Where Is the Bend in the Cosmic Ray Proton Spectrum?

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Abstract

The JACEE collaboration has recently presented measurements of the cosmic ray hydrogen and helium spectra with individual particle total energies from ~6 to 800 TeV (Asakimori et al., 1998). No clear evidence is seen for a spectral break. Both the hydrogen and helium spectra are consistent with power laws over the entire energy range, with integral spectral indices 1.80 ± 0.04 and $1.68\ ^{+0.04}/_{-0.06}$ for the protons and helium respectively. With 644 m^2-hrs of accumulated exposure (including the results from two >200 hr Antarctic flights), JACEE has measured 656 proton events above 6 TeV and 414 helium above 2 TeV/nucleon. The high-energy statistics are still limited, however: Although no break is visible, a likelihood analysis shows that there is no statistical evidence ruling out a break in the proton spectrum at energies above 40-90 TeV.

1 Introduction:

The high energy cosmic ray spectrum is important for understanding the acceleration mechanism(s) and conditions at the cosmic ray source(s), the propagation of energetic cosmic rays through the galaxy, the cosmological issues of galactic vs. extragalactic origin, and the particle physics of high energy interactions. The steepening of the all-particle spectrum above the knee near 10^{15} – 10^{16} eV, and the intensity enhancement observed below the knee (both derived indirectly from air shower data) have been the subject of numerous speculations on the acceleration and propagation mechanisms of galactic cosmic rays. If the acceleration and propagation mechanisms depend on particle rigidity, a change in the proton energy spectrum is expected at an energy lower than that of any Z > 1 component and lower than any bend in the all-particle spectrum. If a bend in the proton spectrum is detected due to a maximum rigidity for the acceleration process, then the helium should show a similar bend at a kinetic energy per nucleon Z/A times the proton break energy. A steepening of the proton spectrum at some energy E_p without a corresponding steepening for helium could imply that the theoretical prediction of a maximum total energy/nucleon ZE_p/A from a supernova shock is oversimplified, or it could suggest that the protons and helium come from different sources. The JACEE results based on measurements through JACEE flight 12 show no evidence for any spectral steepening but still run out of statistics by ~90 TeV.

2 JACEE Spectrum Results:

Figure 1 shows the measured JACEE 1-12 integral spectra N(>E) for hydrogen and helium, including an atmospheric correction and corrections for the interaction height, target volume, and geometry for each event. Each point on the plot corresponds to one more event than the point to the right. The wavy shape of the low-statistics high-energy points (e.g., the dip in the proton spectrum between 60 and 100 TeV, and in the helium integral spectrum near 20 - 30 TeV) is characteristic of the point-to-point correlations in an integral plot. The straight lines shown in Fig. 1 are maximum likelihood fits with power law indices $\gamma_H = 1.80 \pm 0.04$ and $\gamma_{He} = 1.68\ ^{+0.04}/_{-0.06}$. The JACEE 1-12 data are consistent with a single power law over the entire energy range. Although we cannot rule out the two-component spectrum of Asakimori et al. (1993) with the full JACEE 1-12 statistics, we nevertheless see no evidence for a break in the spectrum. The hydrogen spectrum appears to be steeper than that of the helium, with a difference between the spectral indices of 0.12 ± 0.06. The best-fit differential spectra are given by

$$dN/dE\,\big|_H = 1.11\ ^{+0.08}/_{-0.06} \times 10^{-1}\ E^{-2.80 \pm 0.04}\ (m^2\text{-sr-s-TeV})^{-1}$$

and $$dN/dE\,|_{He} = (7.86 \pm 0.24) \times 10^{-3}\ E^{-2.68\ +0.04/-0.06}\ (m^2\text{-sr-s-TeV/n})^{-1} \quad . \qquad (1)$$

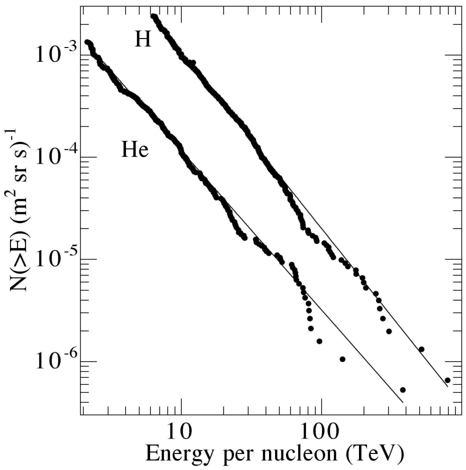

Fig1. Measured JACEE 1-12 integral spectra N(>E) for hydrogen and helium.

If we assume a standard leaky box model for the cosmic ray propagation with an escape pathlength $\lambda \sim E^{-0.6}$, then the measurements suggest source spectra of the form $dN/dE|_{source,H} \sim E^{-2.2}$ and $dN/dE|_{source,He} \sim E^{-2.1}$. A helium spectrum slightly flatter than that of the hydrogen is consistent both with the non-linear shock acceleration calculations of Ellison (1993) and the multiple source models of Biermann and collaborators (1993), which suggest shock acceleration from a supernova exploding into the interstellar medium to explain the hydrogen spectrum, and a supernova exploding into the stellar wind of the pre-supernova star (e.g. a Wolf-Rayet star) to explain the high energy helium spectrum.

The maximum proton energy expected from acceleration at a parallel shock in a standard galactic supernova remnant, assuming a value of 3 µG for the interstellar magnetic field, is E_p ~100 TeV (Lagage and Cesarsky, 1983). This value can be extended upward by employing quasi-perpendicular shocks (Jokipii, 1987) or higher magnetic fields, as might be encountered by expansion into the wind of a massive progenitor star (Völk and Biermann, 1988). Likewise, reacceleration by multiple supernova remnants (Axford, 1991) or a galactic termination shock (Jokipii and Morfill, 1991) may extend the spectrum to higher energies than can be achieved in a single typical supernova remnant. The absence of a spectral break can therefore still be readily accommodated both by the original Lagage and Cesarsky model and by various extensions to it.

3 Statistical Analysis of a Break in the Spectrum:

To fit the low-statistics JACEE spectra and search for evidence of a break, we use a Poisson-weighted maximum likelihood approach. The individual events in Fig. 1 are ordered by decreasing energy from $E_1 = E_{max}$ to $E_n = E_{min}$. In any interval $E_{i-1} - E_i$, the expected number of events is

$$< n >_i = dN/dE_i\ (E_{i-1} - E_i\ )\ (G/\varepsilon)_i \qquad (2)$$

where G_i is the geometry (acceptance) factor (m^2-sr-s-TeV) for the i-th interval and ε_i is the expected efficiency. The Poisson probability of seeing one event when $<n>_i$ are expected is then

$$P_i(n=1) = <n>_i\ e^{-<n>i} \qquad (3)$$

We assume a broken power law of the form

$$dN/dE = aE^{-\gamma} / [1 + (E/E_o)^{\delta}\ ] \qquad (4)$$

and evaluate the likelihood of the spectrum (4) from the product of the probabilities

$$\ln L = \ln \Pi_i\ P_i = \Sigma_i \ln <n>_i - N_{events} \qquad (5)$$

where N_{events} is the total number of points in the spectrum. The fitted spectra (Eq. 1) are obtained by setting E_0 to be very large and varying the free parameters a and γ in Eq. (4) in order to maximize ln L.

In order to look for evidence of a break in the spectrum near energy E_0 (i.e., a steepening from a low-energy spectrum with power law index γ_1 to a high-energy spectrum with index γ_2), we constrain the low-energy spectral index $\gamma_1 = \gamma$ to be in the range $2.6 \leq \gamma_1 \leq 2.7$ based on the measured low-energy data (cf. the references in Asakimori et al., 1998). At high energies (Boothby et al., 1997; Matthews, 1998; Glasmacher et al., 1999), we require the limiting high-energy index $\gamma_2 = \gamma + \delta$ satisfy $3.0 \leq \gamma_2 \leq 3.3$. By requiring a steepening somewhere in the range 1 - 10^4 TeV, we constrain δ to be in the range $0.3 \leq \delta \leq 0.7$. As a function of the break energy E_0, and for various values of δ, we choose a and γ to maximize ln L and plot the maximized ln L vs. E_0 for the JACEE proton data in Fig. 2. Also in Fig. 2 we show the maximized likelihood for the case of no break ($\delta = 0$). In all cases with $\delta > 0.3$, the maximized likelihood peaks gradually near 100 TeV. The difference between the peak value of ln L (approximately -613.5 to -614.2) and the value without a break (-614.7) is small (~0.1%), and the peak occurs at an energy sufficiently high that it is governed mainly by the ~20 protons above 100 TeV. In other words, within 0.1% in ln L, it is equally likely that there is or is not a break in the spectrum. The statistics of the high energy JACEE data preclude a definite answer.

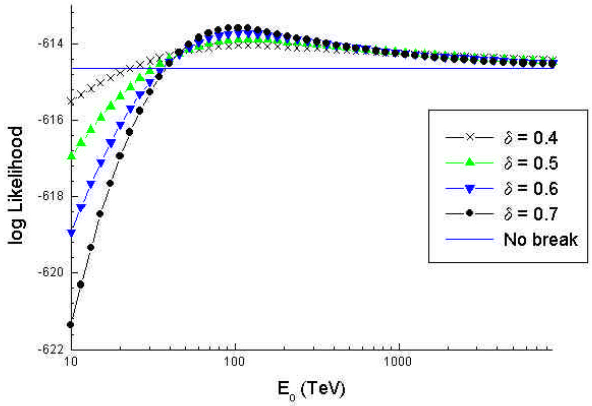

Fig. 2. Log likelihood of a steepening in the JACEE proton spectrum by δ in the power law spectral index at a break energy E_0.

If the measured JACEE protons are taken to be a parent distribution, and randomized data sets are generated by applying Poisson statistics to the parent set, then ln L can be maximized for the randomized data. In this case, the random statistical variation in ln L (for the assumed case of no break in the spectrum, $\delta = 0$) is ~ ± 25, much larger than the difference between the curves with and without a break (ln L for $\delta > 0$ and ln L for $\delta = 0$ respectively) in Fig. 2. This observed variation of ± 25 is expected from Eq. 5: In the case of an unlikely but perfect fit ($\langle n \rangle_i = 1$ for all i), ln L = $-N_{events}$ and therefore has a standard deviation (due to statistics only, and for N_{events} sufficiently large) equal to $\sqrt{N_{events}}$. This is ~25 for the JACEE proton data.

As indicated in Fig. 2, a break in the spectrum corresponds to the ratio

$$R = \frac{L_{break}}{L_{no\,break}} = \frac{\Pi_i P_{i,break}}{\Pi_i P_{i,no\,break}} = \frac{\Pi_i \langle n \rangle_i^b e^{-N_{events}}}{\Pi_i \langle n \rangle_i^n e^{-N_{events}}} \tag{6}$$

in excess of unity. The numerator in Eq. 6 is calculated with a broken power law spectrum of the form (4); the denominator is calculated with a straight spectrum where $E_o \rightarrow 8$. (We note that in both the numerator and the denominator, the fitted spectrum is normalized so that $\Sigma_i \langle n \rangle_i = N_{events}$.) Given the uncertainty derived above for ln L, and the corresponding uncertainty in ln R, the condition that a break occurs in the spectrum corresponds to the requirement that (at 68% confidence)

$$\ln R \geq \sqrt{N_{events}} \quad . \tag{7}$$

In order for condition (7) to be satisfied, it can be shown that the number $N_{>E_o}$ of events at energies higher than E_o must satisfy

$$N_{>E_o} \geq \xi^{-1}\sqrt{N_{events}} \;\sim\; (1-3)\sqrt{N_{events}} \qquad (8)$$

where ξ is a numerical factor approximately equal to the value of ln $[1+(E/E_o)^{\delta}]$ averaged over all points i with $E_i > E_o$. Since the energies corresponding to 25 and 75 events in the JACEE proton data set are at 90 and 40 TeV respectively, below the peaks in Fig. 2, we again conclude that JACEE has no evidence for or against any bend in the high energy spectrum.

This argument can be turned around to determine the maximum energy at which an experiment has sufficient statistical accuracy to detect a bend in the spectrum. In the case of JACEE, this corresponds from condition (8) to a maximum detectable E_o ~40 - 90 TeV. For an experiment with 50 times the collecting power (geometry factor x efficiency x exposure time), $N_{>E_o}$ increases by ~7 based on Eq. 8. To compensate for the factor of 50 in collecting power, E_o increases to the point where JACEE would see (25-75)/7 ~ 4-10 events. In Fig. 1, this would correspond to an energy of 200-500 TeV depending on the value of δ.

4 Conclusions:

The JACEE results represent the highest energy direct particle-by-particle measurements available on the spectrum of cosmic ray hydrogen and helium. The resulting spectra are consistent with power laws with no spectral breaks. The hydrogen spectral index is steeper than that of the helium by 0.12, corresponding to 2 standard deviations. With the improved statistics from the Antarctic flights, the results appear to be consistent with the predictions based on models of supernova shock acceleration and leaky box propagation. Although the highest energy proton event measured by JACEE is at ~ 800 TeV, there is no evidence for or against a break in the spectrum above approximately 90 TeV due to the limited statistics at the highest energies. Significantly greater collecting power will be required in order to address the question of a spectral break with better statistics than JACEE.

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