COSMOLOGICAL ORIGIN FOR COSMIC RAYS ABOVE $10^{19}$ eV

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Received 1995 June 28; accepted 1995 August 4

ABSTRACT

The cosmic-ray spectrum at $10^{19}$–$10^{20}$ eV, reported by the Fly’s Eye and the AGASA experiments, is shown to be consistent with a cosmological distribution of sources of protons, with a power-law generation spectrum $dN/d\ln E = -2.3 \pm 0.5$ and energy production rate of $4.5 \pm 1.5 \times 10^{44}$ ergs Mpc$^{-3}$ yr$^{-1}$. The two events measured above $10^{20}$ eV are not inconsistent with this model. Verifying the existence of a “blackbody cutoff,” currently observed with low significance, would require $\sim 30$ observation years with existing experiments, but only $\sim 1$ year with the proposed $\sim 5000$ km$^2$ detectors. For a cosmological source distribution, no anisotropy is expected in the angular distribution of events with energies up to $\sim 5 \times 10^{19}$ eV.

Subject headings: acceleration of particles — cosmic rays — gamma rays: bursts

1. INTRODUCTION

Recent results, reported by the Fly’s Eye (Bird et al. 1993, 1994) and the AGASA (Hayashida et al. 1994; Yoshida et al. 1995) experiments, show two major features in the cosmic-ray (CR) energy spectrum above $10^{17}$ eV. A break in the shape of the spectrum is observed at $\sim 5 \times 10^{18}$ eV; the CR composition also changes from predominantly heavy nuclei below the break to predominantly light nuclei above the break. Evidence for these features existed in the results of previous experiments with weaker statistics (see, e.g., Watson 1991 for a review). Coupled with the lack of observed anisotropy, these features strongly suggest that below $\sim 10^{19}$ eV the cosmic rays are mostly heavy ions of Galactic origin, and that an extragalactic component of protons takes over above $\sim 10^{19}$ eV. If the particles observed above $10^{18}$ eV are indeed protons of extragalactic origin, then their interaction with the microwave background radiation (MBR) is expected to produce a “blackbody cutoff” in the CR spectrum at $\sim 5 \times 10^{19}$ eV (Greisen 1966; Zatsepin & Kuzmin 1966).

In this Letter we compare the CR spectrum above $10^{19}$ eV, reported by the Fly’s Eye and the AGASA experiments, with that expected from a homogeneous cosmological distribution of CR sources. We assume that each source generates high-energy protons with a power-law differential spectrum $dN/dE \propto E^{-\alpha}$. The expected spectrum is shown to be insensitive to source evolution with redshift and to the cosmological parameters, such as the Hubble constant and the average universe density. We find that current observations are consistent with a cosmological distribution of sources with $\alpha \approx 2$ and energy production rate of $\sim 4 \times 10^{44}$ ergs Mpc$^{-3}$ yr$^{-1}$ in the range $10^{19}$–$10^{21}$ eV. However, the statistical significance with which the blackbody cutoff is observed in current data is small. We show that the signature of the interaction with the MBR should be sought in the energy range $2 \times 10^{19}$–$10^{20}$ eV rather than above $10^{20}$ eV. At energies above $10^{20}$ eV, the spectrum is sensitive to inhomogeneities in the source distribution over scales $\sim 10$ Mpc. We also show that for a cosmological source distribution, no anisotropy is expected in the angular distribution of events with energies up to $\sim 5 \times 10^{19}$ eV.

2. METHOD

As they propagate, high-energy protons lose energy as a result of the cosmological redshift and as a result of production of pions and $e^+e^-$ pairs in interactions with MBR photons. Here we approximate the energy loss caused by scattering, which is a random process, as a continuous energy loss (CEL). In this approximation, the energy loss rate of a proton of given energy is taken to be the mean loss rate of an ensemble of protons of the same energy. The CEL approximation is excellent for pair production, for which the mean free path is small and the relative energy loss in a single scattering, of order $m_p/m_e \sim 10^{-3}$, is also small. For pion production, the average relative energy loss in a single collision is 0.13 at the threshold and rises to 0.5 at higher energy. However, fluctuations in proton energy resulting from this process are significant only for propagation distances smaller than 100 Mpc and proton energy $>10^{20}$ eV (Aharonian & Cronin 1994). The CEL approximation therefore gives accurate results for the flux below $10^{20}$ eV. At higher energies, the flux obtained by this approximation drops faster than that obtained when fluctuations in proton energy are taken into account. It has been shown (Berezinski, Grigor’eva, & Zatsepin 1975; Berezinski & Grigor’eva 1988) that for a flat generation spectrum, $\alpha \approx 2.6$, the flux obtained using the CEL approximation is accurate to better than 10% up to $3 \times 10^{20}$ eV, the highest energy at which events have been reported. We have confirmed this by comparing the Monte Carlo calculation of the spectrum obtained for cosmological sources with $\alpha = 2$, given in Yoshida & Teshima (1993), to our results. We find an agreement to better than 20% up to $2 \times 10^{20}$ eV. (For the comparison we have used the energy loss rate given by Fig. 3 of Yoshida & Teshima 1993. This rate is close to our approximation [described below] everywhere except near...
The energy loss rate resulting from cosmological redshift is \( E^{-1} \frac{dE}{dt} = (1 + z)^{-1} \frac{dz}{dt} \), where \( z \) is the redshift. The energy loss rate resulting from pair or pion production is

\[
\tau(E, z = 0) = \max \left[ \frac{\tau_0 \exp(E/E_0)}{\tau_0} \right],
\]

with \( \tau_0 = 2.33 \times 10^7 \) yr, \( E_0 = 3.25 \times 10^{20} \) eV, and \( \tau = 4.55 \times 10^7 \) yr. These values give an approximation for equation (1) with \( \sim 10\% \) accuracy for \( E > 5 \times 10^{19} \) eV. Berezinski & Grigor'eva (1988) have shown that for \( E \ll 10^{20} \) eV, \( \tau_0 \) is given by

\[
\tau_0(E, z = 0) = \frac{\pi^2 \hbar^2 m_p}{2G(z = 0)} \exp \left[ \frac{\frac{\varepsilon_{\text{th}} m_p c^2}{2G(z = 0)}}{E} \right].
\]

It should be noted that we do not use the value estimated by equation (3) for \( \tau_0 \). Using this value gives an accurate \( \tau_0 \) for \( E \ll 10^{20} \) eV but results in a large deviation from the accurate \( \tau_0 \) above \( 5 \times 10^{19} \) eV (~30\% at \( 10^{20} \) eV). Since the energy loss caused by pion production dominates over that caused by pair production only above \( 5 \times 10^{19} \) eV, we have chosen a value of \( \tau_0 \) which gives a better approximation at this energy range.

The above rates of energy loss, we compute the energy \( E_0(E, z) \) at which a proton should be produced at an epoch \( z \) in order to be observed at present \((z = 0)\) with energy \( E \). We denote by \( f_0(E) \) the present CR production rate per unit energy and volume and allow a redshift evolution of the form \( f(E, z) = (1 + z)^{\alpha} f_0(E) \) \((m = 0\) implies no evolution). The present number density per unit energy of high-energy protons is then given by

\[
\frac{dn}{dE} = H_0 \int_0^{z_{\text{max}}} dz g(z) (1 + z)^m \frac{\partial E_0(E, z)}{\partial E}.
\]
cosmological model for $E < 2 \times 10^{19}$ eV is consistent with the Bird et al. fit to the extragalactic component. The number of events observed above $2 \times 10^{19}$ eV does not allow an accurate determination of $\alpha$. The value of $\alpha$ should be less than 2.8, since for larger values the flux predicted from the model (with normalization chosen to fit the data in the range $2 \times 10^{19}$ eV $\leq E < 10^{20}$ eV) exceeds the observed flux at $10^{19}$ eV. However, $\chi^2$ of less than 1 per degree of freedom is obtained for $1.8 < \alpha < 2.8$. For these models, the present rate of energy produced as $10^{19}$–$10^{21}$ eV protons is $4.5 \pm 1.5 \times 10^{44}$ ergs Mpc$^{-3}$ yr$^{-1}$. The systematic uncertainty in the experimental event energies, which is of order 30%, does not influence the above conclusions significantly.

We now turn to the two events observed above $10^{20}$ eV. As seen in Figure 1, the flux deduced from these events is higher than that predicted from the cosmological model normalized to fit the data in the range $2 \times 10^{19}$ eV $\leq E < 10^{20}$ eV. It therefore seems that a homogeneous cosmological distribution of power-law CR sources producing the CR flux in the range $2 \times 10^{19}$ eV $\leq E < 10^{20}$ eV cannot account for the existence of the greater than $10^{20}$ eV events. However, it should be noted that the statistical significance of the apparent discrepancy is not high. For the Fly’s Eye exposure, the model predicts an average of $\sim 1.3$ events above $10^{20}$ eV, and the probability that the first event observed at this energy range is above $2 \times 10^{20}$ eV is $\sim 15\%$. For the AGASA exposure, the probability of observing an event above $10^{20}$ eV is $\sim 20\%$. With one event observed by each experiment, the possibility that these events are produced by a homogeneous cosmological source distribution cannot be ruled out. It should further be noted that the flux above $10^{20}$ eV is sensitive to inhomogeneities in the production of protons over scales of order 10 Mpc. In Figure 2 the fraction of the integral flux contributed by sources located further than a certain distance is plotted for several distances. The flux above $10^{20}$ eV is dominated by sources closer than 30 Mpc and is therefore sensitive to $\sim 10$ Mpc scale inhomogeneities. Such inhomogeneities are likely to exist, since they may arise from large-scale clustering or, if the typical number of sources in an $\sim 10$ Mpc sphere is not large, from fluctuations in individual source intensity. Thus, the characteristic signature of a cosmological model, as a result of interaction of protons with the MBR, may be obscured above $10^{20}$ eV by inhomogeneities. A local overdensity of CR sources, for example, would result in a flux above $10^{20}$ eV which is higher than that predicted from a cosmological source distribution homogeneous down to $\sim 10$ Mpc scale.

As seen in Figure 2, the flux above $5 \times 10^{19}$ eV is dominated by sources at distances greater than 100 Mpc and is therefore not expected to be sensitive to inhomogeneities. For this reason, the “blackbody cutoff” at $\sim 5 \times 10^{19}$ eV should be a robust signature of the cosmological model. It is clear from Figure 1 that the number of events detected above $5 \times 10^{19}$ eV is smaller than would be expected from a power-law extrapolation of the flux at lower energy. To estimate the significance of this “cutoff,” we fitted a power law to the Fly’s Eye and AGASA flux in the range $1$–$5 \times 10^{19}$ eV. The minimum in $\chi^2$ (0.8 per degree of freedom) is obtained for $J \propto E^{-1.8}$, with 20.4 events expected above $5 \times 10^{19}$ eV for the combined exposure of both experiments. With 12 events actually observed, the “cutoff” is detected with only 1.8 $\sigma$ significance. In order to rule out the “power-law” hypothesis, that the flux in the range $5$–$10 \times 10^{19}$ eV is described by an extrapolation of the lower energy power-law fit, larger exposures are required. If the high-energy CR flux is indeed described by the cosmological model presented in Figure 1, then the probability that the “power-law” hypothesis would be ruled out with a $3\sigma$ significance increases with increased exposure. With current experiments (AGASA and Fly’s Eye), additional $\sim 30$ years of observation are required for this probability to exceed 70% (For the estimate of the required time, we have taken into account the fact that the AGASA experiment triggering was recently improved). The required observation time would be reduced if new, larger, CR experiments become operative: $\sim 10$ observation years would be required with the new High-Resolution Fly’s Eye experiment (Corbato et al. 1992), which is planned to become operative in 2 years; Only $\sim 1$ year of observation would be required if the proposed $\sim 5000$ km$^2$ detectors are built (Cronin 1992; Watson 1993).

The flux above $10^{19}$ eV is produced in a cosmological model by sources at distances smaller than 1 Gpc (see Fig. 1). For this reason, the flux predicted is insensitive to the assumed values of the average universe density and cosmological constant and also insensitive to source evolution and to the maximal redshift $z_{\text{max}}$ (as long as $z_{\text{max}} > 0.5$). The flux does depend on the value of the Hubble constant. However, for the reasonable range of $50$–$100$ km s$^{-1}$ Mpc$^{-1}$, the changes in the predicted flux are small ($<10\%$ at a fixed energy).

4. CONCLUSIONS

We have shown that the CR spectrum in the range $10^{19}$ eV $< E < 10^{20}$ eV, reported by the Fly’s Eye and the AGASA experiments, is consistent with that expected from a homogeneous cosmological distribution of CR sources, each generating high-energy protons with a power-law differential spectrum $dN/dE \propto E^{-\alpha}$. With the small number of events observed, the value of $\alpha$ is only constrained to the range $1.8 < \alpha < 2.8$. The rate of energy produced by the cosmological sources as $10^{19}$–$10^{20}$ eV protons should be $4.5 \pm 1.5 \times 10^{44}$ ergs Mpc$^{-3}$.
yr$^{-1}$. As recently pointed out by Waxman (1995), this rate is comparable to that produced in $\gamma$-rays by cosmological $\gamma$-ray bursts. The “blackbody cutoff,” expected in a cosmological model at $\sim 5 \times 10^{19}$ eV, is observed in current data with only marginal statistical significance. Raising the statistical significance to an $\sim 3 \sigma$ level would require $\sim 30$ years of observations with current experiments ($\sim 10$ years with the new High-Resolution Fly’s Eye experiment, planned to become operative in 2 years [Corbato et al. 1992]), but only $\sim 1$ year if the proposed $\sim 5000$ km$^2$ detectors (Cronin 1992; Watson 1993) are built. The flux just above $5 \times 10^{19}$ eV is dominated by sources at distances greater than 100 Mpc and is not expected to be sensitive to source inhomogeneities. This implies that the “blackbody cutoff” is a robust signature of the cosmological model. It also implies that no anisotropy related to large-scale source clustering is expected in the angular distribution of cosmic-ray events with energies up to $\sim 5 \times 10^{19}$ eV.

The flux above $10^{20}$ eV is dominated by sources at distances less than 30 Mpc and is therefore likely to be sensitive to source inhomogeneities. Therefore, above $10^{20}$ eV inhomogeneities may obscure the characteristic signature of a cosmological model, which is produced by the interaction of protons with the MBR. Nevertheless, the two events measured by the Fly’s Eye and the AGASA experiments are not inconsistent with the homogeneous cosmological model, which predicts an average of one event above $10^{20}$ eV for the Fly’s Eye exposure. The detection of events above $10^{20}$ eV is, of course, extremely important, since they are likely to point to the location of nearby extragalactic high-energy CR sources.

I thank J. N. Bahcall for invaluable suggestions and comments, and the unknown referee for constructive criticism which led to an improved manuscript. This research was partially supported by a W. M. Keck Foundation grant and NSF grant PHY 92-45317.

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