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Cosmic Rays

IV. The spectrum and chemical composition above 10^4 GeV

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Summary. Using the concept developed in earlier papers, that the cosmic rays originate in three different main sites, a) the normal supernova explosions into the interstellar medium, b) the supernova explosions into a stellar wind, and c) powerful radio galaxies, we demonstrate in this paper that the spectrum and chemical abundances above 10^4 GeV can be well understood. Using existing data on the chemical composition of cosmic rays near TeV energies as a constraint, we adjust the parameters of the model to fit the shower size data from the Akeno experiment; this is necessary since the derivation of an all particle spectrum involves an assumption about the chemical composition of the cosmic rays and so we have to fit the shower size data first and then derive the all particle spectrum. We present a successful fit to the shower size data which allows us to draw three main conclusions: a) For most of the energy range above 10^5 GeV the wind explosions can account for both chemical composition and spectrum including the knee feature, b) the highest particle energies required from the stellar wind explosions imply a magnetic field in the preexisting stellar wind of at least 3 Gauss at a fiducial distance of 10^{14} cm, c) the chemical abundances above 10^5 GeV are dominated by heavy nuclei such as Neon and higher. The bump observed in the all particle spectrum below the knee gets weakened with the proper treatment of the energy dependent chemical composition. At the high energy end we obtain an estimate of the extragalactic flux of protons.

Key words: Cosmic Rays – Plasma Physics – Supernovae – Shockwaves

1. Introduction

With the introduction of a new concept to treat particle acceleration in shocks where the shock normal is perpendicular to the prevailing magnetic field, Biermann (1993, paper CR I) has been able to interpret the cosmic ray spectrum from GeV to EeV energies, including the exact spectrum and the feature of the knee. The cosmic ray spectrum is composed of three components:

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1) The explosions of normal supernovae into an approximately homogeneous interstellar medium drive blast waves which can accelerate to about 10^5 GeV for Hydrogen (Lagage and Cesarsky 1983). For these particles the spectrum is near -2.75 after taking leakage from the Galaxy into account. Particles get accelerated continuously during the expansion of the spherical shockwave, with the highest particle energy reached at the beginning of the adiabatic expansion, the Sedov phase. However, after acceleration particles lose energy due to adiabatic expansion and hence, the maximum particle energy which is relevant, is the maximum particle energy achieved at the end of the Sedov phase, when cooling sets in and the shell can break up. At that point the accelerated particle population gets mixed with the interstellar medium. We will refer to this phase and the associated particle population as Sedov phase explosion and Sedov phase acceleration subsequently. We note that the strongest dependence of this maximum energy is on the density of the interstellar medium with the highest particle energy being achieved in the most tenuous medium. Protons can get accelerated up to about 10^5 GeV in the tenuous part of the interstellar medium. A detailed discussion of the acceleration process and the differences between protons, heavier nuclei and electrons as well as the observed radio emission from normal supernova remnants is made in Biermann and Strom (1993, paper CR III).

2) Explosions of stars into their former stellar winds (like Wolf Rayet stars) produce particles up to energies of about $3\,10^9$ GeV (for iron, and rigidity dependent); these particles have a slightly flatter spectrum of near -2.67 (this is 0.08 flatter than the Sedov phase explosion spectrum) up to a rigidity dependent bend in the spectrum and then beyond that a steeper spectrum of near -2.97 up to the rigidity dependent cutoff. This spectral index difference is due to a difference in the detailed acceleration efficiency, which in turn depends on particle drift energy gains. Below the knee energy the drifts are stronger because the particles experience a stronger curvature drift due to turbulence, and beyond the knee energy the particles just experience the basic curvature and gradient of the stellar wind, since their Larmor radius gets large (the details are explained in paper CR I). The discussion (Biermann and Cassinelli 1993, paper CR II) of the acceleration of particles in the strong shocks in radiosupernovae on the one hand, and the weaker shocks in the winds of OB and WR stars on the other hand yields the results: a) the magnetic field in the winds of

WR stars is of order 3 Gauss at a fiducial distance of 10^{14} cm from the star, b) that thus particle energies up to about $3\,10^9$ GeV in iron nuclei are possible from acceleration in strong supernova shocks in such winds, and c) that there is a critical velocity of order 10^9 cm/sec below which electron injection is strongly inhibited.

3) The hot spots of Fanaroff Riley class II radio galaxies produce particles with even higher energies, up to near 10^{11} GeV; their spectrum is approximately E^{-2} up to the pileup just below the cutoff due to the interaction with the cosmological microwave background. This extragalactic component has been modelled by Rachen and Biermann (1992, 1993: paper UHE CR I): this latter model has been shown to be consistent with Fly's Eye data on the proton contribution below EeV energies (Gaisser et al. 1993, Rachen, Stanev, Biermann 1993, paper UHE CR II).

The main fraction of the cosmic rays above 10 TeV is accelerated in shocks that traverse stellar winds. Stellar wind magnetic fields have asymptotically a Parker type topology, with $B_\phi \sim 1/r$ dominating over most of 4π and a polar cap where the radial field $B_r \sim 1/r^2$ dominates. In CR I Biermann developed a theory to treat perpendicular shocks in a spherical geometry for particle acceleration. This process produces $E^{-7/3}$ particle spectra in the limiting case of large shock velocities. In the geometrically small polar cap region, however, the geometry is that of a parallel shock, which in the limit of large shock velocities produces E^{-2} particle spectra. Although the total amount of energy carried by the polar cap component is small, we shall show that it has important contribution in the region of the knee.

The Parker spiral magnetic field topology requires a region near the pole where the magnetic field is almost exactly radial; further out from the pole the magnetic field becomes helical to approach asymptotically the tight Archimedian spiral at the equator. There is a critical angle not far from the pole where the Larmor radii of the particles accelerated in the pole region overlap with the Larmor radii of the particles accelerated in the Archimedian spiral region; this critical angle separates the two regions where the acceleration is well approximated by a shock normal parallel to the magnetic field yielding an E^{-2} spectrum for strong shocks, and the region where the acceleration is best described by shock normal perpendicular to the magnetic field giving an $E^{-7/3}$ spectrum. Since the pole region where the parallel acceleration dominates is only about 0.01 of 4π the contribution of this region to the overall spectrum is very small except for the particle energies near 10^6 GeV, i.e. near the bend in the overall spectrum and the identical cutoff for the polar cap particles; the polar cap particles have a steep cutoff at the bend energy because at that energy the acceleration is limited by lack of space as discussed above. Fig. 1 shows a a schematic representation of the composite model we are discussing, broken down into its four components.

Here we wish to test the overall model proposed by asking whether it can successfully account for the spectrum and chemical composition at particle energies beyond 10^4 GeV: the special difficulty in this endeavour is the fact that we know the chemical abundances near TeV particle energies already, and extrapolating these spectra does not give the bump and knee of the well established overall particle spectrum. On the other hand, the particle energies themselves and the known chemical abundances can indeed be understood with the concept that explosions into a wind like that of a WR star are their origin (Völk and Biermann 1988, Silberberg et al. 1990).

Fig. 1. The generic spectrum of one nuclear species with all four cosmic ray components, here for Hydrogen: Component 1 is due to the Sedov phase explosions in the interstellar medium, component 2 is due to stellar winds, with 3 the polar cap component, and component 4 is extragalactic. E_1 is the cutoff energy for component 1, and E_2 is the bend energy for the wind component and also the cutoff energy for the polar cap component.

The difficulty in all such attempts originates in the relation between energy estimation with air showers and the mass of the primary nucleus. Generally showers initiated by heavy nuclei develop and are absorbed faster in the atmosphere. Heavy nuclei thus produce showers of smaller size at the observation levels of all existing experiments. The effect is stronger for inclined showers, which have to penetrate through larger atmospheric thickness. In this paper we model the shower size that the primary cosmic ray flux generates in the Akeno detector (Nagano et al. 1984), using both vertical showers and slanted showers; having performed such a fit, we then reconstruct the all particle spectrum.

The paper is organized as follows: First we describe our input data and the most important parameters; then we present the data we wish to fit (Akeno) and the shower code used to calculate the observable parameter; our successful fits are shown with a discussion of possible errors in another section; we conclude with a discussion of the newly derived all particle spectrum and an outlook at possible next steps of interest.

2. Input parameters

Various cosmic ray experiments have given data about the chemical composition near TeV energies and somewhat beyond, up to 100 TeV, most notably from the Chicago Group

(Grunsfeld et al. 1988, Müller 1989, Swordy et al. 1990, and Müller et al. 1991), the JACEE experiment (Parnell et al. 1989, Burnett et al. 1990, and Asakimori et al. 1991a, b), Simon et al. (1980) and Engelmann et al. (1990). As an illustrative example we show in Fig. 2 the Oxygen data, where we have averaged existing data from all four experiments when independent measurements exist in the same energy range. The data for the different experiments are quite consistent with each other. Energy ranges covered only by a single experiment are not represented.

Fig. 2. The Oxygen spectrum derived from all existing data by binning and then averaging with the weight of the error bars. A fit is shown to the resulting average spectrum showing a -2.64 spectral index.

Data clearly demonstrate a power law behaviour with a somewhat flatter spectrum than the low energy index of about 2.75. Oxygen has a spectrum of about 2.64, corresponding well to the argument made in CR I, that supernova explosions into existing stellar winds produce not only higher particle energies, but also spectra flatter than the lower energy particles from Sedov phase explosions into the interstellar medium. We use all these known chemical abundances as a given input, combining the elements into six groups, and the sources into three different sites as discussed above. The six element groups which we use are: a) Hydrogen, b) Helium, c) Carbon, Nitrogen and Oxygen, d) Neon to Sulfur, e) Chlorine to Manganese, and f) Iron. We assume that the galactic cosmic rays cut off at $10^8\,Z$ GeV and that the extragalactic component is nearly all protons. In paper CR II (Biermann and Cassinelli 1993) we argue that this is in fact suggested by a number of stellar observations.

The main uncertain parameters are then the following:

1) The spectral difference between the Sedov phase explosion particles and the wind explosion particles. Simple first order theory gives 0.08 for this parameter, the difference between 2.75 and 2.67, as described above. Arguments given in paper CR I and in Silberberg et al. (1990) suggest that the heavier elements in the TeV range come dominantly from shock acceleration in winds; therefore, we ought to look for a slight difference in spectrum between Hydrogen and heavy nuclei. For example, for Oxygen we find 2.62 ± 0.03 and for Hydrogen 2.74 ± 0.02, which corresponds to a spectral difference 0.12 ± 0.04, consistent with our theoretical expectation for the difference between the Sedov phase particles and the wind shock accelerated particles. We will therefore explore a range for the spectral index of the wind particles below the knee close to 2.67.

2) The spectral difference at the knee. Again, simple theory (CR I) gives for this number the value 0.30, see above. The data on the spectrum above the knee suggest a spectral index of 3.0 ± 0.1. We will try a small range for the spectral index of the particles beyond the knee close to 3.00.

3) The particle energy at the cutoff for the Sedov phase explosion acceleration. The Jacee data suggest for this number approximately 100 TeV for Hydrogen. Our model firmly requires that this energy scale with the charge Z of the nucleus.

4) The particle energy of the knee. Observations suggest an energy overall of about $5\,10^3$ TeV. Our theory requires that this energy also scale with nuclear charge Z, and if the knee is indeed dominated by heavy nuclei this energy for Hydrogen is likely to be above 200 TeV.

The division of the abundances between the Sedov phase accelerated particles and the wind explosion accelerated particles can be made using existing data, especially from JACEE.

3. The data to be fitted and the shower development Monte Carlo code

The Akeno air shower experiment measures the size of showers arriving at the detector at different zenith angles. The resulting shower size spectra are converted into constant intensity curves, i.e. groups of showers having the same experimental rate at different angles, thus initiated by primary nuclei of the same energy.

Fig. 3. Average shower profiles for a primary particle energy of 10^8 GeV for Hydrogen, Nitrogen and Iron. The two different slant depths which we use are indicated.

The angular dependence of the constant intensity curves is then used to extrapolate to size at shower maximum, from which an estimate of the primary energy that corresponds to a given intensity can be made. This fairly model independent procedure is still influenced by the chemical composition of the cosmic ray flux, especially if it has a strong energy dependence. The reason for this is illustrated in Fig. 3 which shows the development of showers with the same primary energy but different nuclei. We have decided to use directly the shower size spectra to reconstruct the cosmic ray spectrum under the assumption of different chemical compositions. We do this simultaneously for two zenith angles, vertical ($secan\,\theta = 1.0$) and for $secan\,\theta = 1.2$, i.e. one moderate slant angle. At these angles the statistical errors are small. The shower size is expressed by N_e - the total number of charged particles at observation level. The flux of showers with $N_e = 10^6$ at $secan\,\theta = 1.2$ is smaller than the vertical one by a factor of 7. The shapes of the size spectra are also different, as seen in Fig. 4.

We use a simple parametrization (Gaisser, 1979) to calculate the size at the two slant depths (920 g/cm^2 for $secan\,\theta = 1.0$ and 1104 g/cm^2 for $secan\,\theta = 1.2$). While the original formula is for a constant inelastic cross-section, in this estimate we use a proton inelastic cross-section on air growing with the energy as $(log\,E_p)^{1.8}$ (Gaisser et al., 1987). For all nuclei heavier than Hydrogen we assume superposition, i.e. that all constituent nucleons interact independently in the atmosphere. This assumption is known to represent correctly the average shower size and underestimate its fluctuations.

Our technique is intermediate between numerical integration and Monte Carlo. We step through the energy spectrum of each chemical component in small ($10^{0.01}$) steps and calculate the shower size generated at the two depths by a nucleus of energy E. To estimate the fluctuations in N_e, which are very important in view of the steep energy spectra, we calculate 100 showers at each step, sampling the interaction depth for each nucleon. The resulting N_e are binned with the appropriate weights.

Although generally correct, the procedure used is not exact. A proper comparison of the cosmic ray spectrum and composition model with experimental data should account fully for the fluctuations in the shower development (i.e. use a non-superposition nuclear fragmentation model as in Engel et al., 1992) and those induced by the detection technique. This is a long term project which requires a close collaboration with the experimental groups. The technique used here, which is very sensitive to the cosmic ray spectrum and composition as we show further down, is fully sufficient as a first pass in the analysis of air shower data in terms of rapidly changing composition.

The most important point here is to remember that shower size is reduced for particles at a given energy with higher nuclear mass: e.g. an Iron particle and a proton of the same energy will produce very different shower sizes, with the shower size of the Iron nucleus being much smaller (see Fig. 3).

4. The model fit

We present the fits of the shower size distributions in Fig. 4, where the bands represent the experimental errors.

Fig. 4. The fit of our model to the Akeno shower size data, both for vertical showers as well as for a slanted shower. Shown are the data as small boxes with the shading indicating the 1 sigma error range, as well as the model as a bold histogram.

The comparison demonstrates that the fits are well within the acceptable error ranges. The model has the following parameters:

The cutoff energy (exponential cutoff) for the Sedov phase accelerated particles is 120 TeV for protons; the spectral index of the wind component is 2.66 below the knee and 3.07 above the knee; this steepening occurs at 700 TeV for protons and is rigidity dependent. The ratio of the polar cap component to the steeper wind component is 1 for heavy nuclei at the bend. Although the polar cap component does not contribute to shower sizes significantly below or above the knee, it is essential for reproducing the sharp break at $N_e = 10^6$. The reproduction of this shower break, as well as the observed continuous flattening of the spectra of all heavy nuclei requires the introduction of a very flat ($\gamma = 2$) acceleration component, i.e. the polar cap component. We see that all four major parameters are close to their expected values. In Fig. 5 we show the contributions of the six chemical composition groups which we have distinguished, H, He, CNO, Ne-S, Cl-Mn, and Fe. We emphasize that all three critical particle energies, the cutoff energy for the Sedov phase accelerated particles, and both the bend energy and the cutoff energy for the wind accelerated particles are proportional to the nuclear charge Z, and are thus in our model fit 120 Z TeV, 700 Z TeV, and 10^5 Z TeV, respectively.

Fig. 5. The various contributions from the six element groups we distinguish: H (solid), He (dots), CNO (dash), Ne-S (long dash), Cl-Mn (dash dot), and Fe (long dash dot).

It is clear that within the framework of our picture the knee feature in the overall spectrum can only be due to the addition of the polar cap component. Without it the generated size spectrum cannot have a sharp bend in any model similar to ours, with rigidity dependent features and composed of different nuclear components.

In presenting the fits we could have achieved smoother histograms by applying an exponential cutoff also to the polar cap component. We prefer to present the histograms in their present form, because a closer inspection now allows the reader to identify the component that causes the bend in the shower size spectra. In reality every single nuclear component has its own rigidity dependent behaviour which of course generates both smoother particle spectra and smoother size spectra.

We note that the shower size distribution is very sensitive to changes in the parameters. Relatively small changes (by more than 20%) of the cutoff and bend energy, as well as in the composition of the wind component, affect the calculated size spectra so strongly that they become inconsistent with data. Together with the direct measurements in the 1 TeV region the shower size distributions constrain the models within a small parameter space. Fitting the shower size distribution at different zenith angles is critical despite its fairly large error bars.

We also note that the code we use for reproducing the shower size distributions itself depends rather strongly on model fits to accelerator data to describe high energy interactions of nuclei; this is especially important for slanted showers where the tail of the shower profile is measured. Thus, the particle physics used introduces an additional uncertainty which is difficult to assess.

5. Conclusions

In Fig. 6 we show the all particle spectrum which results from our analysis. We compare it with the conventionally derived all particle spectrum, which does not explicity account for changes in composition.

Fig. 6. Comparison of our all particle spectrum with the conventionally derived spectrum, as well as the various contributions from the different element groups. Here the symbols denote the following experiments: open circles, Akeno; open squares, Haverah Park; open triangles, pointing down, Yakutsk; open triangles, pointing up, Tien Shan; open hexagons, Fly's Eye; full squares, Proton 4; full circles, Jacee. The various references are given in detail in Stanev (1992) and in Hillas (1984).

Several properties stand out:

1) The correct spectrum is lower in the knee region and beyond than the conventionally derived spectrum; the factor is about 2. The knee itself is not as sharp but the change of the spectral index takes place at approximately the same energy.

2) The composition changes rapidly in the knee region, becomes increasingly heavier, and in our current interpretation is dominated by the Neon group above the knee. One should note that the derivation of the exact charge of the dominating group depends strongly on the cascade model and that many observable parameters are not very different for Ne- and Fe-induced showers. The data will, however, be inconsistent with

a component lighter than Ne dominating the cosmic ray flux above 10^7 GeV.

3) The proton flux shown in Fig. 6 at energy above 10^8 Gev represents the extragalactic component. Because the wind component has a maximum energy of 10^8 GeV for protons ($2.6\,10^9$ GeV for Fe) the calculated shower size spectra would become too steep for sizes above 10^7 without this extra component. Although the exact shape of the extragalactic spectrum needs further adjustments, its magnitude is limited by the comparison with the size spectra. This implies an extragalactic flux (presumably protons) that is consistent with the independently derived estimate by Gaisser et al. (1993) using the Fly's Eye data; a full comparison with an extragalactic model (Rachen and Biermann, 1992, 1993: paper UHE CR I) has been done in Rachen et al. (1993, paper UHE CR II).

4) The comparison with existing direct data on the chemical composition is shown in Fig. 7 for the particle energy range 1 to 100 TeV. Hydrogen, Helium and Iron groups data are shown.

Fig. 7. A comparison of the measured element abundances for Hydrogen, full squares, Helium, full circles, and Iron, full stars, with our model, again together with the all particle spectrum. The sources of the data are given in the first paragraph of section 2.

The comparison demonstrates that our curves fit all existing data quite well, including the trend, observed in heavy nuclei, to exhibit a flattening of the spectrum at the approach to the knee. The seeming inconsistency with the highest energy direct data for iron is possibly due to the fact the the JACEE experiment (where these points come from) has presented its measurements for nuclei with $Z > 17$. It is difficult to judge what the absolute normalization of the cosmic ray flux beyond the knee is. The presentation of the spectrum in the form used here ($E^{2.75}\,dN/dE$) tends to exaggerate differences in the absolute normalization. A relatively small error of the energy determination in air showers (typical error of 20%) changes the normalization of the absolute flux by a large amount (65%).

We conclude that the most stringent test yet of the model proposed in the earlier papers of this series (CR I, CR II, CR III, UHE CR I, UHE CR II), which give predicted spectral shapes for all three sites of origin for cosmic rays is successful. Several detailed conclusions can be made:

1) The abundances of the cosmic rays from explosions into stellar winds do not require nor imply any admixture from the heavy elements newly produced in the star exploding. All the heavy elements already present in the stellar wind prior to the explosion participate in the feeding of the accelerated particle population, and no other additional source is required.

2) The nuclei accelerated in the polar cap region are essential for a successful fit of the shower size spectra. Although the total energy carried by such nuclei is not more than 1/100 of the total wind component, they contribute a major fraction in the knee region.

3) There is no requirement for other cosmic ray sources, either from spectral arguments or from abundance arguments; thus pulsars and compact X-ray binary systems may accelerate lots of particles, but they need not play a dominant role out in the typical interstellar medium.

4) The large fraction of heavy nuclei inferred from the Fly's Eye data (Gaisser et al. 1993) requires the acceleration of heavy element nuclei out to at least $3\,10^9$ GeV. This implies (see CR I and II) that the winds of the stars that explode as supernovae have magnetic fields at least as strong as 3 Gauss at a fiducial distance from the star of 10^{14} cm. Since this limiting particle energy is already derived by using the spatial limit given by the condition that the Larmor radius of the particle fit into the space available, there is no other way than indeed having these high fields in the stellar winds of massive stars. Should a more sophisticated analysis of the Akeno and Fly's Eye data require a galactic Cosmic Ray contribution of iron nuclei even at 10^{10} GeV (see the discussion in Rachen, Stanev and Biermann 1993, UHE CR II), then a correspondingly higher magnetic field strength is required, with a lower limit of near 10 Gauss at 10^{14} cm from the star.

The next steps possible and maybe desirable with better data or a more complete analysis of the existing data by the experimenters are the following:

1) One must refine the cascade code to describe more accurately the high energy range and the highly slanted showers. Several different valid particle physics extrapolations to ultrahigh energy should be used for an estimate of the errors caused by the uncertainty of the particle physics input. In addition, a non-superposition fragmentation model should be used to account more correctly for the shower development fluctuations.

2) Also, one might combine all such source based calculations with a proper propagation model in the Galaxy; after all, many of the heavy nuclei break up due to spallation. The task then would be to fit also the well known chemical abundances of the cosmic rays at GeV energies.

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