ACCELERATION AND PROPAGATION OF HIGH Z COSMIC RAYS IN A PULSAR ENVIRONMENT

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ABSTRACT

The survival of high Z nuclei in the X-ray photon field of a pulsar is investigated. For heavy nuclei with energies $\geq$ 100 GeV/nucleon, 100 keV X-ray photons have sufficient energy to cause photodisintegration with cross sections of $\approx 10^{-25}$ cm^2. Using the observed properties of the Crab pulsar, extrapolation back to epochs when the pulsar was more active indicates that the photon field is sufficiently dense to prevent the acceleration of heavy nuclei within the velocity of light cylinder. On this model, the upper limit on the energy of the escaping nuclei varies with time. The models for cosmic ray acceleration in supernova explosions or by pulsars will be related to experimental observations.

1. Introduction

The discovery of pulsars associated with supernova remnants in the Crab Nebula (NP0532) and the Gum Nebula (PSR0833-45) have led to a detailed description of the radiation processes in the pulsar environment (Goldreich, 1969) and also to an extremely efficient acceleration model for energetic cosmic rays (Gunn and Ostriker, 1969).

The possibility of photodisintegration of heavy nuclei by the blue shifted photon flux in the radial shock wave of Colgate's model has been considered by Kinsey (1969) and Colgate (1969). In this paper, we will discuss the more general problem of photodisintegration of heavy nuclei (pointed out by Appa Rao and Rengarajan, 1970) by the recently detected flux of high energy X-rays emitted by pulsars (Kurfess, 1971). We shall consider the implications of the latest cosmic ray observations on the various acceleration models.

2. Experimental Observations and Calculations

Results of the direct observation of charged cosmic rays with energies less than 10^{12} eV/nucleon are shown in Figure 1. The experimental method and detailed results will be published elsewhere. These results are in reasonable quantitative agreement with the spectra of all charged particles as presented by Grigorov et al. (1969) who also used ionization calorimeter techniques and of Koshiba et al. (1967) using a limited sample of events from emulsion stacks. Indirect observations at extensive air shower energies suggest that the composition remains unchanged up to energies of 10^{15} eV (Brandt and Rappaport, 1969; Bray et al., 1965), but above these energies, it is likely that there is a change in composition (Peters, 1960). The total spectrum from 10^9 to 10^{15} eV is shown in Figure 2.

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The X-ray flux from the most popular (and hopefully, most typical) pulsar NP0532 has now been measured by several groups. Figure 3 is taken from the paper for Kurfess (1971) and shows the observed flux from 1 keV up to several MeV. The total energy emitted above 100 keV is comparable with that from all energies below 100 keV and in this energy region the pulsed flux accounts for nearly half the emission of the nebula. X-rays of these energies can cause photodisintegration of heavy nuclei whose energies exceed 100 GeV/nuc., with a cross-section $\approx 10^{-25}$ cm^2.

Taking NP0532 to be at a distance of 2 kpc and assuming isotropic emission, the number density of 100 keV photons at a distance R(cm) from the pulsar is

$$n = 4.0 \times 10^{31} R^{-2} \text{ photons/cm}^3 \tag{1}$$

We shall first consider the region within the velocity of light circle of the pulsar. The energy loss of the pulsar as a function of time is given by Bachall et al. (1970)

$$I(t) = I(o)[1 + \frac{2t}{t_o}]^{-2} \tag{2}$$

where I(o) is the intensity at t = 0 and $t_o \approx 1$ year.

This expression assumes that the main source of loss is by magnetic dipole radiation. We assume that the X-ray emission has a similar time dependence, since the observed X-ray emission of $\sim 2.5 \times 10^{36}$ ergs sec^{-1} (Kurfess, 1971) is a large fraction of the total electromagnetic radiation.

Consequently the photon density within the light circle was much higher in the past, because of the increased emission and the smaller radius. The probability of survival of a heavy nucleus propagating radially through this flux within the light circle

$$P = \exp\ (-R\ n\ \sigma) \tag{3}$$

If the energy loss is by magnetic dipole radiation, then

$$R \propto I^{-1/4} \tag{4}$$

and

$$P = \exp\ [-1.7 \times 10^8 (1 + 2t)^{-2.5}] \tag{5}$$

This expression is shown by the 100 GeV/nucleon curve in Fig. 4. Also shown are the curves for 10 GeV/nucleon and 1 GeV/nucleon particles which have been calculated assuming the photon flux spectrum continues with a constant exponent = -1.2 up to 10 MeV.

The intense fields of the pulsar and its emitted radiation will not allow straight line motion of the heavy nuclei, as assumed here, and this will result in an increased probability of disintegration.

Outside the light circle in the nebula itself, the X-ray flux is assumed to have a similar radial and time dependence to that given by equations (1) and (2), but in this case the radius will be that of the supernova shell. If we assume the parameters quoted by Shklovsky (1968) then,

$$R = 789\ t + 1.2 \times 10^{-8} \times t^2\ \text{km} \qquad (6).$$

The probabilities of photodisintegration using these parameters is $< 10^{-2}$ for 100 GeV/nucleon particles except for times $t \approx 1$ year. During this time the pulsar parameters are uncertain because of the possibility of large energy loss by gravitational radiation (Ostriker, 1969).

3. Discussion and Conclusions

If all the charged cosmic rays are accelerated in the supernova shock wave process, then the observed spectra shown in Figure 1 definitely refute Kinsey's original suggestion that there would be a sharp cut-off at 15 GeV/nucleon for a field acceleration process or about 32 GeV/nucleon for a plasma wave process. However, if as pointed out by Colgate (1967) the final energy of the stellar matter is proportional to γ^2 shock the cut-off energies become 225 and 1000 GeV/nucleon respectively (Kinsey, 1969). More recent calculations by Colgate (1969) predict for small mass supernovae an attenuation of heavy nuclei at $\approx$ 400 GeV/nuc. These energies are beyond the limits of the detailed measurements of Figure 1. The lack of a bend in the all particle spectrum of Grigorov (1969) suggests that this is not the dominant cosmic ray acceleration mechanism. If resynthesis of the heavy nuclei should occur behind the shock wave, it is unlikely that the resulting composition would be energy independent.

The Gunn and Ostriker mechanism of acceleration by the E x B fields of low frequency, large amplitude electromagnetic waves is so efficient, that for a pulsar with properties similar to NP0532, all particles will be accelerated to an energy of at least 2×10^{12} eV/nucleon in the vicinity of the light circle. But as shown earlier, it is unlikely that the heavy nuclei can survive in this region, especially at earlier epochs. It is at these times that the major fraction of the pulsar's energy is lost and that most of the particle acceleration would occur.

Consequently if a pulsar acceleration process is responsible for the majority of the observed heavy cosmic rays then we should expect a steepening of the spectrum in the region of 10^{11} eV/nucleon. In this model, it is expected that the composition of cosmic rays would be that ejected by the neutron star (Ostriker 1970) but strongly modified by photodisintegration. The net result will be a complex composition enhanced in particles of lower charge.

However, photodisintegration in the nebula itself has a very small probability of occurrence so that the suggestion by Ostriker (1970) of acceleration in that region is tenable. This model makes use of the energy dissipated by the interaction of the magnetic dipole radiation with the expanding envelope. The composition of cosmic rays accelerated in this region is expected to be similar to that of supernova ejecta. On this model it is possible that the observed steepening of the all particle spectrum at $\approx 10^{16}$ eV is caused by photodisintegration in the nebula by intense ultraviolet fluxes near the acceleration regions of these cosmic rays.

If the constancy of the ratio of protons to heavy charged particles (directly observed up to 10^{11} eV) remains up to 10^{15} eV as suggested by the E.A.S. results, then the nebula acceleration process is the only likely mechanism for accelerating the charged particles within a discrete source.

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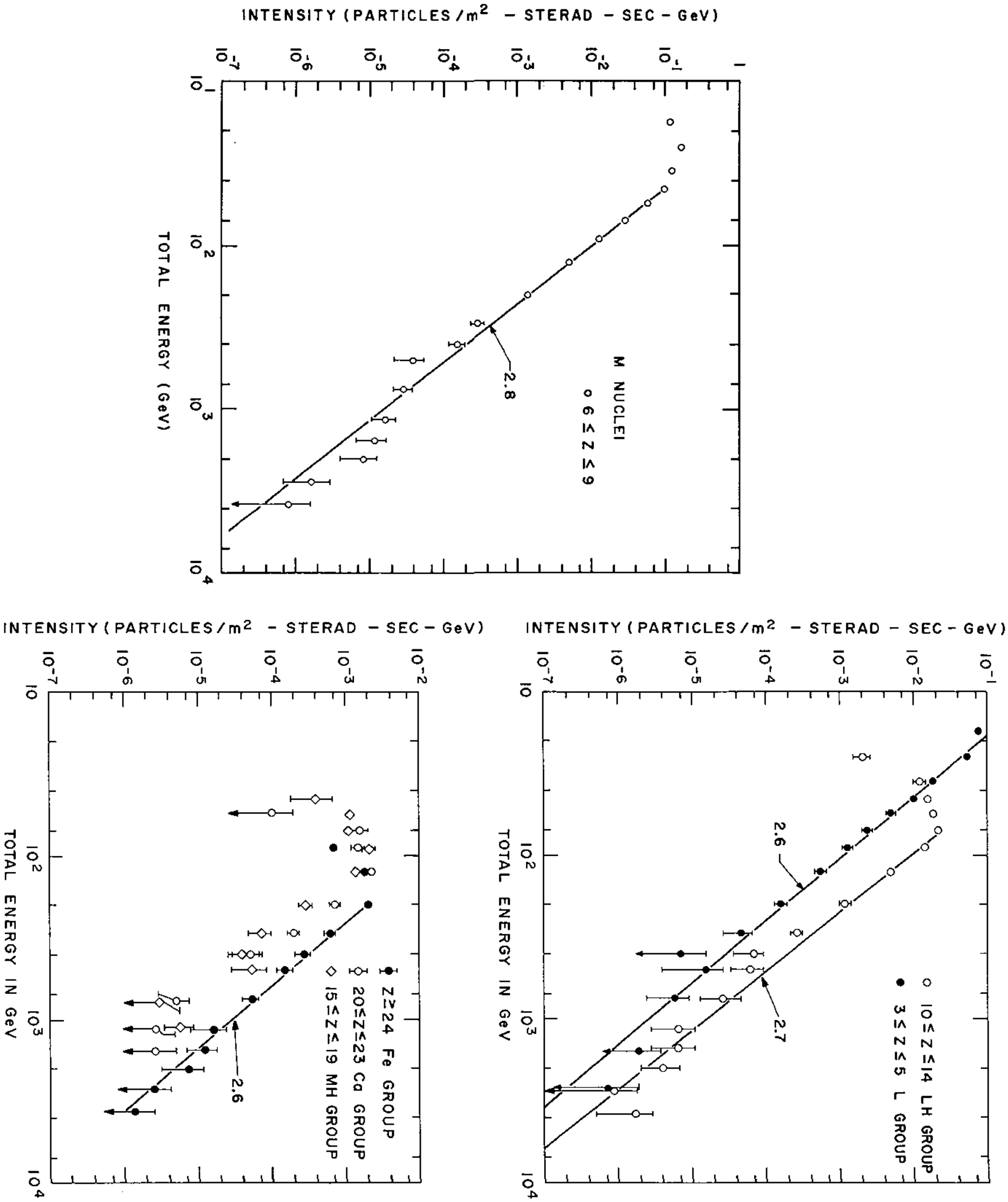
Figure Captions

Fig. 1 - Total energy spectra of L, M, LH, MH, Ca and Fe group of nuclei observed with an ionization spectrometer flown on a balloon on 14 Nov. 1970. The intensities have been corrected for spallation in the atmosphere and in the detector. The turnover at low energies is due to the geomagnetic cut-off. The straight lines are the best power law fit to the observed points.

Fig. 2 - Cosmic ray energy spectra from 10^{10} to 10^{16} eV. The Goddard Space Flight Center results and the results of Grigorov et al. are in close agreement but at higher energies there is a discrepancy between Grigorov et al. and the air shower results. There is a change in the spectral exponent from -1.7 to -2.2 at 2 x 10^{15} eV.

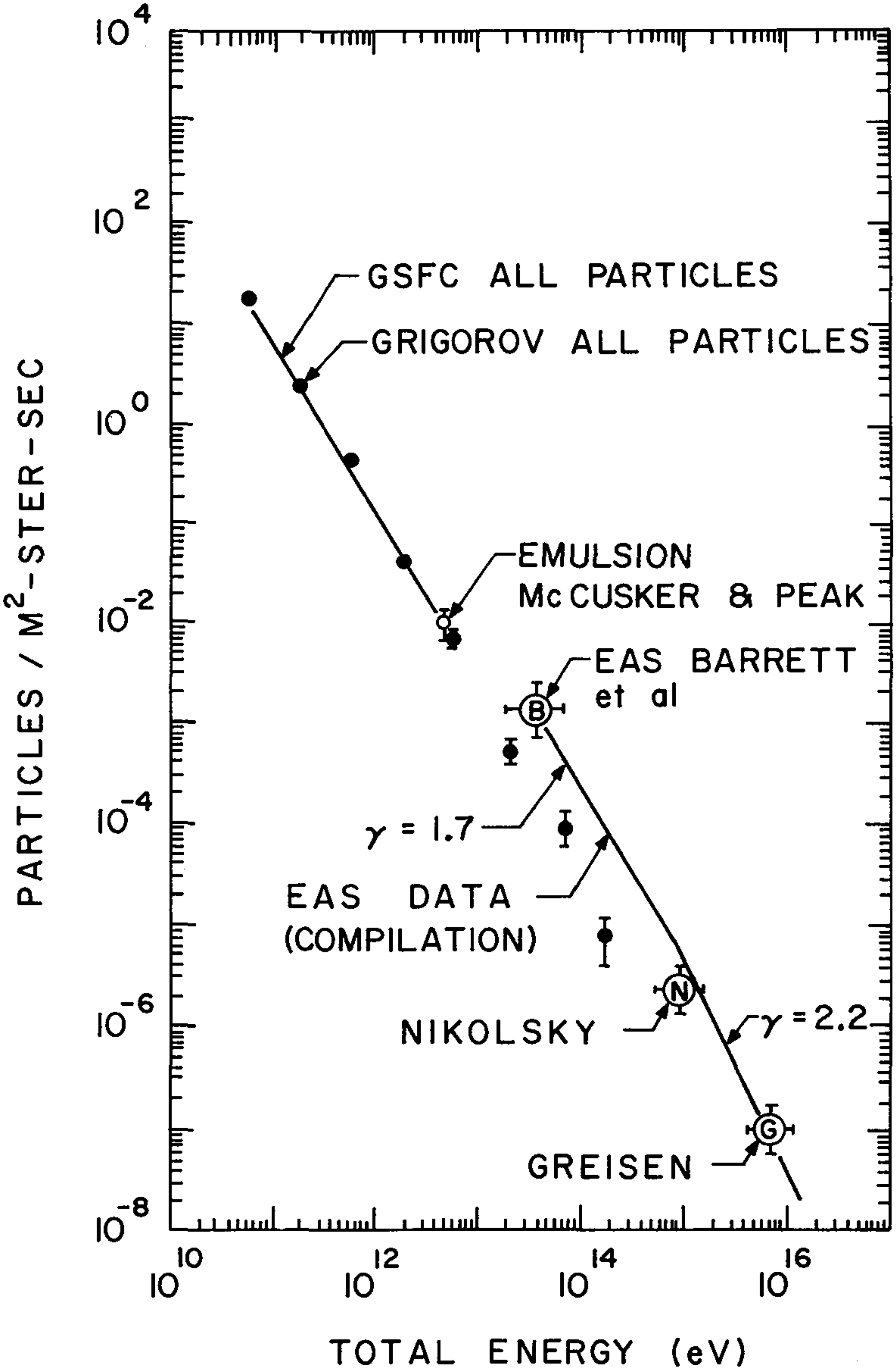
Fig. 3 - Observed X-ray flux from the Crab Nebula and its associated pulsar NP0532. Taken from Kurfess (1971).

Fig. 4 - Survival probability of an iron nucleus near the velocity of light cylinder of a pulsar similar to NP0532 at different epochs. Particles with energies greater than 100 GeV/nucleon will not survive for ages less than 1,000 years.



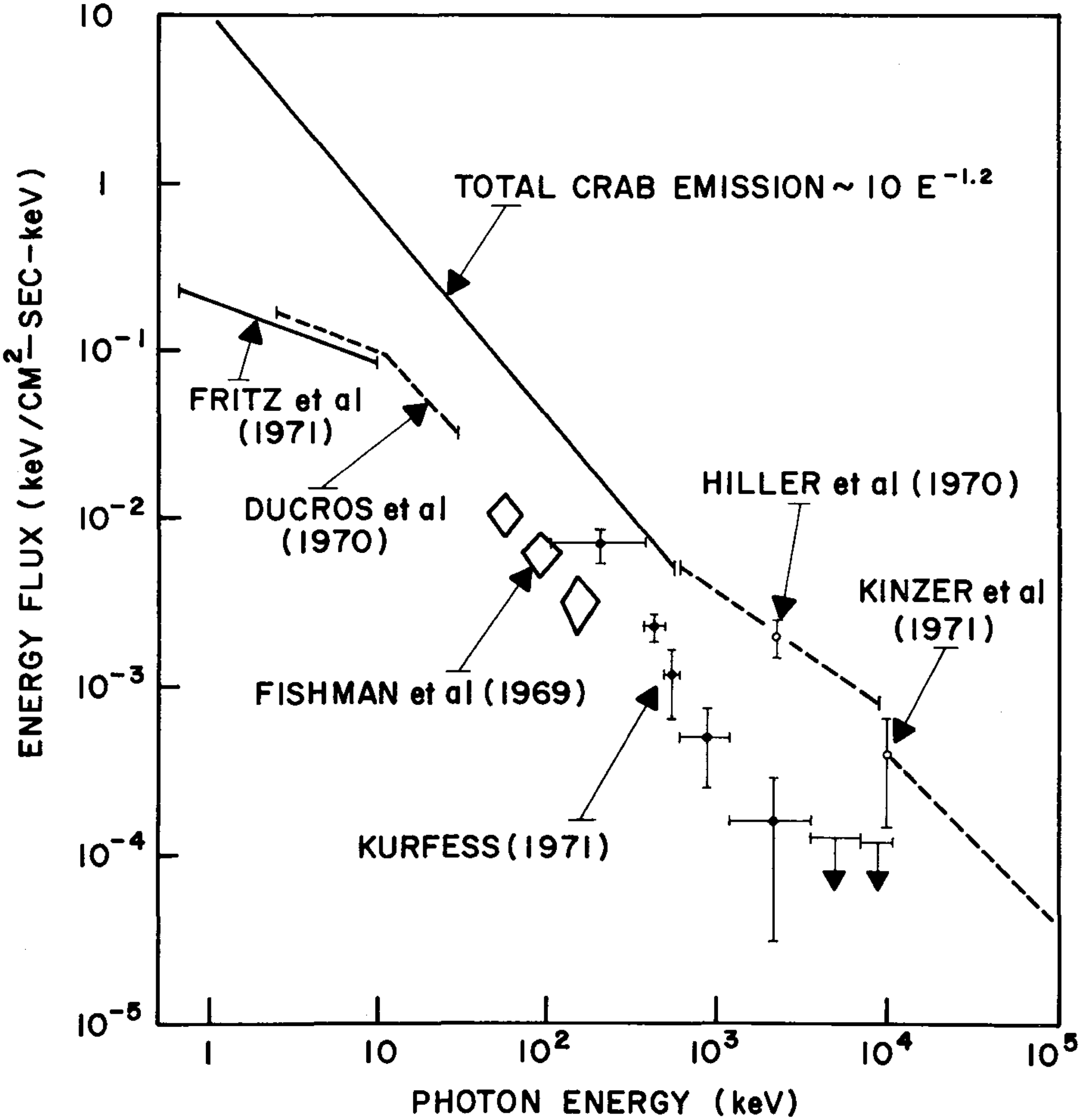
INTENSITY (PARTICLES / m² - STERAD - SEC - GeV)
TOTAL ENERGY (GeV)
M NUCLEI
o 6 ≤ Z ≤ 9
2.8
INTENSITY (PARTICLES / m² - STERAD - SEC - GeV)
TOTAL ENERGY IN GeV
o 10≤ Z ≤14 LH GROUP
● 3 ≤ Z ≤ 5 L GROUP
2.6
2.7
INTENSITY (PARTICLES / m² - STERAD - SEC - GeV)
TOTAL ENERGY IN GeV
● Z≥24 Fe GROUP
o 20≤Z≤23 Ca GROUP
◇ 15≤ Z ≤19 MH GROUP
2.6

FIGURE 1



GSFC ALL PARTICLES
GRIGOROV ALL PARTICLES
EMULSION
McCUSKER & PEAK
EAS BARRETT
et al
γ = 1.7
EAS DATA
(COMPILATION)
NIKOLSKY
γ = 2.2
GREISEN
PARTICLES / M²-STER-SEC
TOTAL ENERGY (eV)

FIGURE 2



TOTAL CRAB EMISSION ~ 10 E^-1.2
FRITZ et al (1971)
DUCROS et al (1970)
FISHMAN et al (1969)
HILLER et al (1970)
KINZER et al (1971)
KURFESS (1971)
ENERGY FLUX (keV/CM²-SEC-keV)
PHOTON ENERGY (keV)
10
1
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
1
10
10²
10³
10⁴
10⁵

FIGURE 3

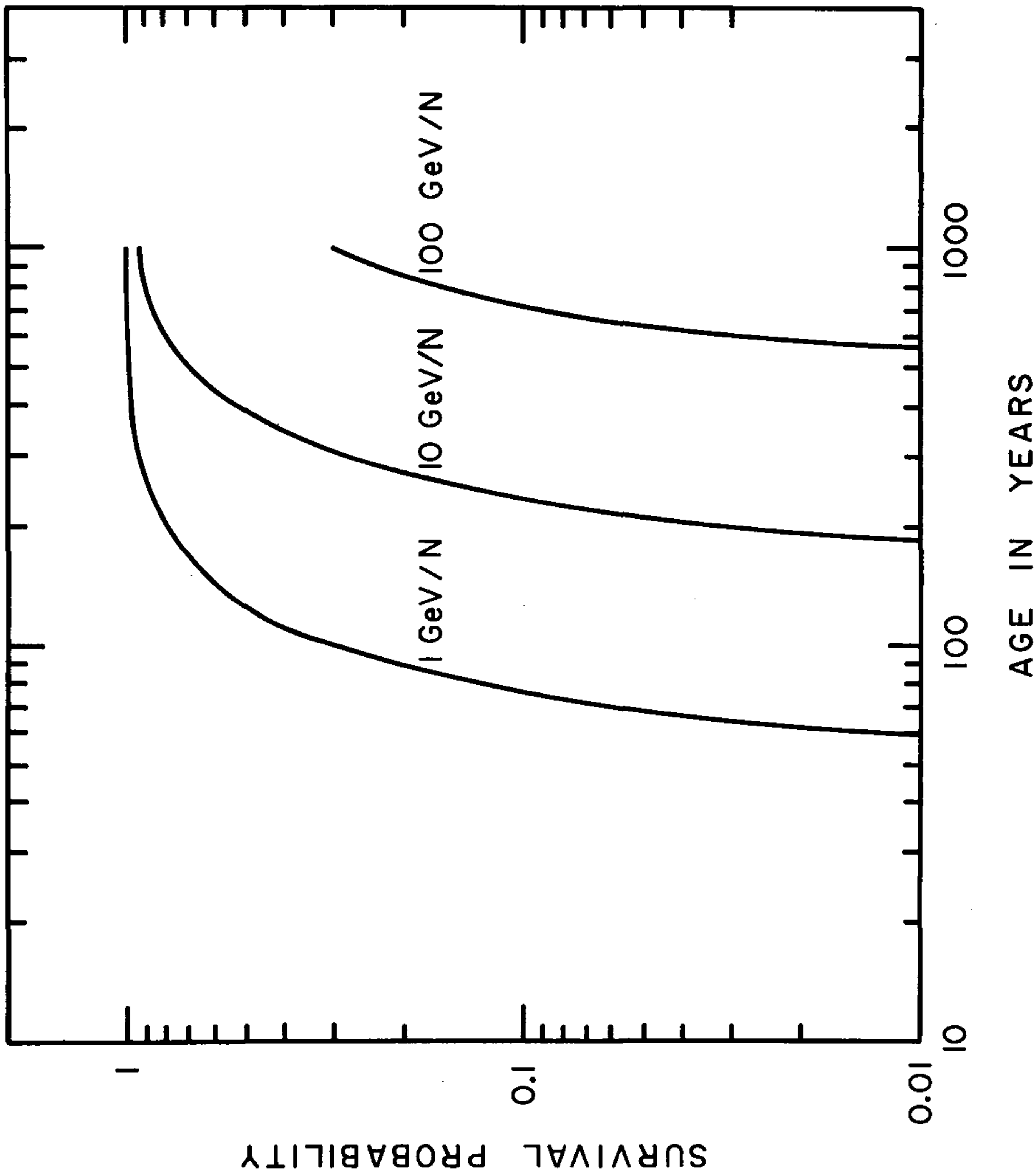

SURVIVAL PROBABILITY
AGE IN YEARS
1 GeV/N
10 GeV/N
100 GeV/N
10
100
1000
1
0.1
0.01

FIGURE 4