *Preprint* astro-ph/0002501
—— 2001 *Preprint* astro-ph/0106131
Wibig T and Wolfendale A W 1999 *J. Phys. G: Nucl. Part. Phys.* **25** 1099