X-661-73-27
PREPRINT

NASA TM X-66181

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FEBRUARY 1973

(NASA-TM-X-66181) LOW ENERGY COSMIC RAY PROTONS FROM NUCLEAR INTERACTIONS OF COSMIC RAYS WITH THE INTERSTELLAR MEDIUM (NASA) 15 p HC $3.00 CSCL 03B

N73-17829
Unclas
G3/29 62602

GSFC

GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

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Low Energy Cosmic Ray Protons from Nuclear Interactions of Cosmic Rays with the Interstellar Medium

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The intensity of low energy (< 100 MeV) protons from nuclear interactions of higher energy (> 100 MeV) cosmic rays with the interstellar medium is calculated. The resultant intensity in the 10 ~ 100 MeV range is larger by a factor of three to five than the observed proton intensity near earth. The calculated intensity from nuclear interactions constitutes a lower limit on the actual proton intensity in interstellar space.

The knowledge of the intensity of the low energy cosmic rays in interstellar space is very important for the understanding of the origin of the cosmic rays, the heating of interstellar gas and the solar modulation of the cosmic rays. However, because of the expansion of the solar wind, cosmic ray particles suffer significant energy losses in the interplanetary medium, and the observed protons near the earth below about 100 MeV have all higher energies in interstellar space (Parker 1965, Goldstein, Fisk, and Ramaty 1970). The actual interstellar intensity below 100 MeV thus has to be determined by direct measurement on space probes at large distances from the sun. However, a component of this intensity can be directly calculated from presently available data. This component is produced by nuclear interactions in the interstellar medium of higher energy cosmic rays which do not suffer the above mentioned energy losses.

The purpose of the present paper is to calculate the flux of secondary protons in interstellar space. The nature of this calculation is similar to previous calculations of low energy knock-on electrons (Abraham, Brunstein and Cline, 1966), secondary positrons (Ramaty and Lingenfelter, 1966), and deuterons and helium-3 nuclei (Ramaty and Lingenfelter, 1969). A very crude estimate of the intensity of secondary protons was made by Feit and Milford (1965) at a time when the concept of adiabatic deceleration in the solar wind was not yet fully appreciated. In the present paper we use detailed cross sections and kinematics for proton-proton and proton-alpha particle interactions in order to calculate the secondary proton intensity below 100 MeV.

Secondary Protons Production

The rate of production of secondary protons by cosmic-ray interaction with the interstellar material is given by:

$$q_s\,(E_s) = 4\pi \sum_i \int dE\; j_i\,(E)\; n_i\; \sigma_i\,(E)\; F_i\,(E,\, E_s) \tag{1}$$

where q_s is the production spectrum of secondary protons per cubic centimeter of interstellar space per second; E and E_s are the energies per nucleon of the primary and secondary particles, respectively; j is the interstellar intensity of cosmic ray nuclei; n_i is the number of target nuclei per cubic centimeter of interstellar space; σ is the interaction cross section; and $F(E,\, E_s)dE_s$ is the probability that a primary cosmic-ray nucleus of energy per nucleon E will produce a secondary proton of energy in dE_s around E_s.

The production is summed over all interactions i, which produce secondary protons. The interactions which we considered are listed in Table 1. We treat the secondary neutrons as protons because the neutrons decay to protons of essentially the same energy on a time scale which is negligible in comparison with the age of the cosmic rays. We have neglected the small contribution from the more complicated interactions such as α-He^4 and p-CNO. It should be noted that α-He^4 reactions are not entirely negligible but the contribution should not exceed 20% of the secondary proton intensity that we calculated.

Both the center of mass differential cross sections for pp and $p\alpha$ elastic scattering and the total pp inelastic scattering cross sections were taken from Meyer (1971). The partial cross sections for the different breakup modes of alpha particles in $p\alpha$ inelastic interactions were taken from Ramaty and Lingenfelter (1969). The energy distribution $F(E,E_s)$ for pp and $p\alpha$ elastic scattering are directly obtained from the differential cross sections. The distribution $F(E,E_s)$ for pp inelastic scattering is taken from the experimental data compiled by D. Lal (private communication). The method for the evaluation of $F(E,E_s)$ for $p\alpha$ inelastic interactions is similar to that of Ramaty and Lingenfelter (1969) for deuterium and helium-3 production. A detailed discussion of cross sections and kinematics used in the present calculation will be given in a forthcoming thesis (Wang, University of Maryland, dissertation).

For the primary proton and alpha particle spectra in interstellar space, we use power laws in total energy with low energy cutoffs at

100 MeV per nucleon. Such spectra were found to be consistent with the modulation of both protons and electrons in the interplanetary medium and the non-thermal radio background produced by cosmic electrons (Goldstein, Ramaty, and Fisk 1970).

Using equation (1), we can now calculate the production rate of the secondary protons. The production of each breakup mode for $p\alpha$ and αp inelastic interactions are shown in Figure 1 and Figure 2, respectively. We show in Figure 3 the production spectra of pp elastic and inelastic scattering, $p\alpha$ and αp elastic scattering, and the sum of $p\alpha$ and αp inelastic interactions. The low energy cutoff in the $p\alpha$ elastic scattering production spectrum results from the low energy cutoff at 100 MeV per nucleon and the fact that it is impossible for a light particle to give all its energy to a heavier target particle in one interaction. The complicated structure of the spectra in Figure 1 and Figure 2 are the results of the following reasons. First we have added the spectra with pion production to that without pion production. Second we have evaluated the kinematic quantities of multinucleon particles (d, He^3 etc) first and these particles have a minimum secondary energy about 10 MeV per nucleon in αp inelastic interactions (Ramaty and Lingenfelter, 1969) and hence a same cutoff in proton production is obtained. Third, as in αp elastic scattering, there is a cutoff in the primary intensity. We note that αp plus $p\alpha$ inelastic interactions contribute approximately 30 percent of the total production. Because several assumptions have been made about the kinematics of these interactions, an uncertainty of thirty percent is introduced.

Secondary Proton Intensity in Interstellar Space

From the production spectrum in interstellar space computed above, we may determine the equilibrium density of secondary protons in the galaxy. We use the following equation:

$$\frac{N_s}{\tau} + \frac{\partial}{\partial E}\left(\frac{dE}{dt} N_s\right) = q_s \ (E), \tag{2}$$

where N_s is the secondary equilibrium density; q_s is the secondary production rate calculated above; τ is the effective leakage life time, $\frac{dE}{dt}$ is the rate of energy loss due to ionization. Changing parameter from time t to matter traversal $x = \rho vt$, where ρ is the density of interstellar material in gcm^{-3}, v is the velocity of the secondary particle, we find that the secondary intensity j_s is given by:

$$j_s \ (E) = \frac{1}{4\pi \rho \ \frac{dE}{dx}} \int_E^\infty dE' \ q_s(E') \ \exp\left(- \frac{1}{x_o} \int_E^{E'} \frac{dE''}{\frac{dE''}{dx}}\right), \tag{3}$$

where m_p is the proton mass and $x_o = \rho v\tau$. The numerical value for x_o is about $5g \ cm^{-2}$ (Ramaty and Lingenfelter, 1971). Below 500 MeV, the ionization loss rate $\frac{dE}{dx}$ in MeV $g^{-1}cm^2$ can be approximated by $102 \ (\frac{E}{10})^{-0.8}$ (Barkas and Berger, 1964). The resultant proton intensity is shown in Figure 4.. Also shown in Figure 4 are the primary proton interstellar intensity that produces the secondary protons by the nuclear interactions. The data points represent the observed intensity near earth (Fan, et al, 1966; Balasubrahmanyan, et al., 1966 (a,b); Waddington and Freier, 1966; Ormes and Webber, 1966; McDonald, 1968). As can be seen the calculated secondary intensity is larger by a factor of three to five than the observed intensity and could be measurable by detectors on space probes at large distances from earth.

In order to get some idea about the magnitude of this intensity in comparison with the low energy proton intensity that may exist in interstellar space, we calculate the rate of ionization ξ of the interstellar medium by the secondary intensity shown in Figure 4. We find that $\xi = 3 \times 10^{-19}$ (sec Hatom)$^{-1}$. This value is several order of magnitude lower than values of $\xi(10^{-15} \sim 10^{-14})$ obtained from Hα and Hβ observations (Reynold, Roesler, and Sherb, 1972). However, because the ionization of interstellar medium is not necessarily due to low energy protons, the observed values of ξ only set upper limits on the low energy proton intensity in interstellar space. The present calculation constitutes a lower limit on the intensity of these particles.

Acknowledgement: I wish to thank Dr. Reuven Ramaty for valuable suggestions and helpful discussions on this problem.

The research was supported by the National Aeronautics and Space Administration under grant NGR 21-002-033.

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Table 1

Secondary Proton Production

1.	$p + H^1$	$\rightarrow$	$p + p$ (elastic)
2.	$p + H^1$	$\rightarrow$	$p + p + (\pi)$ (inelastic)
3.	$p + He^4$	$\rightarrow$	$p + \alpha$ (elastic)
4.	$\alpha + H^1$	$\rightarrow$	$p + \alpha$ (elastic)
5.	$p + He^4$	$\rightarrow$	$t + 2p + (\pi)$
6.	$\alpha + H^1$	$\rightarrow$	$t + 2p + (\pi)$
7.	$p + He^4$	$\rightarrow$	$He^3 + p + n + (\pi)$
8.	$\alpha + H^1$	$\rightarrow$	$He^3 + p + n + (\pi)$
9.	$p + He^4$	$\rightarrow$	$d + 2p + n + (\pi)$
10.	$\alpha + H^1$	$\rightarrow$	$d + 2p + n + (\pi)$
11.	$p + He^4$	$\rightarrow$	$2d + p + (\pi)$
12.	$\alpha + H^1$	$\rightarrow$	$2d + p + (\pi)$
13.	$p + He^4$	$\rightarrow$	$3p + 2n + (\pi)$
14.	$\alpha + H^1$	$\rightarrow$	$3p + 2n + (\pi)$

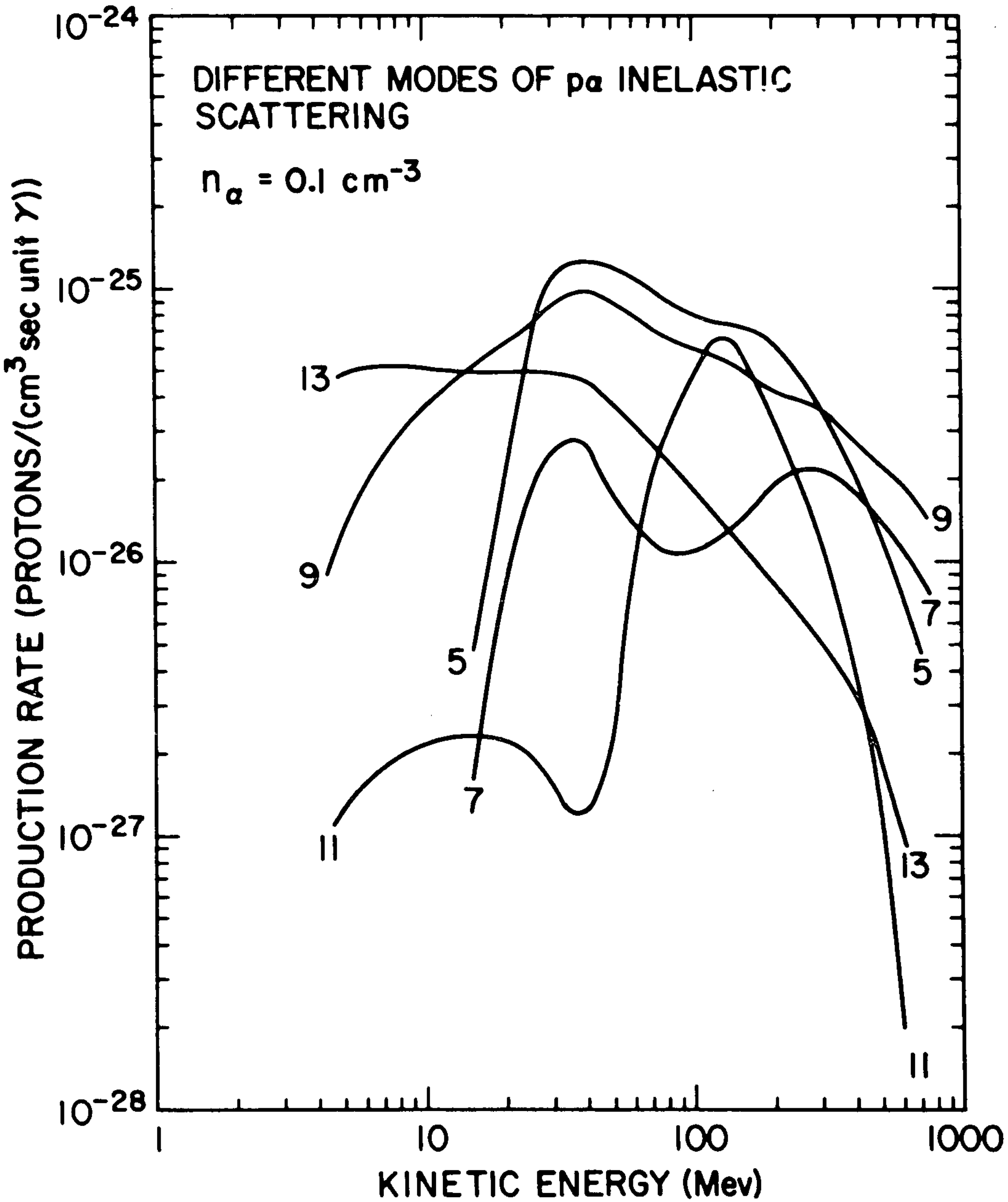

DIFFERENT MODES OF pα INELASTIC SCATTERING
$n_\alpha = 0.1\ cm^{-3}$
PRODUCTION RATE (PROTONS/(cm³ sec unit γ))
KINETIC ENERGY (Mev)
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
1
10
100
1000
13
9
5
7
11
13
9
7
5
13
11

FIGURE 1

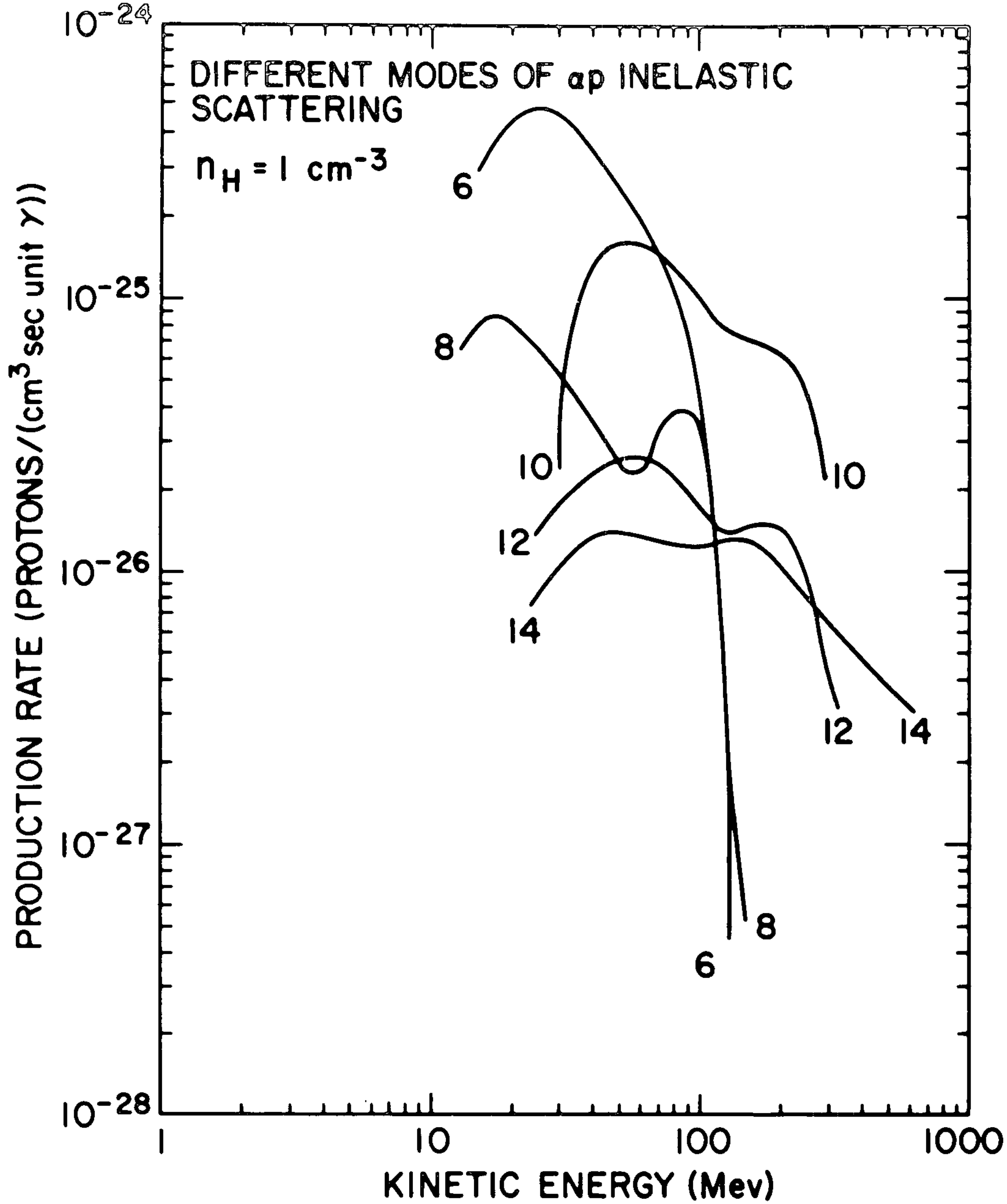

DIFFERENT MODES OF αp INELASTIC SCATTERING
$n_H = 1\ cm^{-3}$
PRODUCTION RATE (PROTONS/(cm^3 sec unit γ))
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
1
10
100
1000
KINETIC ENERGY (Mev)
6
8
10
12
14

FIGURE 2

11

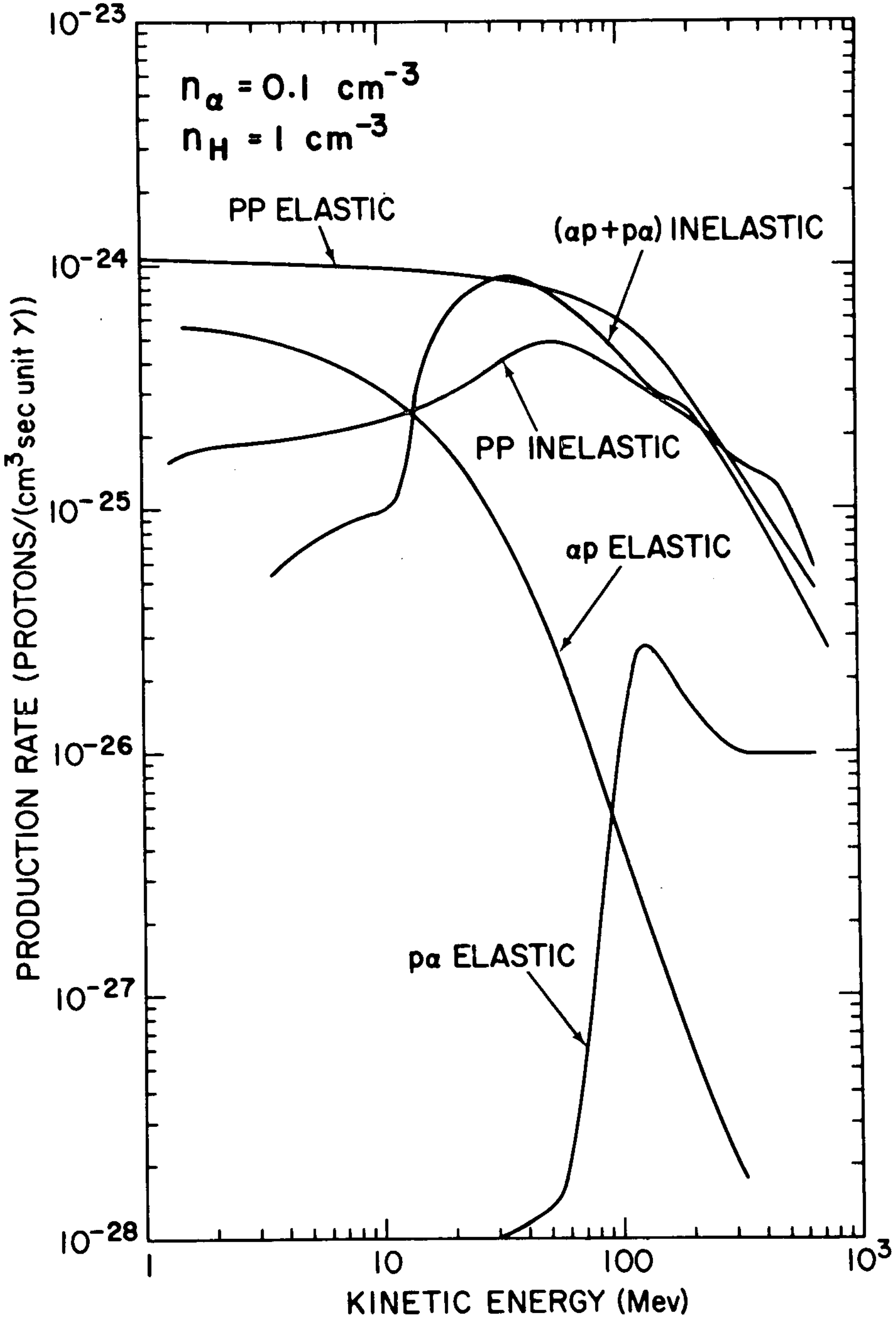
Figure Captions

Figure 1 Proton production spectra for different breakup modes for pα inelastic reactions shown in Table 1.

Figure 2 Proton production spectra for different breakup modes for αp inelastic reactions shown in Table 1.

Figure 3 Proton production spectra for pp elastic and inelastic scatterings, αp and pα elastic scatterings, and pα plus αp inelastic reactions.

Figure 4 Proton intensities.



$n_\alpha = 0.1\ cm^{-3}$
$n_H = 1\ cm^{-3}$
PP ELASTIC
(αp+pα) INELASTIC
PP INELASTIC
αp ELASTIC
pα ELASTIC
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
PRODUCTION RATE (PROTONS/(cm^3sec unit γ))
1
10
100
10^3
KINETIC ENERGY (Mev)

FIGURE 3

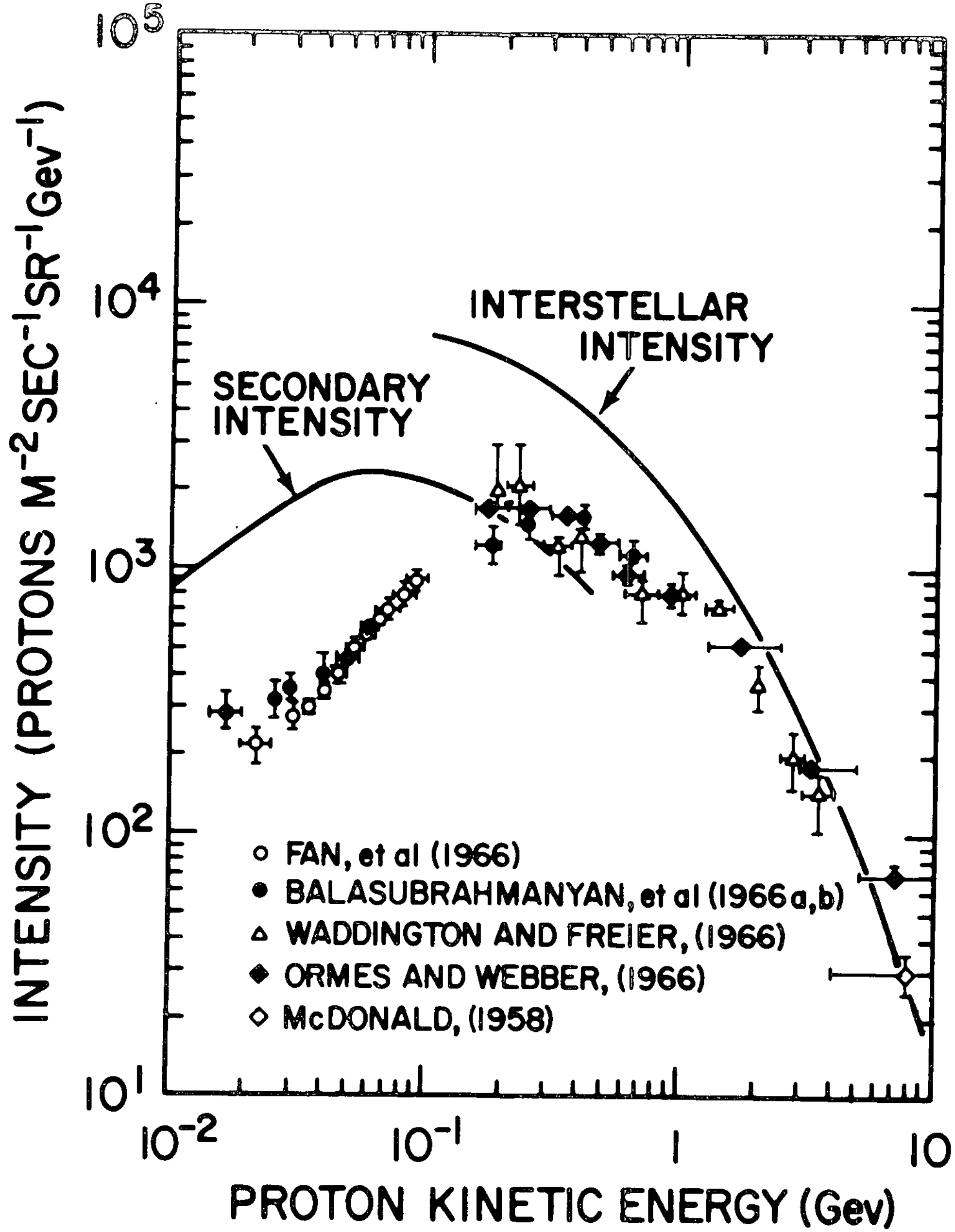


FIGURE 4

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