X-660-70-121
PREPRINT

NASA TM X-63874

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APRIL 1970

GSFC

GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

FACILITY FORM 602

N70-25289	
(ACCESSION NUMBER)	(THRU)
12	1
(PAGES)	(CODE)
TMX 63874	29
(NASA CR OR TMX OR AD NUMBER)	(CATEGORY)

INTERSTELLAR COSMIC RAY SPECTRA FROM THE NONTHERMAL RADIO BACKGROUND FROM 0.4 TO 400 MHz

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ABSTRACT

We deduce the interstellar electron spectrum from the nonthermal radio background. From 200 MeV to a few GeV the spectral index is 1.8 and there is evidence for residual solar modulation. Above a few GeV, the spectrum is steeper and the intensity is similar to that observed at earth. A consistent modulation for electrons and protons of the same rigidity can be obtained by using the complete diffusion-convection-energy loss theory of solar modulation.

Alexander et al.[1,2] have recently reported satellite measurements of the galactic radio background in the range 0.4 to 6.5 MHz. When their measurements in the direction of the galactic anticenter are combined with the corresponding high-frequency data[3], the radio spectrum is consistent with synchrotron emission by cosmic electrons, free-free absorption by ionized hydrogen, and a uniform interstellar mixture of the emitting and absorbing regions. The radio data in both the optically thin and optically thick regimes requires that the emissivity from 0.4 MHz to about 100 MHz be of the form $\nu^{-0.4}$. The corresponding electron spectrum from about 200 MeV to several GeV is of the form $E^{-1.8}$. The observations at higher frequencies ($\gtrsim$ 100 MHz) can be interpreted as a steepening in the radio spectrum, which suggests that above a few GeV, the electron spectral index is close to 2.5.

It has been suggested (e.g., reference 4) that it is possible to determine the residual solar modulation from a comparison of the electron spectrum inferred from radio observations with the spectrum observed at the earth at solar minimum. However, such a comparison will give a meaningful result at low energies where modulation is important only if reliable low-frequency radio data are used.

From a preliminary analysis, Alexander et al.[2] obtained an interstellar electron spectrum around 200 MeV, which, on the average, is greater by a factor of 50 to 100 than that observed at the earth at solar minimum. This finding depends critically on the values assumed for the interstellar parameters, and clearly, a more detailed study is needed before firm conclusions about solar modulation can be made.

In this letter, we present the results of extensive calculations of synchrotron emission by cosmic electrons, absorption by ionized interstellar hydrogen, and modulation in the interplanetary medium. All the radio data are consistent with an interstellar electron intensity that is significantly smaller than that given in reference 2. The deduced modulation agrees with measured values of the solar wind speed and the particle diffusion coefficient in interplanetary space.

The synchrotron emissivity produced by an arbitrary electron density N(E) is given by[5]

$$\mathcal{E}(\nu) = \sqrt{3}\, e^3 H/(4\pi mc^2) \int_{mc^2}^{\infty} \left\{ \nu/\nu_c \int_{\nu/\nu_c}^{\infty} K_{5/3}(y)\, dy \right\} N(E)\, dE \qquad (1)$$

where $\nu_c = 3eH/(4\pi mc)(E/mc^2)^2$ and H is the mean value of the magnetic field perpendicular to the line of sight. Possible values of H in the interstellar medium range from about 3 to 5 μG[6]. The values we have chosen for interstellar parameters enable us to deduce a minimal interstellar cosmic electron intensity and, hence, a plausible lower limit to the solar modulation. Consequently, we used H = 5 μG.

The free-free absorption coefficient in ionized hydrogen is given by[7]

$$K(\nu) = 10^{-2} n_e/(\nu^2 T_e^{3/2})\left[17.7 + \ln(T_e^{3/2}\nu)\right] \qquad (2)$$

where ν is measured in Hz, and n_e and T_e are the density and temperature of the ambient electrons. Recent studies of interstellar heating[8,9] have indicated that a two-component model consisting of cold clouds and a hot intercloud medium is required to characterize the interstellar gas. We have used an ambient electron density and temperature in cold clouds of 0.05 cm^{-3} and 60°K respectively, consistent with observations of 21 cm absorption[10]. We also used an intercloud electron density of 0.03 cm^{-3}, consistent with pulsar dispersion measures[11]. There is no direct observational information on the temperature, T_i, of the intercloud medium. Because theoretical investigations indicate values ranging from 500°K to 10^{4}°K, we assumed that the intercloud temperature is a free parameter within this range.

The average fraction of a line of sight toward the anticenter intercepted by cold clouds is about 10^{-3} to 10^{-2}[8,9]. The radio spectrum at low frequencies is consistent with absorption by a diffuse medium and does not exhibit an exponential fall-off characteristic of a compact absorber between the observer and the emitting region. We used a uniform distribution of cold clouds with a cloud diameter of 1 pc and intercloud separation of 1 kpc as a model. Furthermore, we assumed that the closest cloud is at a distance of 1 kpc, so that the radio intensity from the anticenter is given by

$$I = \varepsilon/K\,[1-\exp(-\tau_i)][1-\exp(-L(\tau_c+\tau_i))][1-\exp(-\tau_c-\tau_i)]^{-1} \qquad (3)$$

where τ_c and τ_i are the optical depths corresponding to one cloud and one intercloud separation, respectively, and L is the size of the emitting region in kpc.

We evaluated equations (1) - (3) for several values of T_i and L. For $T_i = 10^{4}$°, K is small and a value of L of about 10 kpc is needed to account for all the absorption at low frequencies. But for such a large value of L, even for the minimal conditions we have used, absorption by cold clouds becomes significant below a few MHz, so that the theoretical spectrum no longer fits the data. For $T_i < 10^{3^\circ}$, K is large, and to fit the data, L must be less than about 1 kpc. Such a small value of L means that radiation is collected only over a small fraction of the available line of sight distance toward the anticenter. At several GeV, this small value of L requires an average electron flux that is $\gtrsim$ 10 times larger than is observed near the earth. Solar modulation is probably negligible at these energies and hence the difference must be due to interstellar fluctuations in the cosmic electron intensity. Because fluctuations of this magnitude over a scale smaller than 1 kpc seem unlikely, values of $T_i < 10^{3^\circ}$K appear untenable.

We achieved a good fit to the radio data with $T_i \approx 4000$°K, which requires $L \approx 4$ kpc. The computed radio spectra for these parameters are shown in Figure 1, with the observations from the anticenter. Curves A, B, and C correspond to the assumed interstellar electron spectra which are shown in Figure 2 with the electron observations at earth near solar minimum.

The spectral index for these spectra is 1.8, increasing to 2.5 above E_c, where E_c is 1, 2, and 5 GeV for A, B, and C, respectively. Because synchrotron and Compton energy losses in interstellar space are not expected to have a major effect on the spectrum below a few GeV, the electron injection spectral index is also close to 1.8. This is consistent with observed spectral indices of radio emission from galactic nonthermal sources. These indices are centered on a value of 0.5 with an rms scatter of about 0.3 and show little evidence of an evolutionary trend[12]. Within the framework of synchrotron theory, this means that the electron spectra in the supernova remnants have an index of 2.0 ± 0.6, and could very well be representative of the initial injection spectrum.

Above E_c, all solutions agree with the measured electron intensity

at the earth. Within the uncertainties of the cosmic ray measurements and the interstellar parameters, the observed electron intensity at a few GeV equals the intensity required to produce the radio emission.
Hence, interstellar fluctuations do not play a major role at these energies[13].

Below E_c, all solutions require a finite solar modulation. For example, at 200 MeV, our modulating factor is about 10, which is somewhat below the lower limit obtained by Alexander et al.[2]. However, their mean modulating factor of about 50 to 100 results from using an intercloud temperature of 10^3°K which, as discussed above, leads to a fluctuation of ~ 10 in the cosmic electron intensity over a distance of less than 1 kpc. It appears to us that our solution with $T_i \approx 4000$°K gives a more reasonable cosmic electron spectrum in terms of both interstellar propagation and interplanetary modulation.

Modulation has frequently been discussed in terms of a function of the form $M = \exp[\eta/f(R)\beta]$. R and β are rigidity and velocity, respectively, and $\eta = \int_{r_e}^{r_b} dr\, V/D(r)$, where V is the speed of the solar wind, D(r) is the radial dependence of the particle diffusion coefficient, and r_e and r_b are the heliocentric distances to the earth and boundary of the modulating region, respectively. The results shown in Figure 2 can be interpreted in terms of such a modulating function with $\eta \simeq 0.64$ GV and $f(R) = R$ for $R \geq R_0 = 350$ MV, and $f(R) = (R R_0)^{1/2}$ for $R < R_0$. When this modulating function is applied to protons, $M_p(R) = [Me(R)]^{1/\beta}$, where p and e denote protons and electrons respectively. In particular, $M_e = 10$ at 200 MeV implies that $M_p \simeq 5 \times 10^4$ at ~ 20 MeV. This leads to a very large cosmic ray energy density in interstellar space and is probably in conflict with the dynamics of the interstellar medium.[6]

A more reasonable fit for the modulation of both electrons and protons can be obtained with a detailed theory of modulation that includes the effects of adiabatic deceleration[14,15]. In Figures 2 and 3, we present the results of numerical solutions of the Fokker-Planck equation that describe the modulation of electrons and protons in this theory[16]. The functional form of f(R) that we used is the same as that given above, the solar wind speed is 400 km/sec, and $D(r) = 1.5\times10^{21}\exp[0.625(r-1)]\ \mathrm{cm}^2/(\mathrm{sec\ BV})$, where r is in A.U. These values of D and f(R) are consistent with the diffusion coefficient determined from the observed radial gradient of high-energy protons[17] and the measured power spectra of magnetic fluctuations[18].

The effects of adiabatic deceleration are most important when the modulation is large and the interplanetary spectrum is increasing with increasing energy. In this case, energy losses diminish the effects of diffusion and simple convection. Consequently, adiabatic deceleration is extremely significant for protons below ~ 200 MeV, but does not play an important part in the modulation of electrons. Therefore, the proton spectrum suffers a much smaller modulation than that deduced from the simple formula $M_p(R) = [M_e(R)]^{1/\beta}$, and thus there is no inconsistency with the dynamics of the interstellar medium.

The residual electron modulation can also be estimated from the comparison of the measured positron intensity and the interstellar positron flux produced by the π-μ-e process[19,20]. The measured $e^+/(e^+ + e^-)$ ratio at the earth at 200 MeV is about 0.1[20,21]. The positron intensity in interstellar space is ~ $2.5\times10^2\ (\mathrm{m}^2.\mathrm{sec}.\mathrm{sr}.\mathrm{GeV})^{-1}$(19), which, when combined with the demodulated spectrum shown in Figure 2, also gives $e^+/(e^+ + e^-) \sim 0.1$.

We conclude that the radio data between 0.4 MHz to 400 MHz can be explained by an electron spectrum as shown in Figure 2. Most of the absorption at low frequencies results from the intercloud medium at ~ 4000°K. The cosmic electron spectrum is consistent with injection spectra inferred from radio observations of supernova remnants as well as with the $e^+/(e^+ + e^-)$ ratio. The deduced electron modulation can be applied to cosmic protons of the same rigidity only if the complete diffusion-convection-energy loss theory is used. The resulting interstellar proton intensity is approximately a power law in total energy.

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*Research supported by NASA Grant NGL 21-002-033.
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FIGURE 1. Nonthermal radio background spectrum from the galactic anticenter. Curves A, B, and C were computed using equation (3) with T_i = 4000°K, L = 4 kpc and the electron spectra A, B, and C shown in Figure 2.

FIGURE 2. Electron observations[22] at the earth from 0.1 to 10 GeV. Curves A, B, and C are the interstellar electron spectra required to produce the radio spectra A, B, and C in Figure 1, and are normalized to produce the same radio intensity at low frequencies. The modulated electron intensity was obtained from Curve B, using the complete diffusion-convection-energy loss theory of solar modulation.

FIGURE 3. Proton observations[23] at the earth from 20 MeV to 10 GeV. The modulated intensity is obtained from the interstellar spectra, with the same solar wind speed and diffusion coefficient used in Figure 2. When adiabatic deceleration is included, the interstellar proton spectrum is approximately a power law in total energy.

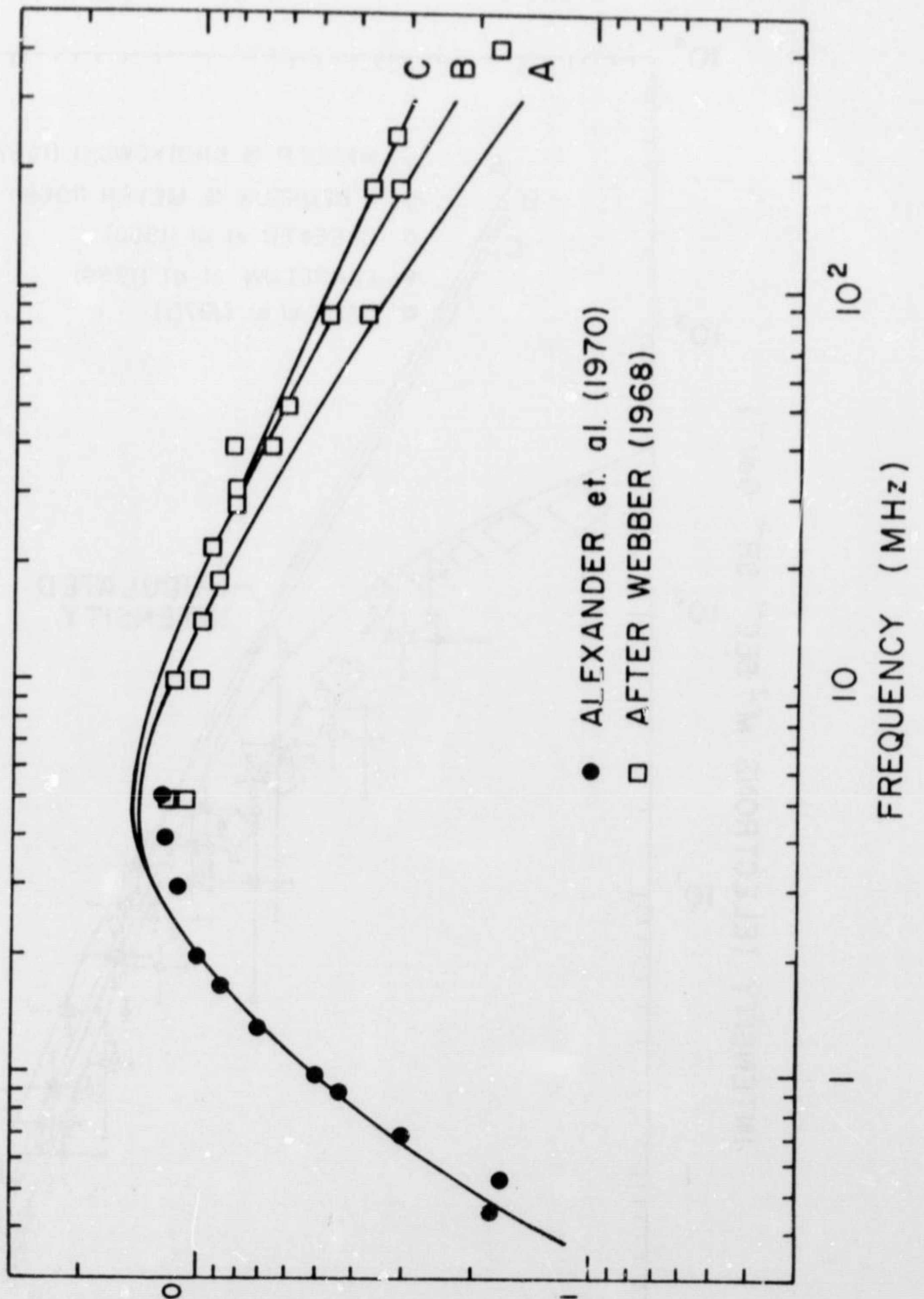

INTENSITY (WATTS M^{-2} SR^{-1} Hz^{-1})
10^{-20}
10^{-21}
FREQUENCY (MHz)
1
10
10^2
● ALEXANDER et. al. (1970)
□ AFTER WEBBER (1968)
A
B
C

FIGURE 1

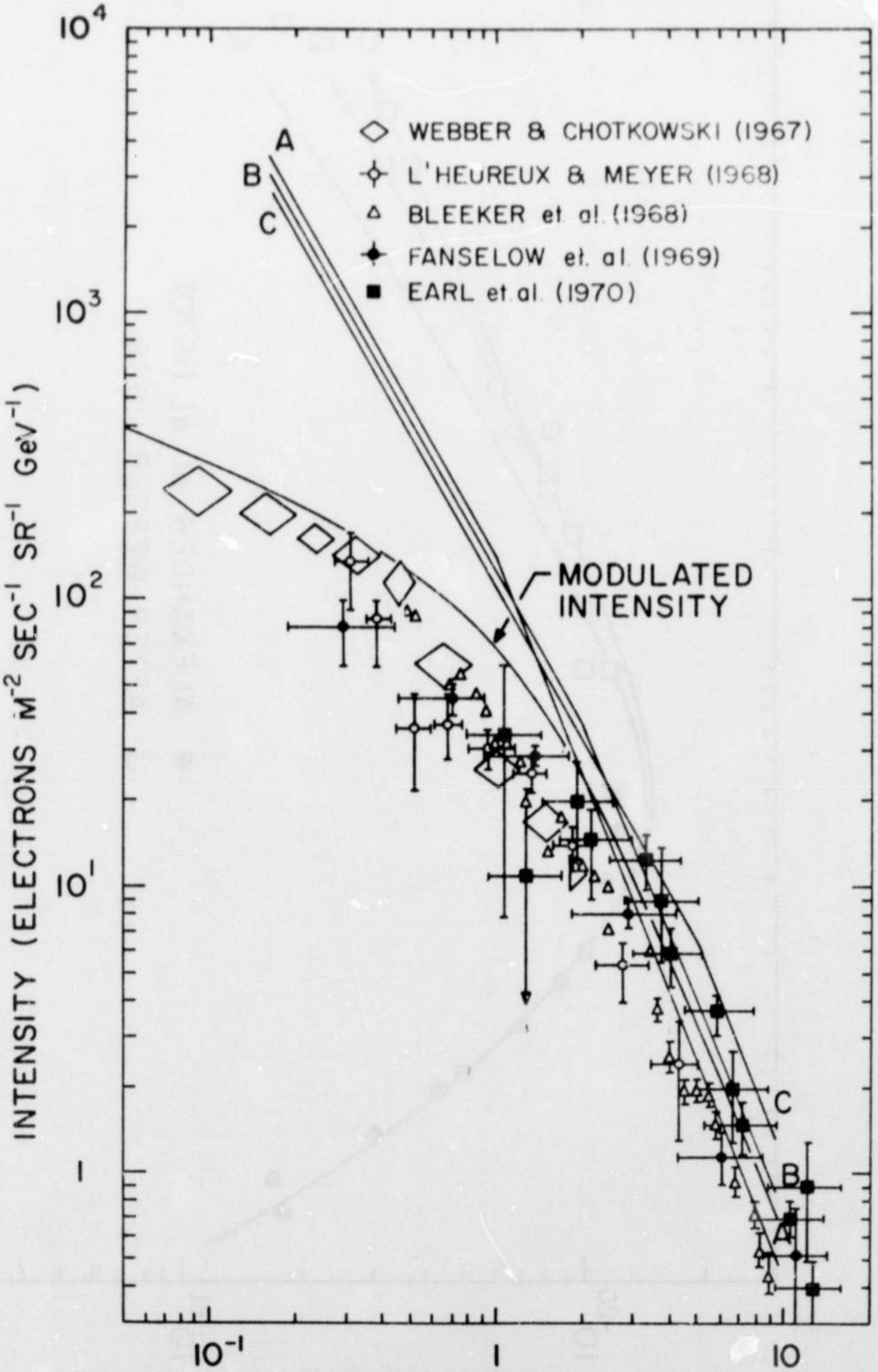
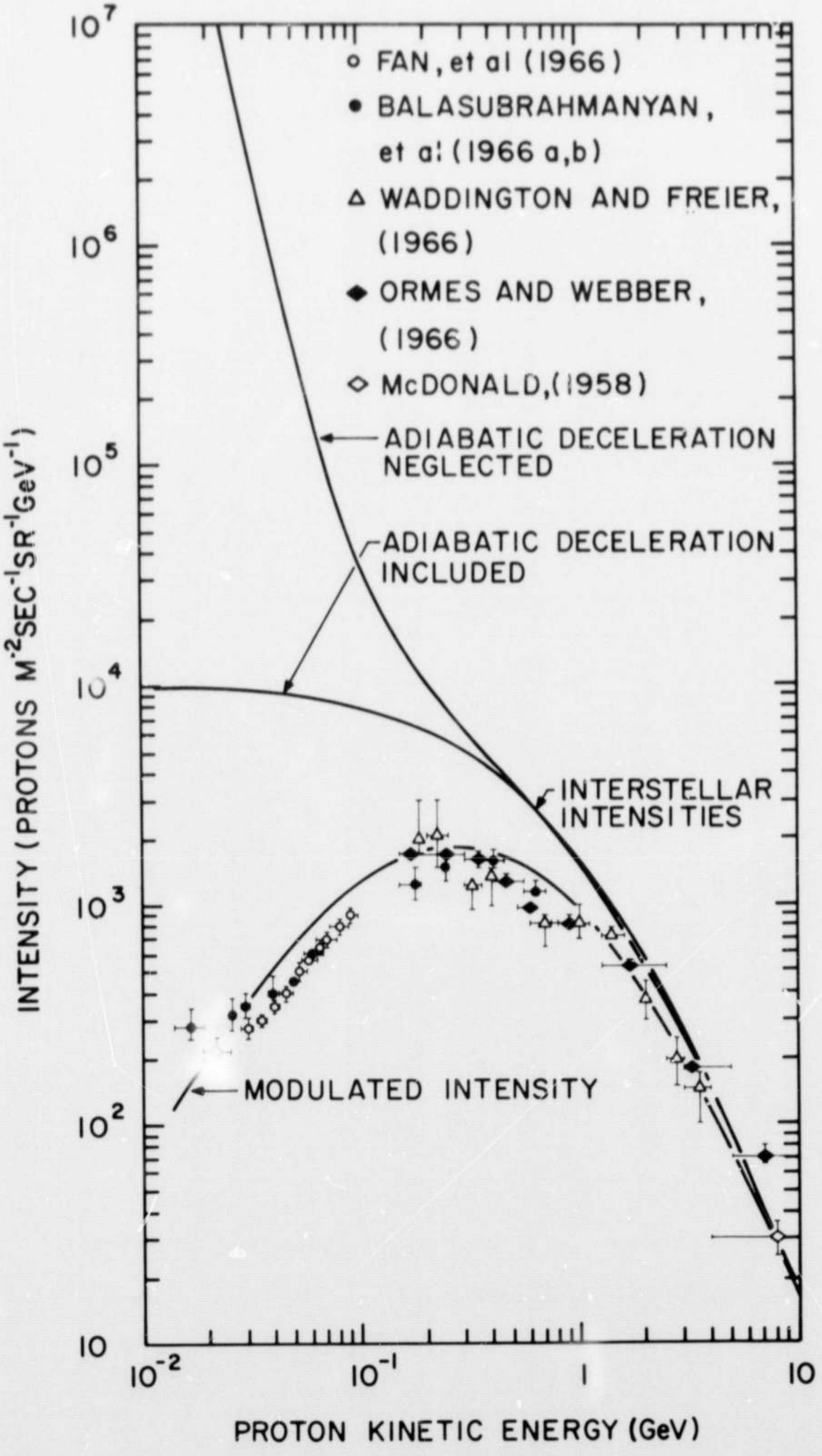

10⁴
10³
10²
10¹
1
INTENSITY (ELECTRONS M⁻² SEC⁻¹ SR⁻¹ GeV⁻¹)
10⁻¹
1
10
ELECTRON ENERGY (GeV)
A
B
C
◇ WEBBER & CHOTKOWSKI (1967)
L'HEUREUX & MEYER (1968)
△ BLEEKER et. al. (1968)
FANSELOW et. al. (1969)
■ EARL et. al. (1970)
MODULATED INTENSITY
C
B
A

FIGURE 2



10^7
10^6
10^5
10^4
10^3
10^2
10
10^{-2}
10^{-1}
1
10
○ FAN, et al (1966)
● BALASUBRAHMANYAN, et al (1966 a,b)
△ WADDINGTON AND FREIER, (1966)
◆ ORMES AND WEBBER, (1966)
◇ McDONALD, (1958)
ADIABATIC DECELERATION NEGLECTED
ADIABATIC DECELERATION INCLUDED
INTERSTELLAR INTENSITIES
MODULATED INTENSITY
INTENSITY (PROTONS $M^{-2}SEC^{-1}SR^{-1}GeV^{-1}$)
PROTON KINETIC ENERGY (GeV)

FIGURE 3