Fermi National Accelerator Laboratory

FERMILAB-Conf-83/36-THY
April, 1983

# The Origin of the Ultra High Energy Cosmic Rays*

DAVID N. SCHRAMM
The University of Chicago, Chicago, Illinois
and
Fermi National Accelerator Laboratory, P.O. Box 500
Batavia Illinois, 60510

AND

CHRISTOPHER T. HILL
Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, IL 60510

## Abstract

The nature of the cosmic ray spectrum above $10^{19}$ ev discriminates between possible primary source models in a limited way. The shape of the spectrum, apart from normalization, is universal after a few photomeson interaction lengths. Fundamental processes, those sensitive to physics at e.g. the grand unification scale, are energy efficient and may be necessary to account for the normalization of the spectrum at the GZ cut-off. Very distant cosmological sources of this kind can generate significant structure above $10^{19}$ev. Local sources are not required and may even be problematic.

*Contributed paper to the 18th International Cosmic Ray Conference, Bangalore, India, August 22, 1983.

I. Introduction

The cosmic ray spectrum above $10^{19}$ ev is a puzzle. Here the degradation effects by photomeson production on $3^{o}K$ photons (1) are expected to set in. In fact, no evidence for the GZ cut-off exists and the quantity $E^3 dN/dE$ actually indicates an enhancement onsetting at $2\times10^{19}$ ev (2). Experimental uncertainties are perhaps such that one should regard the present situation as inconclusive, but it is useful to consider the theoretical expectations for the spectrum at these energies, particularly with regard to what we may or may not expect to learn about fundamental (high energy) physics.

We have recently developed a formalism for treating the evolution of the proton spectrum above the pion threshold, $E_p = m_p m_\pi / 2E_\gamma$ (3). Our approach differs substantially from those preceding and predicts, necessarily, an enhancement in $E^3 dN/dE$ below the expected cut-off energy. Furthermore, we are able to analyze the evolution of an arbitrary input spectrum exactly (in a statistical sense). We find that for a few interaction lengths the cut-off may not appear and we are very sensitive to the input spectrum (this is of course obvious; throughout we define an interaction length to be $L = 1/\rho_\gamma \sigma$ = 8Mpc, where $\rho$=400 photons/cm$^3$ and $\sigma$=100μb). An important new result is that any novel phenomenon above $10^{20}$ev can lead to a "pile-up" between $10^{19}$ and $10^{20}$ev. Local sources are not necessary to accomodate the ankle structure in the spectrum. However, if a significant number of events do exist above $10^{20}$ev, then local sources may be required. However, and perhaps most importantly, we emphasize that the resulting enhancement will, after 10 interaction lengths, become an approximately universal function of energy, up to the overall normalization which retains memory of the original spectrum.

## II. Universal Enhancement

This behavior is demonstated in Figs.(1) and (2) which were obtained by numerical integration of the spectral transport equation (3). In both cases we evolved a conventional $1/E^3$ spectrum with a delta function "spike" at energy $E_o$ with normalization c:

$$dN/dE = \eta(1/E^3 + c\delta(E_0 - E)) \quad . \tag{1}$$

The absolute normalization is observationally $\eta \sim 10^{25} ev^2/m^2 sec$ str, In Fig.(1) we choose c=.2, $E_o = 7.5 \times 10^{20}$ev and evolve to 5, 10 and 40 interaction lengths. In Fig.(2) we choose c=1.0 and $E_o = 1.4 \times 10^{22}$ev. We see clearly the universal form of the spectrum by 10 interaction lengths, apart from overall normalization. Indeed, the maxima differ between Fig.(1) and (2) by log(1.0/.2) as expected.

We may conclude that if events are seen corroborating the enhancement at $E > 10^{20}$ev, then the source must lie within 40Mpc., e.g. the Virgo cluster or more local (this has also been remarked before by Stecker (4), but we see even at 5 i.l. considerable distortion of the primary spectra). This is potentially problematic, however, because the contributions from like sources distributed throughout the Universe should produce a very large "pile-up" at $5\times10^{19}$ev, which should already be quite visible as the dominant structure in the spectrum.

The overall normalization of any high E component remains a puzzle. What mechanisms might account for it? We note first that most astrophysical processes are macroscopic and inherently "soft", i.e. p=(differential index)>2. In this case the total multiplicity $1/E^{p-1}$ is dominated by the lower energy limit of the integral, as is the total energy, $1/E^{p-2}$, which implies that the energy is carried by the many low energy particles. Such a spectrum is thus very inefficient at producing a high energy effect requiring enormous energy input. Indeed, the model of ref.(5) (diffusion through the intergalactic B-field with Virgo as a source requires typically $10^6$(typical galactic energy output) for the entire cluster with $p\sim2.5$).

## III. Fundamental Processes

Alternatively, fundamental processes, i.e. those that probe extremely short distance physics, tend to have a harder spectrum with $1<p<2$. Here the multiplicity is still dominated by the low energy limit of the integral, but the energy is carried off by a few extremely energetic particles. For example, the decay of monopolonium (monopole-antimonopole boundstates) produces a hadron spectrum with p=1.5 (6). The cosmological closure density limit of SU(5) monopoles is of order $10^{32}$/cubic light year. The local enhancement in a cluster may well be 10 times greater. Assuming most monopoles are bound into monopolonia we can accomodate the ankle in the CR spectrum with $10^{20}$ decays per cubic light year per year in the cluster. Such an outrageous suggestion is interesting in that it might simultaneously solve the missing mass problem at the cluster scale and the monopole overabundance problem in the standard big bang if the Virgo cluster is a relic "monopole-antimonopole furnace" (7).

Similar expectations may hold for miniblackhole evaporation (for which the hadron spectrum can be calculated from the quark-gluon spectrum along the lines of ref.(6)), the decays of excited monopoles that are unstable, but may have suppressed decay rates by quantum tunneling (for which the spectrum should be that of gluons fragmenting with initial energy $10^{15}$Gev, which gives roughly p~1.5), and even the more exotic possibilies of false vacuum decay, domain wall annihilation, flux tube (Nielsen-Olessen vortex) collisions, etc. We mention these with tongue in cheek.

It may well be that the neutrino spectrum, which will contain a primary component and an induced component from pi decays and is otherwise immune to the evolution-distortion effects, will be a useful discriminant for the origin of the ultra high energy cosmic rays.

## IV. References

1. K. Greisen, Phys. Rev. Letters 16, 748 (1966) V.A. Kuzmin, G.T. Zatsepin, Zh. Eksp. Teor. Fiz. 4, 78 (1966).
2. See J. Linsley, in Origin of Cosmic Rays, 53-68, ed. Setti, et. al., (1981), and refs. therein.
3. C.T. Hill and D.N. Schramm, this conference, and in preparation.
4. F. Stecker, Phys. Rev. 21, 1016 (1968).
5. M. Giler, J. Wdowsczyk, A.W. Wolfendale, J. Phys. G.; Nucl. Phys. 6, 1561 (1980).
6. C.T. Hill, "Monopolonium", Fermilab-Pub-82/70-THY.
7. See the most recent analysis of D. Dicus, V. Teplitz, and D. Page, Phys. Rev. D26, 1306 (1982) and the refs. therein.

## Figure Captions

Fig. 1: Evolved spectrum of eq.(1) with $E_0 = 7.5\times10^{20}$eV and c = .2 to (A) 5 interaction lengths (il.); (B) 10 il.; (C) 40 il.

Fig. 2: Evolved spectrum of eq.(1) with $E_0 = 1.4\times10^{22}$eV and c = 1.0 to (A) 5 interaction lengths (il.); (B) 10 il.; (C) 40 il.

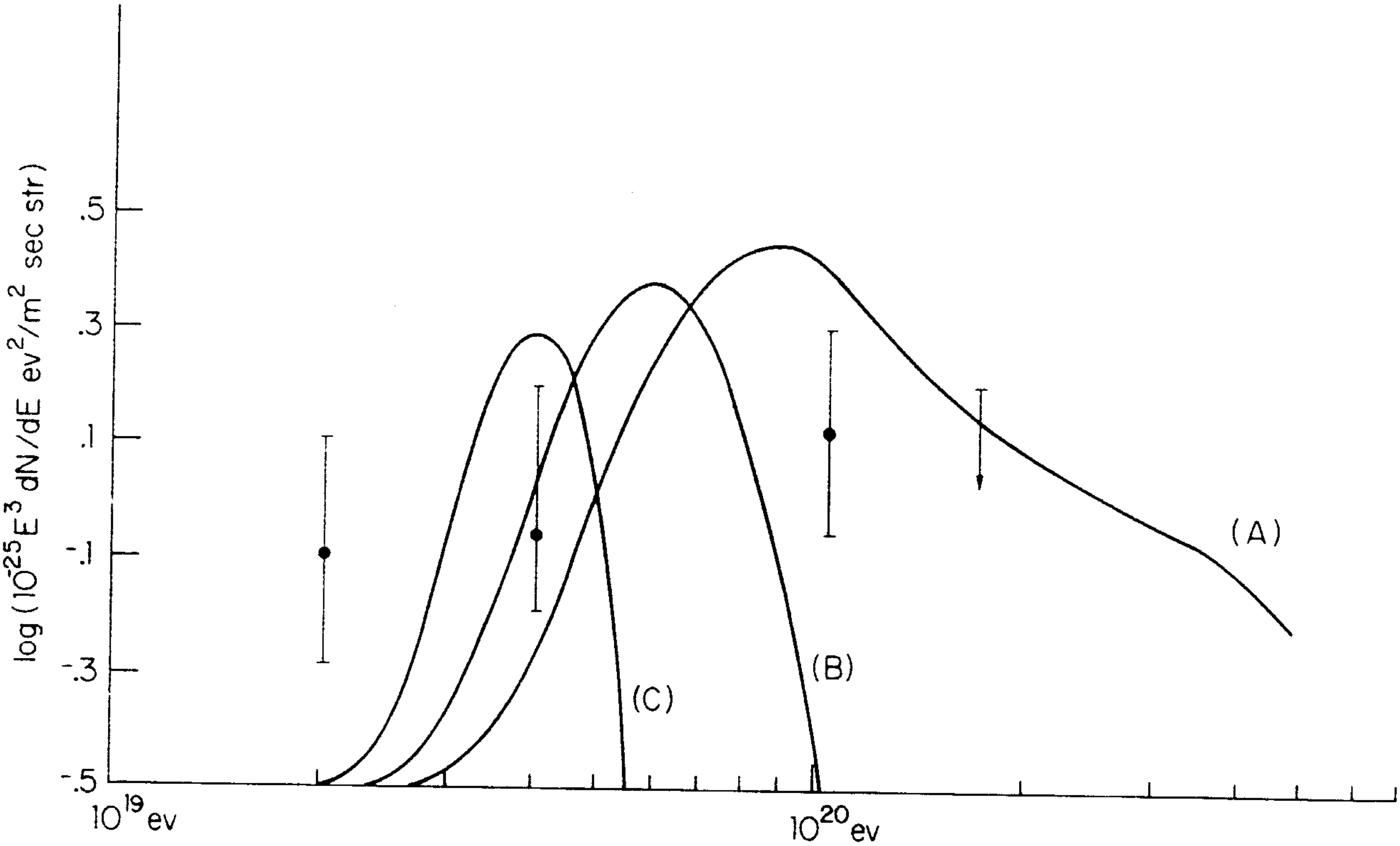


Fig. 1

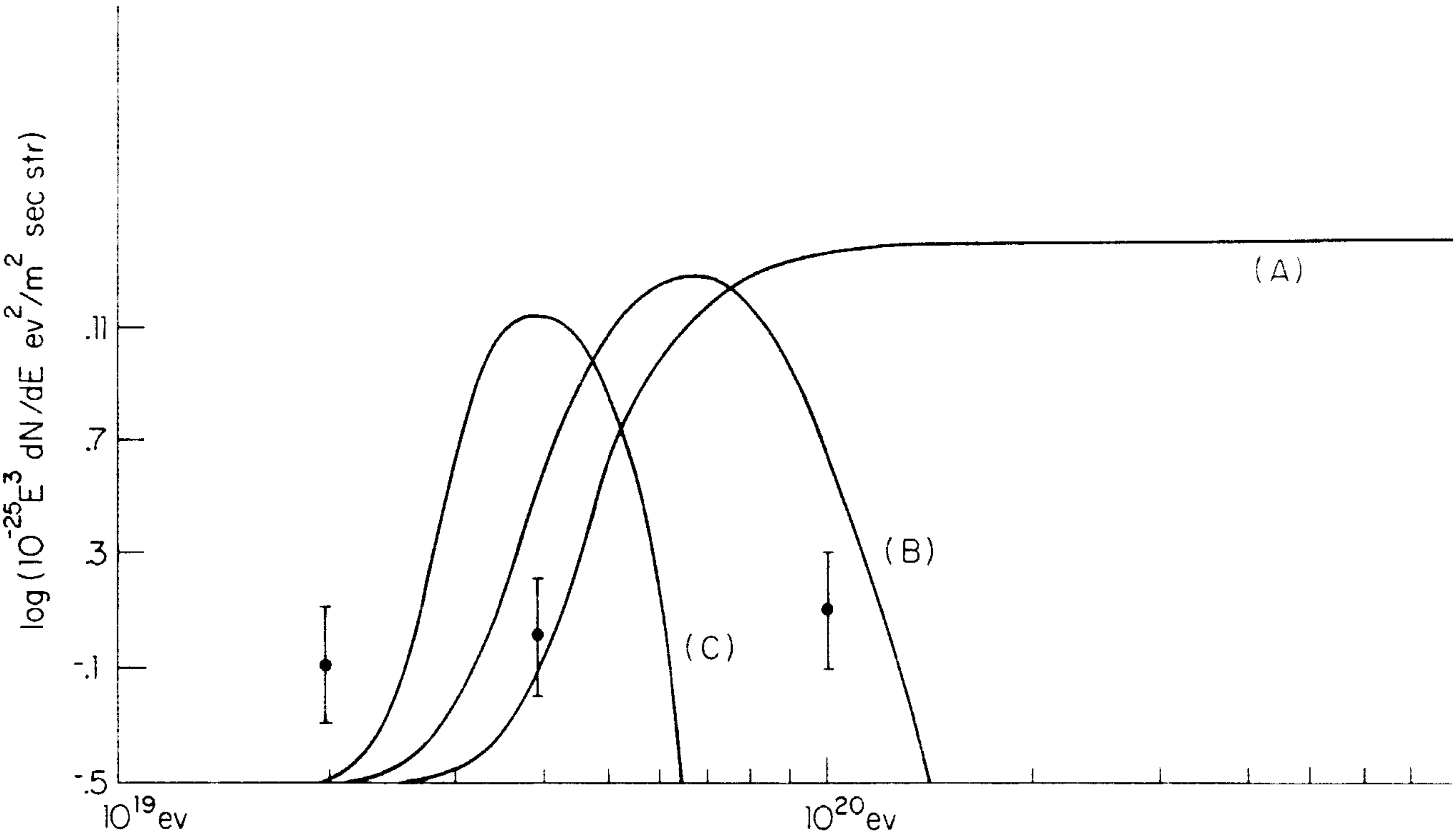


Fig. 2