

The cosmic-ray knee and ensuing spectrum seen as a consequence of Bell's self-magnetized SNR shock acceleration process

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Abstract.

Bell's version of diffusive shock acceleration in supernova remnants, in which the (highly contorted) magnetic field is mainly self-generated by the accelerated particles, seems to explain the sharpness of the knee in the cosmic ray spectrum (an effect of the limitation of acceleration in the source), despite contributions from very many supernovae; and the expected knee has a sharp drop near 3 PV rigidity for each nuclear species, and then a lower rounded shoulder extending towards 100 PV contributed by some of the type II SNRs. It is shown that the all-particle flux determined by very different techniques in air shower observations defines a very precise spectrum, below 10^{19} eV, and this spectrum is discussed in terms of separate nuclear components of Galactic and extragalactic origin. An extragalactic component with similar source spectrum to the Galactic component is favoured, but a helium/hydrogen mixture and a pure proton flux from the extragalactic sources have different attractions, and offer different tests through composition, even below 10^{18} eV.

1. Interpreting the notable features of the cosmic ray spectrum

A major task of cosmic-ray investigations has been to explain the energy spectrum, through quantitative models of the acceleration and release of the particles, and of their subsequent spread and their energy and spallation losses. Below the knee there is the well-known form of energy spectrum, close to $dN/dE \propto E^{-2.7}$, over many decades of energy: then there is the "knee" at $3 - 4 \times 10^{15}$ eV, where the rate of fall steepens, although not by very much; then at a less well-defined "second knee" near 2×10^{17} eV, it steepens further; and at the "ankle" near 4×10^{18} eV, the rate of fall of flux becomes much slower again. Above 5×10^{19} eV, the flux is expected to fall off quite sharply, due to the threshold energy for important interactions between cosmic-ray particles and photons of the cosmic microwave background (the Greisen-Zatsepin-Kuzmin, or GZK, effect) — though it might have been expected to start falling earlier than this because of the great difficulty of accelerating particles to rigidities $\sim 10^{20}$ V (1). However, the difficult measurements in this domain of very low flux have not given a consistent picture above 10^{19} eV, and it is hoped that the Auger project will soon clarify the situation here. The general consensus has been that before the knee the flux is dominated by cosmic rays from Galactic sources, primarily supernova remnants, but above the knee this flux gradually peters out, either because the more energetic particles are able to escape rapidly from the Galaxy, as once thought, or from the accelerator, as now seems likely. For either of these reasons, this Galactic flux eventually falls below the level of a universal flux of cosmic rays generated

in extragalactic sources — probably associated with radio galaxies, or perhaps with gamma ray bursts — and we see the extragalactic flux beyond the ankle, so the sharp decline in flux temporarily ceases here. (However, earlier indications that the flux remained high where the GZK effect predicted a sharp fall in the extragalactic flux stimulated some speculations that heavy nuclei might be accelerated to these ultra-high energies by other types of Galactic source, such as magnetars, and their directions randomized by Galactic magnetic fields.) The “second knee” has been attributed either to a feature of the extragalactic spectrum (2; 3; 4; 5) caused by a threshold for pair-producing interaction with the cosmic microwave background during a long journey from the most active epoch of acceleration, or else to the end of the Galactic component (the heaviest nuclei) (6). In this investigation it will appear probable that both of these effects play a part.

Much the most persuasive model of cosmic ray generation is the process of diffusive shock acceleration, and the thesis of this paper is that, with the recent development by Bell and Lucek (7; 8), in which the magnetic field is largely generated by cosmic-ray-plasma interactions ahead of the shock (at any rate in the most active phase of acceleration), this model may be able to provide a quantitative treatment of the spectrum and composition features, in particular, the position and shape of the knee. This is not simple, as many variants of supernova have to be treated, but results of rough calculations are shown in support of this. (A different earlier attempt to explain these features by Biermann (9) does not appear to the present author to be valid (10).) The nuclear make-up of the whole spectrum up to 10^{19} eV and above is discussed on this basis, although details of the extragalactic component that are shown here are preliminary, and are being refined in ongoing work.

The first apparent success of the diffusive shock acceleration model was in explaining the general slope of the cosmic-ray spectrum. The usual leaky-box analysis of spallation of cosmic rays indicated a confinement time in the Galaxy varying as $E^{-0.6}$, and allied to the expected spectrum $\sim E^{-2.1}$ in the sources, in this model, the observed spectrum, $E^{-2.7}$, was easily understood. However, the absence of signs of rapid loss of particles from the Galaxy at air shower energies, most notably the small anisotropy, is consistent instead (e.g. (11; 10)) with a confinement time falling at the slower rate of $E^{-1/3}$, as would result from scattering by a magnetic field exhibiting a Kolmogorov spectrum of turbulence. This energy dependence of the residence time corresponds to the general consensus expressed at this Aspen workshop, and can be reconciled with the spallation data by the effects of second-order acceleration of particles whilst scattering during propagation (12), but it implies that the sources release cosmic rays with a spectrum $\approx E^{-2.35}$. This modification to the usual picture of diffusive shock acceleration will therefore be assumed in the present work. It could in part reflect the progressive escape of particles at different energies, as the magnetic field falls, for instance, but it must be admitted that it is not certain that the spectrum would then remain such a good power law as we see in the cosmic rays around us. Following from the shock acceleration model, it will be assumed as a good approximation that each nuclear species has the same form of rigidity spectrum at source, with standard relative abundances, these being governed by the composition of the surrounding matter swept up by the shock, modulated by a Q/M and volatility bias intrinsic to the shock acceleration process.

It will firstly be shown, in section 2, that highly developed air shower experiments which derive the primary spectrum in different ways agree astonishingly well on the “all-particle” spectrum except beyond the ankle, where there is some divergence in results at present. This spectrum fits well onto the direct observations of the primary particles made at lower energies, described by a simple power law spectrum where nuclear spallation effects are unimportant, as at high energies. This detailed all-particle spectrum is to be describable as the sum of the fluxes of individual nuclear types. The KASCADE experiment has produced very good evidence that the fluxes of individual nuclear components drop much more sharply than would be guessed by

looking at the total (all-particle) flux; and this principal KASCADE result, together with the air-shower all-particle spectrum, and the more detailed spectra at lower energies from balloon experiments, can all be fitted together by making the assumption of universal rigidity spectra and nuclear composition at source. The result is a specific form for the Galactic part of the energy spectrum, each nucleus having virtually the same power-law energy spectrum, until a sharp turn-down near a rigidity of 3 PV. It will be argued later that there is a rounded extension between about 7 PV and the clearly extragalactic flux, that is probably a part (“part B”) of the Galactic component.

Secondly (section 3), if one adopts Bell’s version of diffusive shock acceleration in supernova remnants (SNR) as a good approximation, its probable result is a sharp knee — a sharp turn-down in the rigidity spectrum — essentially at the observed position, despite the superimposed contributions of many different supernovae, plus a rounded shoulder extending to about 10^{17} V rigidity, that could well be the “part B” that seems to be needed just beyond the sharp knee of the Galactic cosmic rays.

Thirdly, as for extragalactic cosmic rays, in line with the principle of avoiding additional free parameters, it will be argued that the same exponent of source spectrum is a reasonable choice, but the sources must operate to a much higher “knee” rigidity, and the output rate per unit time probably varied rather as the rate of massive star formation in the universe. There is at present an ambiguity in the predicted source composition, depending on where the accelerators operate. For the present, the acceleration of nearly primeval material will be considered, as in radio galaxy lobes. The only free parameter in the fit to the data below about 10^{19} eV is then the overall amplitude of the extragalactic flux, representing the power of the sources, but the “ E_{max} ” of the sources will strongly affect the rate of fall-off of flux above 10^{19} e. and if future work confirms the HiRes spectrum, one may not need acceleration to energies far above 10^{20} eV.

2. Cosmic ray spectrum in a wide energy region

As presented earlier by the present author (13; 10), Figure 1 shows the cosmic ray flux obtained by several selected air shower experiments. Because of the difficulty of finding the energy of the primary particle from the limited measurements of a shower, and imperfect knowledge of hadronic interaction processes at such energies, experiments have been selected in which different shower properties are used for determining the energy — ρ_{600} at low altitude, for example (Haverah Park, AGASA), N_e closer to shower maximum (Tibet array), very detailed measurements of particle distributions in showers near sea level (KASCADE), or more calorimetric measures based on total fluorescent light emission (Fly’s Eye, HiRes), or Cerenkov light emission (TUNKA). Mature experiments which have been developed and calibrated over long periods have been picked out (to which Yakutsk might have been added), although TUNKA only provides independent confirmation of the spectral shape, as independent absolute calibration is not yet available, and so the TUNKA authors normalized at one point to results of an older Moscow experiment. However, the present author has made no adjustments to published fluxes in any of these plotted points. (For references, see (10).) All the works quoted here used a quark gluon string model for calculating particle energy. At energies above the ankle there is more scatter in the points, and there is a gradual drift of the Akeno-AGASA spectrum across the general trend, suggesting a gradual relative drift in the energy assignment, the reason for which is not yet known; but, below 10^{19} eV, the agreement is extraordinarily good, and although it must surely give a misleading impression of absolute accuracy, the spectral form shown here will form the basis of the ensuing discussion.

Below 10^{15} eV, data obtained from balloons on the spectra of individual nuclei may be represented very reasonably by assuming that all nuclei have source spectra of the form $E^{-2.69}$, with relative amplitudes given by the source composition found at 10 GeV per nucleon by

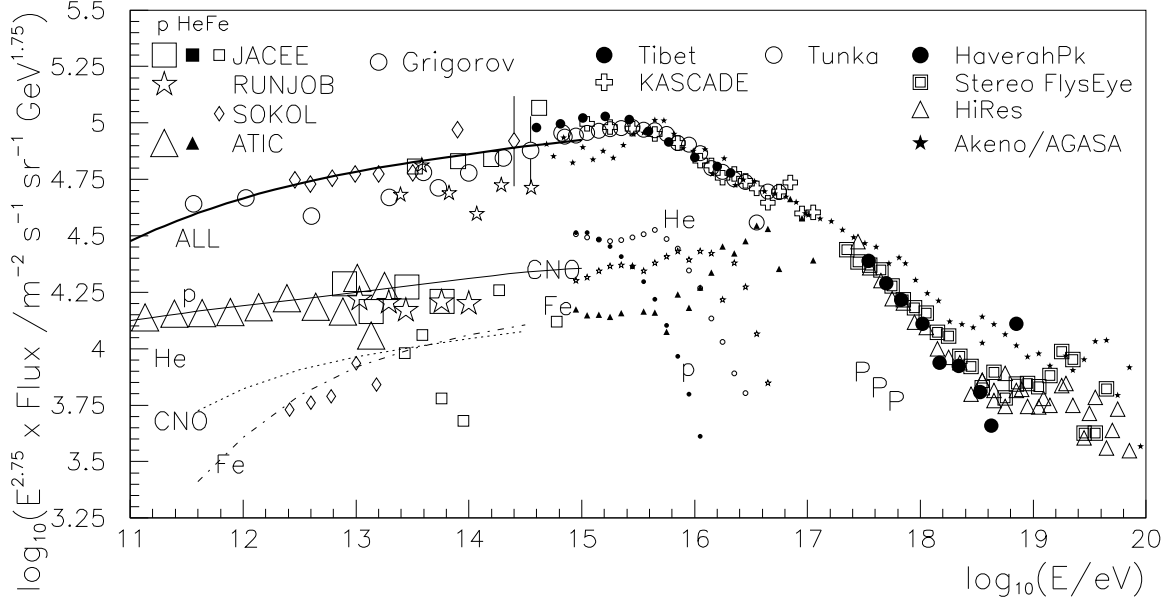


Figure 1. Showing the well-defined shape of cosmic ray energy spectrum above 10^{15} eV derived from air shower experiments using several different approaches to energy measurement, forming a continuous extension of the spectrum obtained from (mainly) balloon-borne experiments at $10^{11} - 10^{15}$ eV. At the latter energies, spectra of some individual nuclear groups are shown by lines (He may be a little too high), with a few data points for p, He (filled points) and Fe. Above 10^{15} eV, the small circles (p,He), stars (CNO) and triangles (Fe) show the provisional decomposition of the flux into 4 nuclear groups by KASCADE (15). ppp marks a proton component deduced by Haverah Park (16).

Engelmann et al. (14) supplemented by appropriate amplitudes for hydrogen and helium. Allowing for the changes caused at lower energies by spallation en route from the sources, the fluxes thus expected are shown for a few nuclei in Figure 1 (from (10)), and the total for all particles is shown by the line “ALL”. This fits very well the flux provided by the air shower data which continues to much higher energies. From 1 to 30 PeV the KASCADE array was able to make such good measurements of N_e and N_μ in individual showers, that the contributions of individual nuclear groups to the total flux could be estimated far better than from any other observations, and the range of N_e for fixed N_μ provides a good constraint on the hadronic interaction models in use. In the most recent 5-component analyses of these observations, reported at this meeting by Engel, it is found that the compositional details deduced can change in some respects with permissible changes to the hadronic interaction model employed, and these alternatives are hard to represent on the simple overview that is attempted here. For this display the earlier analysis (15) is therefore preferred, in which the flux is analysed into only 4 components, beyond which the stability of a free decomposition may be harder to justify. In any case, the methodology of the present paper will be to assume the same shape of rigidity spectrum for each nuclear species, already defined at rigidities below the knee by the lower-energy data. What the KASCADE results show is a very sharp turn-down in this common rigidity spectrum near 3×10^{15} V, and when the fluxes of these nuclear components are added together, each having a “turn-down” shape adopted from the average of the KASCADE components, one does indeed get a total flux that steepens much more gently, just as observed, at least until $\approx 3 \times 10^{16}$

eV, as will be shown in Figure 2.

On this basis, one expects the cosmic rays to be very heavy nuclei at 10^{17} eV and above, but the Haverah Park data (16) had suggested an admixture of $\sim 34\%$ protons at $3 - 5 \times 10^{17}$ eV, and the HiRes experiment has also indicated that smaller nuclei are becoming common here. So another component, not primarily heavy nuclei, must be added in. We therefore next consider the simplest expectation for an extragalactic component, to see whether we have then accounted for the whole spectrum.

2.1. Addition of the most plausible extragalactic component

Near the upper end of the Galactic spectrum, extragalactic particles must contribute part of the flux. Assuming that a process of diffusive shock acceleration also dominates in the extragalactic sources, we take the source spectrum here to be $E^{-2.3}$, close to the $E^{-2.35}$ implied for Galactic accelerators, above, and not very different from $E^{-2.2}$ expected to be produced within a relativistic shock. The important sources here must generate a spectrum extending above 10^{20} eV, rather than to about 3×10^{15} eV as in SNR, which is very difficult to achieve (1) and may require motion of high Lorentz factor in the accelerator region, though this would carry the huge energetic penalty of the bulk energy of the whole accelerator mass. The composition of the cosmic rays would be determined by the composition of the matter swept into the shock. The most plausible source at present is AGN jets or radio hot spots beyond such jets (17; 18). If the jet sweeps up extraneous matter at the hot spots, the material may be intergalactic or intra-cluster matter of low metallicity — the example which will be illustrated here. If, on the other hand, all accelerated particles arrive via the jet, the material may be electrons and protons if the ambient gamma-ray intensity where the jet starts is high enough to disintegrate most nuclei. If less energetic photons can photo-dissociate nuclei when these have reached high energy within the jet, they would also truncate the proton spectrum at a somewhat lower maximum energy than the nuclei, by photo-pion reactions. I take a primordial hydrogen/helium mix, although it is often assumed that all nuclei have been fragmented, leaving only protons, and such a composition will be taken up again in section 4, but the possibilities need a full investigation. Gamma ray bursts (19) are still discussed as possible sources, although Stecker et al. have argued that the available energy there falls far short of the requirements (20; 21). In that case though, more normal matter might be swept up.

The simplest assumption about the power of the sources in the past is to take it to vary as the star formation rate: this would be quite natural for a GRB source, but here we also assume that the power in jets from AGNs is controlled by accretion of stellar matter, and that the star formation rate is a guide. (Evolution of radio galaxies is not easy to find from direct observation, because of crowding effects in the past.) The variation was taken as Porciani and Madau’s SF2 (22). (For reasons not of great relevance now, the calculation whose results are plotted here had increased the logarithmic changes of that reference by a factor 1.13: this would not have a great effect.)

The long travel times since the era of most active star formation leads to considerable energy losses and nuclear fragmentation, mainly due to interactions with the cosmic microwave background. The calculated flux of extragalactic protons and extragalactic “total” (EGT: hydrogen plus helium) is shown in Figure 2, when one takes the production rate as just described, and the production spectrum as $E^{-2.3}$, extending to 10^{22} eV. A higher upper limit would cause little change. Without the losses due to photon interactions, the power-law spectrum would extend as indicated by “EG no losses”, but the interactions cause falls in the flux in two stages. The first drop, starting near 5×10^{17} eV for protons, and four times higher for helium (same energy per nucleon) is due to electron-pair production reactions acting over the very long propagation times, if the history of emission is as described above. The sharper drop above 5×10^{19} eV for protons is due to photopion production, and is much less dependent on early

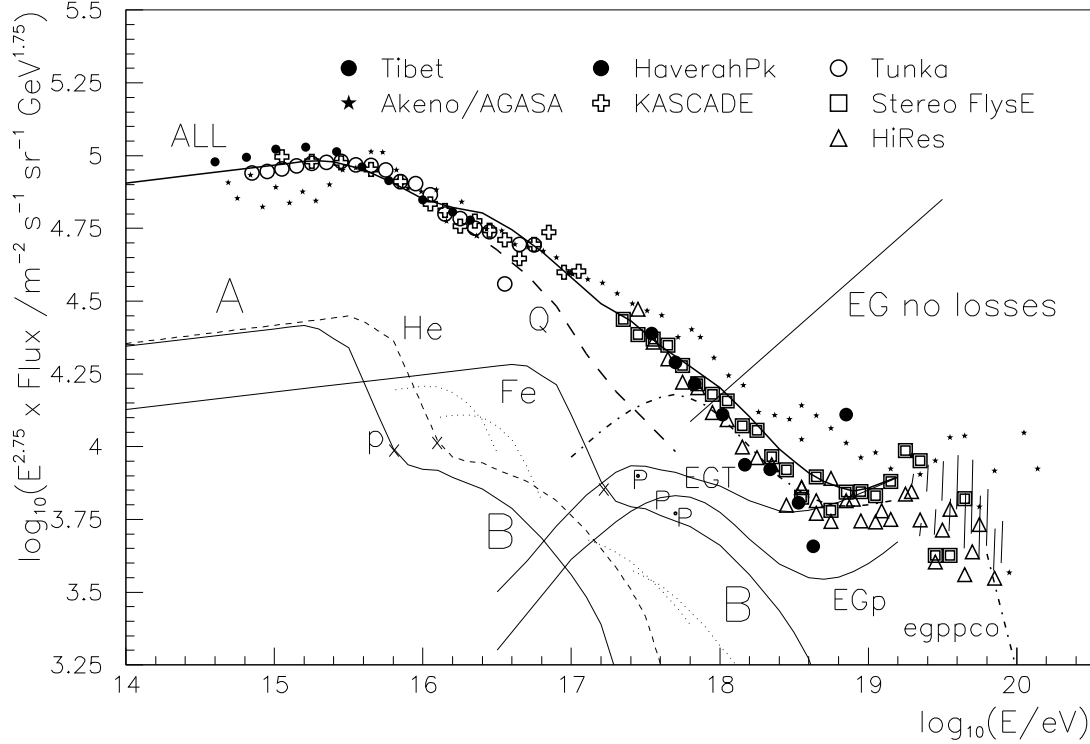


Figure 2. The cosmic ray spectrum as the sum of galactic H, He, CNO, Ne-S and Fe components each having the same rigidity dependence, plus extragalactic H + He (total EGT) having a spectrum $\propto E^{-2.3}$ (and $E_{max} = 10^{22}$ eV) before suffering losses by CMBR and starlight interactions. The galactic components were given a turn-down shape based on KASCADE knee shape as far as the point marked x . The dashed line Q is the total without adding the supposed extended tail B of the galactic flux. The dot-dash line “egppco” above 10^{17} eV refers to an alternative pure proton extragalactic component, with an exponential source cut-off applied at 10^{20} eV to reduce the pile-up peak near 5×10^{19} eV. (Although not shown, such a component could match the total flux even to rather lower energy, without need for a Galactic “B” bump, if the extragalactic sources had a steeper spectrum, say $\sim E^{-2.5}$.)

history of production; the sharp drop for helium above 5×10^{19} eV due to nucleon ejection at the giant photonuclear resonance. Loss effects due to other extragalactic background photons have been included but have lesser effects on these nuclei.

The overall source strength was adjusted to match the all-particle flux from the Stereo Fly’s Eye experiment (in the earlier paper, (13)), and the curve shown should be regarded as approximate, because, firstly, energy or nuclear losses in the GZK region were treated as smooth average losses, rather than fluctuating processes, and, secondly, the source strength should perhaps have been taken somewhat lower, if it is preferred to fit the HiRes flux near 10^{19} eV. The maximum rigidity of the accelerator was taken as 10^{22} for this illustration, and an appreciable variation would have little effect.

2.2. The need for a further part.

The two parts described so far only add up to the total “Q”, shown in Figure 2. In addition to the Galactic power-law spectrum, “A”, sharply terminated near 3 PV rigidity, and the

most natural total extragalactic component, “EGT”, just described, one needs an additional component which will be termed “B”, in order to make up the observed total flux. Of course, this might be an additional extragalactic component, as noted in the next paragraph. However, the first possibility to investigate is that the additional flux is a Galactic component, as a Galactic-related anisotropy is seen in AKENO data near 10^{18} eV. Continuing with the hypothesis of shock acceleration, sweeping up the ambient material, one should assume that a Galactic component B consists of nuclei having a common rigidity spectrum, with the normal proportions. With this constraint, and attempting to match the total observed flux, one requires the Galactic flux to have the rounded extensions, marked “B” in Figure 2. In summary, the component A-B is interpreted as Galactic, with EGT as extragalactic. The shape of part B is of course not very precisely defined, coming from the subtraction of the other expected parts from the total flux. Only part B was not introduced a priori as an expected component — but it will be argued in the next section that something very much like this spectrum A-B is to be expected from Bell’s version of shock acceleration in SNRs.

One can alternatively fit the total flux without a significant Galactic “B” component by assuming that the extragalactic sources generate a steeper spectrum (say $\sim E^{-2.5}$) than do the Galactic SNRs, emitting almost entirely protons. In this case, the extragalactic component would follow the total flux even somewhat further down in energy than the dot-dash curve in Figure 2, before turning down well below the Galactic part at lower energies — a form of spectrum especially advocated at present by Berezhinsky. The proton fraction of the total flux would then have risen to about 50% at 10^{17} eV, 2/3 at 2×10^{17} eV, and would predominate above 5×10^{17} eV, so a reliable measurement of the composition in the energy decade below 1 EeV would provide a good test. This scenario, needing no “B” component, has its attractions, but will not be discussed further here, as attention is turned to a model that leads us to expect a “B” component.

3. “ E_{max} ” for a SNR accelerator according to the Bell-Lucek version of diffusive shock acceleration

It is a basic feature of the diffusive shock acceleration process that Alfvén waves are generated by the diffusing high-energy particles just ahead of the shock front, and these waves impede the motion of the particles, providing the scattering needed to govern the diffusive motion, as originally proposed by Bell (23). More recently, Bell and Lucek have shown that these wave-like disturbances should not remain as small perturbations in the magnetic field (8): the streaming instability, they argued, would generate a highly convoluted magnetic field which completely overwhelms the initial ambient field, and they proposed a simplified treatment to define the strength of magnetic field to be expected (7), which contains the dependence

$$B \propto V_{shock} * (\text{external gas density})^{1/2}, \quad (1)$$

The resulting particle motion would be extremely irregular, akin to Bohm diffusion. According to Ptuskin and Zirakashvili (24), wave damping will reduce the self-generated B after V_{shock} has fallen, but the very early stage is relevant here.

Because of the dependence of B on shock speed, the most energetic particles are now generated very early, well before the Sedov phase of the SNR expansion, and they also escape from the SNR very early, as the field weakens. The field strength in the Bell-Lucek description, and the effect on the maximum energy of particles accelerated in the SNR are discussed in sections 4 and 5 of a longer review (10), and only a few results will be highlighted here. In particular, the standard models for particle acceleration in the simple case of a (type Ia) SNR ejecting a mass M_{ej} into a medium of uniform density, ρ , with an energy release E_{sn} (usually believed to be near 10^{51} erg), would give a maximum energy $E_{max} \propto E_{sn}^{1/2} B M_{ej}^{-1/6} \rho^{-1/3}$, but because of the dependence (1) of the magnetic field, this becomes changed to $E_{max} \propto E_{sn} M_{ej}^{-2/3} \rho^{1/6}$.

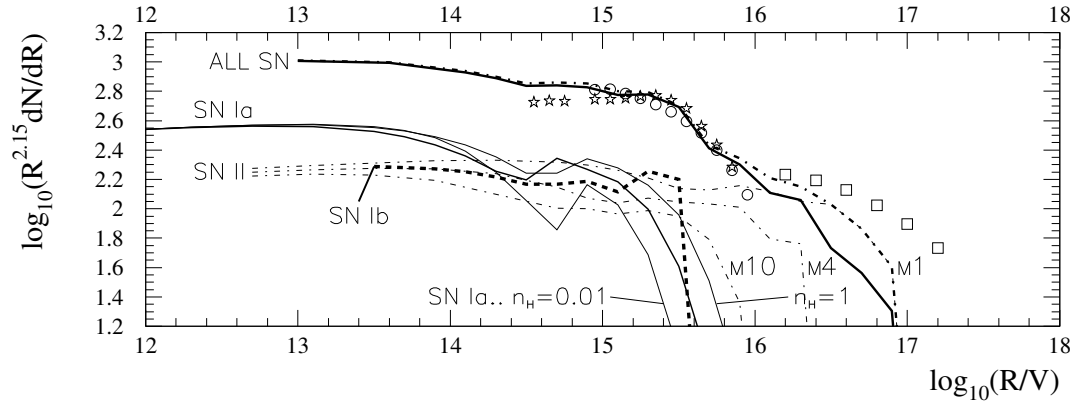


Figure 3. Rigidity spectra calculated in a simplified model to show the position of spectral turn-down obtained using Bell and Lucek’s prescription for the self-generated magnetic field. Thin full lines: $1.4M_{\odot}$ ejected into medium with 1, 0.1 or 0.01 H atoms per cm^3 (Type Ia). Bold dashed line: $3M_{\odot}$ ejected into fast WR wind (type Ib: this a cruder calculation). Dot-dash lines: 10, 4, $1M_{\odot}$ ejected into massive slow wind (Type II). All 1 f.o.e. energy. Circles and stars: observed KASCADE knee shapes for H, (He+CNO): squares show extension as “component B” from fig. 2: all multiplied by $E^{0.6}$ to compensate for galactic trapping time. “ALL SN” is sum of curves for mean type Ia, Ib, and II in ratio 1:1:3 but showing effect of varying proportions of $M=1$, $M=4$ contributions.

Thus the effective maximum energy (the energy above which the spectrum falls very steeply) is no longer governed by the external magnetic field (as B is self-generated), and varies only slightly with the external density (as a decrease in density, which makes a longer time available for acceleration, results in a lower B and lower rate of energy gain), unless the density is extremely large. This offers an explanation for the sharpness of the knee in the cosmic-ray spectrum, despite contributions from supernovae in different environments, provided that the explosion energy does not vary very much from 10^{51} erg.

A calculation of the upper end of the spectrum of cosmic rays resulting from this model, assuming acceleration to be efficient — about half the shocked internal energy of the gas being in relativistic particles at all relevant stages — but using a highly simplified description of the gas dynamics, produced the model energy spectra shown in Figure 3 (10) for (a) representative Type Ia SNRs — $1.4M_{\odot}$ expanding into gas densities 0.01, 0.1 or 1 H atoms per cm^3 , (b) examples of Type II SNR (ejecta masses of 1, 4, 10 M_{\odot} expanding into a dense slow wind of $5 M_{\odot}$ from the preceding red supergiant), and (c) a nominal Type Ib SNR expanding into a very low density fast wind before hitting shells of denser matter — all involving 10^{51} erg. The sum of these spectra, in the ratio of 1:1:3 for type Ia, Ib and II is shown as the line “ALL SN”. Case (c) is a crude indication, as the effect of hitting the dense shells could not be treated properly by the crude dynamical model, and a wider range of masses should be considered for type II SNR, but the overall picture should not be misleading: a sharp initial drop in flux at, surprisingly, just the right rigidity (this comes automatically from the Bell-Lucek model, with the assumed very efficient acceleration), followed by a rounded extension to near 10^{17} V. This suggests that “component B” might be identified with particles accelerated by type II SNRs, whose precursor star emitted a dense slow (~ 10 km/s) wind immediately before the explosion. (Bell and Lucek (7) had indeed proposed a very fast shock entering a very dense wind (citing SN1993J as a prototype) to get Galactic cosmic rays to just over 10^{17} V rigidity.)

Thus Bell’s version of diffusive shock acceleration offers great promise of explaining the

Galactic cosmic ray spectrum, and suggests that there should still be many iron nuclei around near 5×10^{17} eV, where one experiment reported $\approx 34\%$ protons in the flux (16). The extragalactic component illustrated in Figure 1 would neatly fit this proportion, and so this composition may be taken to support the proposal made here that the “component B” required to raise the total Galactic-A component plus the extragalactic component from the level of “Q” to match the observed total is indeed an extended end of the Galactic flux rather than a raised extragalactic (mainly light) flux.

May the composition be different near the knee? Since the particles near the knee are produced very early in the SNR expansion, there are two factors operating at that time which might possibly increase the helium/hydrogen ratio near the knee. In the important type Ib supernovae (such as Cas A), the shock initially moves through a fast wind from a Wolf-Rayet star which has shed its hydrogen, so the accelerated ions at this very early time will be deficient in hydrogen. Secondly, the inner shock can be strong at this early time: it can accelerate newly synthesized matter ejected from the supernova, richer in heavy elements, and as the initially strong field decays, very energetic particles may be able to escape from the compressed-ejecta shell which has been processed by the inner shock. (If they do not escape early, these particles will later suffer strong adiabatic deceleration, and lose their prominence.) However, a rough initial estimate is that although the pressure and the cosmic-ray energy density could be quite high at this stage behind the inner shock, the volume filled with accelerated ejecta is much smaller, so the total cosmic-ray energy from this region is probably not a major part.

4. Summary

Bell’s version of diffusive shock acceleration in supenova remnants, in which the strength of the magnetic field varies under the control of the ram pressure of the plasma, seems to explain the cosmic-ray “knee” as arising from the acceleration process (not leakage from the Galaxy), putting it in the right region, near 3 PV rigidity, and producing a distinct knee despite the contributions of many supernovae exploding in different environments. It leads also to the expectation of an extended shoulder to the rigidity spectrum (arising from some of the Type II SNRs) after the initial sharp drop detected by the KASCADE experiment, which can be sought with the extended KASCADE-GRANDE array. Some evidence for such a rounded extension may already exist when one tries to join together the first part of the Galactic spectrum, that turns down sharply near 3 PV rigidity, to the extragalactic flux, if the extragalactic sources also generate a source spectrum $\sim E^{-2.3}$, rather like the spectrum emerging from Galactic sources. (If this is the case, a modest 1/3 proportion of protons in the cosmic-ray flux near 4×10^{17} eV can be understood.) The model knee shapes presented in Figure 3 derive from very crude dynamical models, and more detailed modelling of SNR hydrodynamics along with early stages of particle acceleration are under way to check the results shown here. A proposed analysis of the total cosmic ray spectrum into Galactic and extragalactic parts contributed by different nuclear species is shown in Figure 2.

If the extragalactic sources produce essentially a pure proton flux, instead of the primordial mixture taken here, a normalization to the observed cosmic ray flux at 10^{19} eV would have produced a very high flux near 5×10^{19} eV, which seems far from the level suggested by data. (See the shape of the EGp curve.) However, if the extragalactic sources had a much lower E_{max} , represented by a multiplying factor $exp(-E/10^{20})$ eV, the spectrum would take the form shown by the dot-dash curve “egppco” (extragalactic pure protons with cut-off) in Figure 2. The extragalactic flux would then be more prominent near 5×10^{17} eV, making a bigger contribution to the second knee. This characteristic is more like the models discussed by Berezhinsky et al. (3; 4), who discuss pure proton compositions, and propose a softer (more steeply falling) source spectrum which would probably remove all need for a “B” component. This pure proton source (if physically justified) would have the attraction that a smaller source E_{max} is called

for, relieving one of the greatest difficulties in accounting for cosmic rays of the highest energy. However, it would require a much smaller “B” component, and so might fit less well with the Bell-Lucek model SNII component, though a more thorough modelling may show that a less prominent “B” extension is indeed expected (see, for example, the crude estimate in Figure 3). The proton fraction in cosmic rays near 4×10^{17} eV would then be very much higher than suggested by Haverah Park, but might fit HiRes observations better. The Fe/proton mixture in this domain will be very informative in deciding this question.. Pending the resolution of the discrepancies between the spectra deduced by different experiments above 10^{19} eV, it is premature to draw clear conclusions about the extragalactic cosmic rays, but the composition at a few EeV will clearly be interesting, as will be the spectral exponent near 2×10^{19} eV.

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