POSSIBLE INITIAL EVIDENCE OF EXTRAGALACTIC COSMIC-RAY PROTONS AND THE AGE OF EXTRAGALACTIC COSMIC-RAY SOURCES

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Abstract. We have compared the recent cosmic background γ-ray observations with spectra predicted by various possible cosmic interactions. We find that the observed isotropic γ-rays with energies > 1 MeV can best be explained as being due to the decay of π°-mesons produced in extragalactic cosmic-ray collisions. This interpretation indicates that extragalactic cosmic-ray sources were more active (or prevalent) in the past and started to form at a redshift of ~ 100 corresponding to 10^7–10^8 years after the 'big-bang'.

For a present extragalactic gas density of 10^{-7}–10^{-5} cm^{-3}, the present extragalactic cosmic-ray flux is inferred to be 10^{-5}–10^{-3} the galactic value.

Recent theoretical studies by the author [1–4] have indicated the importance of observing isotropic cosmic-γ-radiation in the 1–100 MeV energy region. These predictions of isotropic γ-ray spectra from metagalactic inelastic strong interactions [1, 3, 4], matter-antimatter annihilation [2], and bremsstrahlung [4], along with studies of metagalactic Compton γ-rays [5] and bremsstrahlung γ-rays below 1 MeV energy [6] have indicated the following qualitative points:

(1) Bremsstrahlung and Compton processes may be possible alternative explanations of the observed isotropic X-ray spectrum below 1 MeV. The Compton process, however, requires constant regeneration of cosmic-ray electrons [7].

(2) Inelastic proton-proton interactions may account for the observed isotropic γ-ray flux of Clark *et al.*, [8], if the observed flux is considered to be real, rather than an upper limit. Extrapolations of predicted bremsstrahlung ($\sim E_{\gamma}^{-3.6}$) and Compton ($\sim E_{\gamma}^{-2.3}$) photon spectra, normalized to fit the X-ray observations, would only be compatible with the measurement of Clark *et al.* if that measurement is taken as an upper limit due to a spurious signal.

(3) When the predicted γ-ray spectra were normalized to fit the observations below 1 MeV and above 100 MeV (Clark *et al.*), it became apparent that a determination of the dominant process, or combination of processes which produce the observed X- and γ-rays, would only be made possible by a determination of the γ-ray spectrum between 1 and 100 MeV.

The recent observations of Vette *et al.* [9], have now provided us with measurements of background γ-rays up to 6 MeV. These data, along with some of those of Metzger *et al.* [10], are shown in the accompanying figure.* The differential intensity at 100 MeV is found from the integral measurement of Clark *et al.* by assuming that above 100 MeV the spectrum can be approximated by a power law with an index of

* We have also included an upper limit set by a balloon flight of the Rochester group and updated by a recent recalibration (G. Share, private communication).

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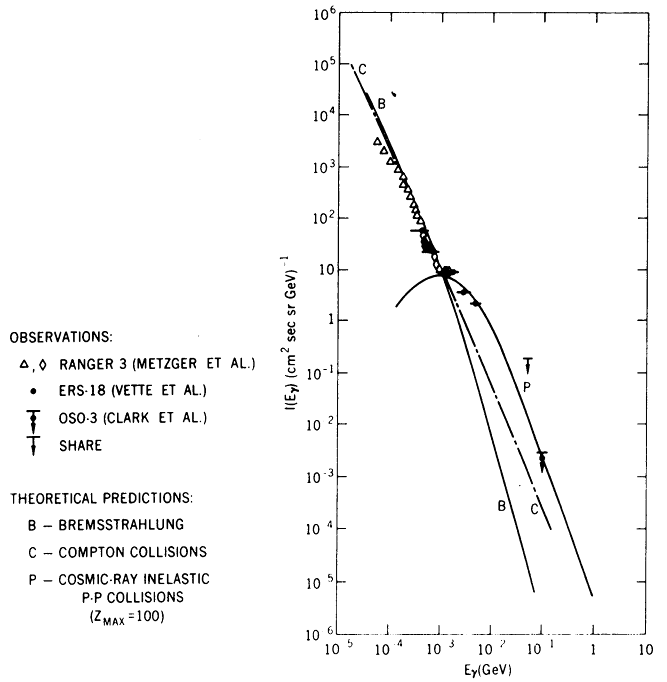

Fig. 1. Extragalactic high energy photon spectra.

~3 as shown for the theoretical p–p spectrum. Also shown in the accompanying figure, are predicted γ-ray spectra due to the various possible metagalactic interactions. These spectra have been discussed in detail in References [1–4] and such detailed discussion will not be repeated here.

The new data of Vette *et al.*, are consistent with the power law trend below 1 MeV as indicated by the Ranger 3 measurements and other observations [11]. However, they indicate a marked departure from the power law above 1 MeV. For example, the 6 MeV point is an order of magnitude higher than what would be expected on the basis of a power law extrapolation of the X-ray data. These data, taken with the data of Clark *et al.*, being interpreted as a real flux, fit the shape of the theoretical γ-ray spectrum from p–p interactions integrated to a maximum redshift of ~100 for a burst or evolving sources model where cosmic-ray production was higher in the past. [1, 4]. They do not seem consistent with the other theoretical spectra for energies above 1 MeV.

These suggestive results make it even more imperative to obtain other γ-ray observations in the 1–100 MeV region in order to confirm the data of Vette *et al.*, and to extend the measurements to higher energies. However, on the basis of these first results we present the following interpretation.

Comparison of the predicted spectra with the γ-ray observations indicates that extragalactic γ-radiation may be due to the decay of neutral pi-mesons produced in inelastic collisions of metagalactic cosmic-ray protons and gas. The peak in the spectrum, which normally occurs at ~ 70 MeV, is redshifted down to ~ 1 MeV energy. This effect is due to the increased collision rate at larger redshifts when our expanding universe was in a more compact state as well as increased cosmic-ray production at large redshifts. A cosmic-ray production rate which is constant over all reshifts will not account for the new observations [3].

Either a burst model or evolving sources model for the time-dependence of cosmic-ray production in the past will fit the predicted spectrum; the position of the peak depends primarily on the maximum redshift at which γ-rays are produced [3]. However, the assumption of various time-dependence models for cosmic-ray production leads to different requirements for the present metagalactic flux needed to produce the observed γ-rays [1, 4]. The maximum redshift needed to produce the observations is ~ 100, which corresponds to an epoch when the age of the universe was 10^7–10^8 years and the temperature of the universal radiation field was ~ 270 K. This may correspond to the epoch when objects of galactic mass were beginning to form from the metagalactic medium [12]. There is mounting evidence that radio sources were more active (or prevalent) at earlier epochs [13], and it is plausible to speculate that in these sources, where electrons are accelerated to cosmic-ray energies, protons may also be accelerated to these energies. Whereas the electrons have short lifetimes at these redshifts due to Compton interactions with the universal radiation field [7, 14] possibly restricting their radio emission stage to redshifts of ~ 10 or less, the protons do not undergo significant depletion from Compton interactions. If we consider present extragalactic gas densities of 10^{-5} to 10^{-7} cm^{-3}, and assume increased cosmic-ray production in the past, we find that the present intergalactic cosmic-ray flux need only be $\sim 10^{-3} - 10^{-5}$ of the galactic value in order to account for the observed γ-ray intensity. Such a flux has been strongly advocated by Ginzburg and Syrovatskii [15].

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