Proceedings of ICRC 2001: 1788 © Copernicus Gesellschaft 2001

ICRC 2001

A two component model for galactic cosmic rays?

D. Kazanas[1], **F. C. Jones**[1], **R. Streitmatter**[1], **and A. Nicolaidis**[2]
[1]LHEA, NASA/GSFC Code 661, Greenbelt, MD 20771
[2]Department of Theoretical Physics, University of Thessaloniki, Thessaloniki 54006, Greece

Abstract.
We propose that the galactic cosmic ray spectrum comprises two components:(a) One due to acceleration in suprenova shocks which yields proton spectra of index $\gamma_{SN} \simeq 2.68$ which cut-off at an energy $E_p \sim 10^{14}$ eV and spectra for higher Z nuclei of similar slopes and cut-off energies $E_Z = ZE_p$, as demanded by the rigidity dependent cut-off of shock acceleration. (b) An additional component of slope $\gamma \simeq 2.6$ that consists mainly of protons and extends to an energy $E_0 \simeq 10^{18.5}$ eV, the limiting energy for confining protons within the galaxy. We examine to what extent the current data are consistent with the above decomposition and the recent proposal that the "knee" of the cosmic ray spectrum at $E \sim 10^{15.5}$ eV is due to new interactions beyond those of the Standard Model of Weak - EM interactions.

1 Introduction, Background

It is generally believed that cosmic rays of energies up to $E_0 \simeq 10^{18.5}$ eV are of galactic origin. The main theoretical argument in support of this belief is that at this energy the gyroradii of protons in the mean galactic magentic field ($B_g \sim 1 - 3$ μG) is of order $R_g \sim 1 - 3$ kpc, i.e. that of the transverse galactic dimension and therefore protons of higher energy would freely escape from the galaxy. This argument receives additional, observational support by the the recently observed increase in the cosmic ray anisotropy toward the galactic center at these energies (Hayashida et al. , 1999). The smaller observed anisotropies at higher and lower energies are consistent then with the notion that cosmic rays i these regimes constitute respectively isotropic extragalactic and galactic components, the former of unknown origin and the latter the result of diffusion of these lower energy particles throughout the volume of the galaxy.

Such a contention, however, is at great odds with our most popular current models of cosmic ray accleration which argue that galactic cosmic rays are accelerated in supernova (SN) shocks. Detailed calculations of this process have indicated that the maximum energy attained by protons at these sites can not be higher than $E_p \simeq 10^{14}$ eV, even with the diffusion coefficient at the Bohm value (Berezhko & Völk , 2000). Actually, the rigidity dependence of shock acceleration implies that nuclei of higher Z achieve energies higher than this by the same factor, leading to a cut-off in the total energy of SN shocks at $\simeq 2\ 10^{15}$ eV for Fe nuclei and correspondingly smaller energies for the He, CNO and Ne, S groups, an energy roughly three orders of magnitude smaller than that associated with the diffusion and escape of cosmic rays from the galaxy.

To further complicate matters, there appears to be a steepening in the cosmic ray spectrum at energies $E_k \sim 10^{15.5} - 10^{16}$ eV from an index of $\gamma \simeq 2.75$, as determined by the lower energy data, to $\gamma \simeq 3$ which extends to $E_0 \sim 10^{18.5}$ eV, with a harder extragalactic component becoming dominant at energies $E \gtrsim E_0$. This additional steepening at $E \simeq E_k$ has been long known as the "knee" in the cosmic ray spectrum.

The origin of the "knee" and the cosmic ray composition in its vicinity have been for a long time open issues associated with the general problem of cosmic ray acceleration and propagation. Because a featureless power law provides very little information about the sources, acceleration and propagation of cosmic rays, features such as the "knee" have been thought to provide valuable clues in our understanding of these problems. However, despite the knowledge of the existence of this feauture for over 20 years not much progress has been made in this direction.

From the point of view of cosmic ray propagation, there exists no obvious scale associated with the galaxy corresponding to the proton gyroradius at the knee energy. Furthermore, the transition of between the two asymptotic indices near the "knee" is sufficiently sharp to preclude an account by propagation effects, which would produce a transition extending over a much broader energy range.

Correspondence to: D. Kazanas
(kazanass@milkyway.gsfc.nasa.gov)

The apparent coincidence of the "knee" with the highest energy thought attainable in SN shocks (albeit only for Fe nuclei) has led to the suggestion that the "knee" denotes the onset of an altogether different (unknown) acceleration mechanism. This proposal might have some merit except for the fact that the spectrum above the "knee" is *steeper* that below it, while the spectrum appears to be without any apparent discontinuity at this energy. These two facts imply that any such mechanism should be able to accelerate (almost) *all* the particles brought to the "knee" energy by acceleration in SN shocks. Given that these particles actually diffuse throughout the entire galaxy, such a requirement seems very hard to satisfy.

Alternatively, based on a model of particle acceleration in and escape from AGN, it has been proposed that the particles above the "knee" are extragalactic (Protheroe & Szabo , 1992), with the "knee" simply denoting the energy at which the SN shock acceleration terminates and the extragalactic contribution begins. However, such a proposal suffers from the following problems: It hard to see how it could produce the "sharpness" of the "knee", given the multi-object, multired-shift AGN contribution. It is also hard to see how the AGN contribution would match that of the galactic cosmic rays at the "knee" without any apparent discontinuity in the cosmic ray flux. The absence of any visible discontinuity in the spectrum other than the change in the slope, then suffers from the same problems that face a galactic acceleration mechanism.

The above lack of satisfactory explanation of the presence of the "knee" with cosmic ray propagation physics has led to the suggestion that it denotes a change in the physics of high energy interactions, in particular to changes in the inelasticity of high energy collisions (Nikolsky , 1993). More recently, Kazanas & Nicolaidis (2001) proposed that the "knee" is due to a novel channel in the high energy proton interactions which "opens-up" at lab energies $E \sim E_k$; in fact they proposed that to be a manifestation of (the long sought) physics beyond the Standard Model of EW interactions. Interestingly, the energy of the "knee" is tantalizingly close to the CM energies (i.e. ~ 1 TeV) at which "new physics" are expected to become operative on the basis of very generic arguments, such as non-violation of unitarity. More specifically, Kazanas & Nicolaidis (2001) proposed that the "knee" is the result of under-estimation of the total energy associated with cosmic ray showers above the "knee", because the "new physics" interaction channels part of the available energy to novel particles which do not trigger the air shower detectors. It turns out that this requirement is a general feature in a number of theories for physics beyond the Standard Model (supersymmetry, technicolor, low scale gravity). Rather than choosing a specific of the available alternatives, Kazanas & Nicolaidis (2001) used gluon fusion and a simple parametrization of the unseen energy fraction, y, and the ratio of the relevant cross section to that of the strong interactions, α, to provide fits to the cosmic ray data between $10^9 - 10^{18}$ eV with a single power law incident proton spectrum of $\gamma = 2.75$.

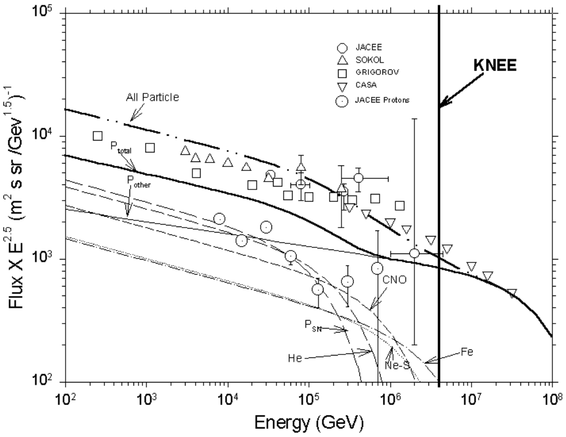

Fig. 1. The decomposition of the galactic cosmic ray spectra below the "knee" as given by our model. The thin curves indicate the SN shock accelerated components for the various nuclear groups, as marked in the figure. The curved marked $\mathrm{P_{other}}$ denotes the spectrum of the additional proton component necessary to account for the entire galactic cosmic ray spectrum. The curve marked All Particle is the sum total of all components along with the all particle spectra of a number of experiments (as indicated in the figure) for comparison.

2 Cosmic Ray Composition Around The "knee"

The fits provided by Kazanas & Nicolaidis (2001), compelling as they may be, they were applied, for simplicity, to the all particle data provided by the air shower experiments. Because the energy scalings indicated in this work were applicable to protons, it is important that the proton contribution be isolated before any more specific conclusions about the precise scale and the relevant parameters associated with a more detailed theory are inferred from the cosmic ray data. It is thus of paramount importance that the composition of cosmic rays near the "knee" be determined and the parameters of the proton component be isolated. Needless to say, the cosmic ray composition is also of great general importance for the determination of the cosmic ray sources and acceleration mechanism. The goal of the present note is to re-examine the issue of the "New Physics" interpretation of the "knee" using a more detailed analysis which takes into account the cosmic ray composition around the "knee".

A number of experiments have measured the composition of cosmic rays both below and above the "knee". The former involve generally emulsion experiments at high altitudes achieved through balloon flights, while the latter rely on interpretation of air-shower results. For brevity we concentrate only on the emulsion results of the JACEE collaboration (Asakimori et al. , 1998) for energies below $\simeq 10^{14}$ eV and the air shower results of CASA BLANCA (Fowler et al. , 2000) (which however provide only the $\langle lnA \rangle$ value of the incident particle atomic mass A rather than the fluxes of individual species) for energies $E \sim 10^{14.5} - 10^{16.5}$ eV.

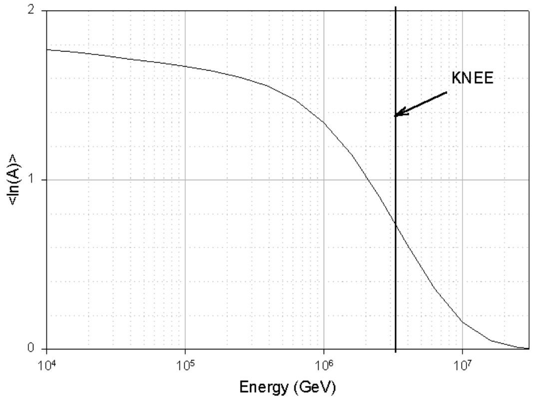

Fig. 2. The value of the mean logarithm of cosmic ray atomic number $\langle lnA \rangle$ as a function of energy, as determined by the elemental decomposition described in the text.

Unfortunately, the lack of sufficient detail in these data and their limited energy span makes necessary the use of specific models in order to allow us to draw conclusions about the cosmic ray spectra over a significanlty broader range of energies, which spans many decades and it is covered by experiments of very different and diverse methodologies.

Thus we assume that galactic cosmic rays must comprise at least two components. One of them is considered to be the output of SN shocks which, however, as discussed earlier are not thought able to produce protons of energies higher than $E_p \sim 10^{14}$ eV. Given the scaling of shock acceleration maximum energy with particle rigidity, it is expected that the spectra of nuclei of atomic number Z accelerated by the same mechanism, must have correspondingly higher cutoffs at energies $E_Z \simeq Z\, E_p$. Using the JACEE results of the He, CNO, Ne-S, and Fe groups to obtain the normalization and slopes (they are all consistent with $\gamma_Z \simeq 2.68$) of the corresponding components, one can by the proper scaling of the cut-off energies produce complete, detailed, model spectra of the SN shock contribution to the galactic cosmic rays. These are expected to extend to $E \gtrsim 10^{15}$ eV for Fe nuclei. Figure 1 presents such a decomposition. The thin lines labeled $\mathrm{P_{SN}}$, He, CNO and Fe provide the spectra of each of these components.

The presence of particles with energies as high as $E_0 \sim 10^{18}$ eV, clearly requires the an additional component in the cosmic rays, which we assume to be exclusively protons. In order that their contribution not violate the low energy results, their spectrum must be flatter than that of the heavier nuclei as determined by JACEE. We tentatively use a slope $s = 2.6$ for this component, denoted as $\mathrm{P_{other}}$ in figure 1. The total proton spectrum is given by the curve labeled $\mathrm{P_{total}}$ while the sum of all spectra is given by the dash-double dot heavy line denoted as All Particle along with a large collection of experimental data which cover the range $\sim 10^2 - 10^7$ GeV. The tentative position of the "knee" is also noted by the thick vertical line, while the total proton flux steepens shortly beyond the "knee", as expected by the "New Physics" interpretation. It is of interest to note that the because of the addition of two proton components, their combined spectrum has locally, around $E \sim 10^5$ GeV a slope greater than that of the heavier nuclei, potentially providing an account of this aspect of the JACEE data.

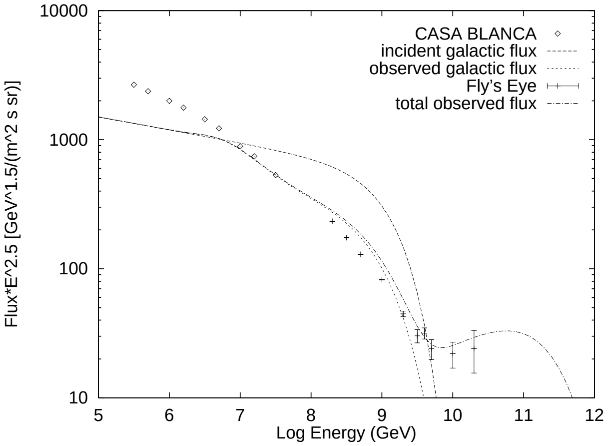

Fig. 3. The incident high energy galactic proton flux (dashed line), the observed galactic flux (dotted line) and the total (galactic plus extragalactic) observed flux (dash-dot line). Also given are the CASA BLANCA data (diamonds) and the Fly's Eye data (crosses).

The correctness of the above decomposition is further tested by computing the mean logarithm of the particles' atomic number $\langle lnA \rangle$, as it is usually done in the interpretation of air shower experiments. This quantity has been computed for the airshowers of CASA BLANCA and it is shown in figure 7 of (Fowler et al. , 2000). In our figure 2 we compute the same quantity as a function of energy. We believe that the agreement between the observations and or model results is reasonable: The value of $\langle lnA \rangle \simeq 1.6$ at $E = 10^{14.5}$ eV, just as in the real data and falls to $\langle lnA \rangle \simeq 0.8$ at the "knee" energy. While it continues to drop to 0 in our caclulations, the real data indicate a very drastic change: Its slope reverses to positive(!) beyond $E \simeq E_k \simeq 10^{15.5}$ eV. The transition takes place in within a very small fraction of a decade in energy. We find this fact extraordinary, since any composition changes due to particle propagation effects take place over at least one decade in energy. This sharp transition has a natural account within our "New Physics" interpretation of the "knee": The "opening" of the new channel effects a dispersion of the fraction of the energy which can trigger the detectors (remember that a fraction y does not trigger them) over a larger number of particles, providing thus the impression of a sudden increase in the mean atomic number of the incident cosmic rays, while the latter consist in fact mainly of protons.

3 Cosmic Ray Spectrum Beyond The “knee”

With the spectrum of the proton component not produced in SN shocks determined through the fits of the lower energy data, we can now produce the spectrum at energies $E \sim 10^{15} - 10^{19}$ eV, using the prescription of Kazanas & Nicolaidis (2001). This figure presents the indident in the atmosphere galactic proton spectrum (dashed lines), the observed galactic spectrum (dotted lines), after its reprocessing through the “New Physics” channels and the total spectrum including an extragalactic component of slope $s = 2.2$, becoming important ata enregies $E \gtrsim 10^{18.5}$ eV, after its reprocessing by the same (lower energy) physics. We also present the data of CASA BLANCA (Fowler et al. , 2000) as well and the data of Fly’s Eye (stereo) (Bird et al. , 1993). For the fit a value for the cut-off energy of the galactic cosmic ray protons $E_0 = 1.5\,10^{18}$ eV was assumed.

It is apparent that the model is in good agreement with the data. It produces a sharp break at the “knee” energy and steepens to the value necessary to reproduce the Fly’s Eye data.

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