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Abstract

The production rates of cosmogenic nuclides in the solar system and in interstellar space were calculated for the primary protons in the galactic and solar cosmic rays. At 1 AU, the long-term average fluxes of solar protons usually produce many more atoms of a cosmogenic nuclide than the primary protons in the galactic cosmic rays (GCR), the exceptions being nuclides made only by high-energy reactions (like ^{10}Be). Because the particle fluxes inside meteorites and other large objects in space include many secondary neutrons, the production rates are much higher and ratios inside large objects are often very different from those by just the primary GCR protons in small objects. The production rates of cosmogenic nuclides are calculated to vary by about factors of 2.5 during a typical 11-year solar cycle, in agreement with measurements of short-lived radionuclides in recently fallen meteorites. The production of cosmogenic nuclides by the GCR particles outside the heliosphere is higher than that by the modulated GCR primaries normally in the solar system. However, there is considerable uncertainty in the fluxes of interstellar protons and, therefore, in the production rates of cosmogenic nuclides in interstellar space. Production rates and ratios for cosmogenic nuclides would be able to identify particles that were small in space or that were exposed to an unmodulated spectrum of GCR particles.

Introduction

The energetic particles in the cosmic rays are about 90% protons and induce a wide variety of nuclear reactions in extraterrestrial matter [Reedy et al., 1983]. Relatively low energy (~10- to 100 MeV) particles are emitted occasionally from the sun, the so-called solar cosmic rays (SCR). The SCR particles are rapidly stopped in matter (within a few centimeters) and produce a high density of product nuclei very near the surface [Reedy and Arnold, 1972]. The high-energy (~1-GeV) galactic cosmic-ray (GCR) particles produce a large cascade of secondary particles, especially neutrons, that penetrate meters into solid matter [Reedy and Arnold, 1972]. The flux of GCR particles in the solar system varies with solar activity and is lowest at periods of maximum solar activity. The highest fluxes of GCR particles observed recently in the solar system, during solar minimum, is less than those of the unmodulated GCR particles in interstellar space. Even higher fluxes of GCR particles, especially at lower energies, probably exist at the sources of the GCR particles. These different spectra and fluxes of cosmic-ray particles will result in a wide range of production rates of nuclides.

Most studies of cosmogenic nuclides have been for large objects (the Earth, moon, and meteorites), for long periods of time (averaged over many solar cycles), and for exposure to the cosmic rays at about 1 AU from the sun. Recently, there has been more interest in cosmogenic nuclide production under different circumstances. There have been a number of measurements of cosmogenic nuclides in very small objects, the cosmic spherules recovered from deep sea sediments [Raisbeck et al., 1983, 1985]. Evans et al. [1982] and Heusser et al. [1978] have reported large variations in the activities of short-lived cosmogenic radionuclides (such as 312-day ^{54}Mn) measured in fresh meteorite falls that indicates that the cosmogenic-nuclide production-rate variations over a solar cycle is ~2-3. Several papers have addressed the possibility of the production of cosmogenic nuclides outside the solar system, with the cosmogenic nuclides being retained even in very small grains [Ray and Völk, 1983] or made in bigger particles now found as cosmic spherules in deep sea sediments. Raisbeck et al. [1985] measured a very high content of ^{10}Be (about 50 dpm kg^{-1}) in a cosmic spherule and suggest that the irradiation occurred outside the solar system. During periods of unusually low solar activity, such as during the Maunder Minimum [Eddy, 1976], high fluxes of GCR particles could be present in the inner solar system and produce enhanced amounts of cosmogenic nuclides [Castagnoli and Lal, 1980]. The production rates for seven common cosmogenic radionuclides or noble-gas isotopes are calculated here for a variety of primary proton spectra. Some of these results were reported earlier Reedy [1983, 1986]; this work changes a few of these earlier spectra and includes a number of new estimates for the primary GCR protons in interstellar space.

Primary Cosmic-Ray Proton Spectra

The spectrum of solar protons is well approximated by an exponential function in rigidity [Reedy and Arnold, 1972]; it has a spectral shape averaged over the last ten million years [Reedy et al., 1983] of R_0 = 100 MV. The intensity adopted for this solar proton spectrum is an integral flux above 10 MeV of 70 protons cm^{-2} s^{-1}, which is the average over the last few million years as determined from lunar-rock measurements by Kohl et al. [1978]. Production rates for other solar-proton spectral shapes can be found from calculations in other papers [for example, Reedy and Arnold, 1972; Michel et al., 1982], by using surface production rates for lunar samples or meteorites multipled by a factor of two to get rates for the omnidirectional irradiation of very small objects in space.

For the GCR protons in interplanetary space and in interstellar space, a variety of spectral shapes and intensities are possible. In the inner solar system, the activity of the sun modifies the spectra of GCR particles as these particles enter the solar system [Reedy et al., 1983]. The activity of the sun usually varies with an 11-year cycle, with the strongest activity period (solar maximum) resulting in the lowest fluxes of GCR particles in the inner solar system. The time of lowest solar activity during a typical 11-year solar cycle (solar minimum) still results in a spectrum of GCR particles that is decreased, especially at lower energies, relative to that in the local interstellar space.

Castagnoli and Lal [1980] give an equation for the flux (in protons cm^{-2} s^{-1}) of the GCR protons as a function of a solar modulation parameter, M,

$$J(E,M) = 1.244\times10^{6} E(E+1876)(E+M+x)^{-2.65} / [(E+M)(E+1876+M)] \quad (1)$$

where E is the proton's kinetic energy and $x = 780 \exp(-2.5\times10^{-4} E)$. (Note that this equation has been corrected from the one in Castagnoli and Lal [1980] [D. Lal and G. Castignoli, personal communication, 1983]). For the GCR protons, spectra like those for the last two solar minima (M = 375 MeV) and maxima (M = 950 MeV) [Reedy et al, 1983; Castagnoli and Lal, 1980] were used, as well as one that is similar to the average over a solar cycle (M = 550 MeV). The solar-cycle-averaged omnidirectional integral flux of GCR protons above 1 GeV used here is 1.8 protons cm^{-2} s^{-1}. which is slightly higher than the value used by Reedy and Arnold [1972], 1.7 protons cm^{-2} s^{-1}. The GCR integral fluxes and spectral shapes used for solar maximum, solar minimum, and the average over an 11-year solar cycle are similar to those of Michel and Stück [1984], Bhandari et al. [1979], and Bhandari [1981], including the slightly higher value for the solar-cycle average. The solar-proton spectrum, the GCR-proton spectra for solar maximum, the solar-cycle average, and solar minimum discussed above, and an IS proton spectrum based on equation (1) with M = 0 are shown in Figure 1.

The spectra of GCR particles in interstellar (IS) space hasn't been measured directly and is hard to model or estimate. The protons with energies below ~100 MeV in IS space never enter the inner solar system, hence it is hard to extrapolate back from measured spectra to IS space. Indirect evidence, such as GCR electrons, interstellar gamma-ray fluxes, and the energy content of the IS medium, are used in estimating the spectrum of IS GCR particles, especially at lower energies [M. Garcia-Munoz, personal communication, 1985]. One spectrum for IS space is the expression of Castagnoli and Lal [1980] with their modulation parameter, M, equal 0. The shape for their expression with M = 0 is very similar to $(E + 1050)^{-2.87}$, with E in MeV. Castagnoli and Lal [1980] also note that a value of M = 100 MeV would give a GCR-proton spectrum that is similar to estimates for that in the local IS space. Other determinations of the GCR spectra in IS space used here are those of Webber and Yushak [1983] and Ip and Axford [1985]. Webber and Yushak [1983] give an equation for their interstellar spectrum,

$$J(E, T_o) = 1.2 \times 10^6 E^{0.3} (E + T_o)^{-3.0} , \quad (2)$$

where E is kinetic energy, and include an uncertainty for their IS-spectral shape parameter, which they determined to be $T_o = 300 \pm 100$ MeV $nucleon^{-1}$. These IS spectra are shown in Figure 2. Note the large spread in the fluxes, especially at lower energies, for these

IS spectra. All of these estimates of the IS GCR-particle spectrum are fairly flat at lower energies and all approach a spectra shape of about $E^{-2.65}$ at high energies. Such unmodulated IS spectra could be approached in the solar system during the long periods of essentially no solar activity that occur about every few hundred years [Eddy, 1976], such as the Maunder Minimum [Reedy et al., 1983; Castagnoli and Lal, 1980].

One estimate of the proton spectrum at the source of GCR particles is a power law in rigidity [H. Völk, personal communication, 1983]. At high energies, this rigidity power law was assumed to have the same intensity and shape as that observed in the solar system (see Figure 2). (Note that the intensity used here was based on the values of the interstellar spectra discussed above and is lower than that used in Reedy [1986].) The intense, low-energy part of this spectrum is similar to that required for the nucleosynthesis of most the the isotopes of lithium, beryllium, and boron by spallation reactions with heavier elements [Audouze, 1980]. As any source GCR-particle spectrum is modified by passage through ~5 g cm^{-2} of interstellar matter, this pure rigidity power-law spectrum overestimates the proton fluxes at lower energies in the local interstellar space [Reedy and Arnold, 1972], especially below ~100 MeV. Production rates for seven cosmogenic nuclides were calculated with these proton spectra, a C2-chondritic composition [Mason, 1979], and with cross sections for proton-induced reactions (mainly experimental values, e.g., see Tuniz et al. [1984] for the cross sections used for ^{10}Be) and are given in Table 1 for in the solar system and in Table 2 for outside the solar system. Typical production rates of these nuclides observed in stony meteorites (usually with radii of 10 to 30 cm) are also given in Table 1.

Cosmogenic-Nuclide Production Rates

Production by solar protons usually dominates that by primary GCR protons. Only nuclides made mainly by high-energy protons, such as ^{10}Be and ^{36}Cl, have very low production rates by the low-energy solar protons. These high rates by solar protons only occur very near the surface of an irradiated object, and solar-proton production rates become relatively unimportant below depths of a few centimeters [Reedy et al., 1983; Reedy and Arnold, 1972]. Only the GCR source spectrum exceeds the solar-proton production rates, because of its high fluxes at lower energies. In most meteorites, production by solar protons is usually not observable because the surface layers are removed by ablation during the meteorite's passage through the Earth's atmosphere. The ratio of the amount of a nuclide readily made by solar protons (for example, ^{26}Al) to that of a high-energy product (such as ^{10}Be) is a good indicator of the object's size when it was irradiated in space. Activities of ^{26}Al and ^{10}Be were measured in several groups of small (0.3- to 0.5-mm) spherules collected from sediments on the ocean floor [Raisbeck et al., 1983]. The $^{26}Al/^{10}Be$ ratio and the ^{26}Al activity were quite high in several of them, which indicate that those spherules probably came from parent bodies less than a few centimeters in diameter. Studies of such small objects would be interesting because they may be different from the forms of solar system matter found in most meteorites.

During periods of normal solar variations when the sun is having an 11-year cycle of solar activity, such as sunspot numbers, the extremes in the activity of the sun and its subsequent modulation of the GCR particles are represented by the solar minimum and maximum used in Table 1. Most cosmogenic nuclides in extraterrestrial matter are made by secondary cosmogenic neutrons. The cross sections as a function of energy for making neutrons are similar in shape to those for making ^{3}He, so the relative rates for making ^{3}He given in Tables 1 and 2 can be used to estimate the relative rates for producing cosmogenic nuclides in large objects in space. The ratio of 2.4 for the ^{3}He production rates between the extremes for an 11-year solar cycle is about the variation that would be expected for the production of secondary neutrons and cosmogenic nuclides. When Evans et al. [1982] measured the activities of short-lived radionuclides in a number of meteorites that fell from 1967 to 1978, the activities varied in phase with the solar activity and implied a production-rate variation over a solar cycle of a factor of 2.5-3. Heusser et al. [1978]

reported similar but slightly smaller production-rate changes over a solar cycle. Some of the measured variations in activities of cosmogenic radionuclides could have been caused by differences in the meteorites' sizes or shapes or in the sample location. However, the calculations reported here show that most of these radioactivity variations are caused by the solar modulation of the GCR-particle flux. Larger variations in nuclide production rates would be expected if the solar activity exceeded the average extremes used here, such as during the Maunder Minimum or the Grand Maximum [Eddy, 1976].

In Table 1, the ratio of the GCR production rates typically observed in meteorites to the solar-cycle-averaged rates for primary GCR protons ranged from 2.3 (for ^{36}Cl) to 8.0 (for ^{26}Al). Because the flux of primary protons inside a meteorite is attenuated by nuclear interactions, the ratios of observed activities to those made only by the primary GCR protons should be even larger. These relatively low contributions by the primary particles illustrate the importance of secondary particles in nuclide production in large objects like meteorites. Similar results for the production of cosmogenic nuclides by primary GCR particles were reported by Michel and Stück [1984]. This big difference between nuclide production by primaries only and by the fully developed secondary cascade present in most meteorites, which are relatively large (10 to 30 cm in radius), indicates that small meteorites without a fully developed cascade could have some unusual production rates or ratios. Studies of cosmogenic nuclides in such small meteorites or in isotropic irradiations of small spheres at accelerators [Michel et al., 1986] also would help us understand the production and transport of secondary particles in meteorites and other matter in space.

The production rates of nuclides by GCR protons in interstellar space are high, roughly similar to the rates produced by both primary and secondary GCR particles in meteorites. The relatively low-energy protons normally removed by solar modulation in the inner solar system have produced about the same number of nuclides as are made by secondary neutrons in meteorites. These high production rates, plus the relatively low loss of product nuclides by recoil in small grains [Ray and Völk, 1983], mean that one should be able to identify grains that were irradiated in interstellar space. Such grains may have been incorporated in meteorites or could enter the Earth's atmosphere as cosmic dust. Some grains may have been exposed to unmodulated GCR particles in an asteroidal regolith and then incorporated in gas-rich meteorites [Caffee et al., 1986]. The ^{3}He production rate in interstellar space is about 4 times that for the average over a solar cycle, and the flux of protons above 1 GeV in interstellar space is 2-3 times that for the solar-cycle average. Thus, the production rates of cosmogenic nuclides by GCR particles that have not been modulated are higher (by factors up to 2 to 4) than those observed near the Earth during long periods of typical solar activity.

Such high production rates in the interstellar medium could account for the high ^{10}Be seen in a cosmic spherule [Raisbeck et al., 1985], although the measured ^{10}Be activity of 50 dpm kg^{-1} is higher than the IS rates and the GCR source rate. However, the ^{26}Al activity in the same spherule is not unusually high (about 71 dpm kg^{-1}), which it would be if made with a GCR spectrum that can make 50 dpm kg^{-1} of ^{10}Be. Production of ^{10}Be from carbon was not included in these calculations but should not be a significant source of ^{10}Be unless very large amounts of carbon were originally present in the spherule.

Conclusions

The results of the calculations given in Tables 1 and 2 show that the production of cosmogenic nuclides by primary cosmic-ray protons can vary considerably with both the size of the extraterrestrial object and the amount of the solar modulation of the primary GCR particles. Very small objects have high production rates by solar protons. Typical meteorites are large enough that the cascade of secondary particles dominates nuclide production. Intermediate-size objects could have some unusual production rates and ratios. Temporal and spatial variations in nuclide production can also result from differing GCR-particle modulation. Variations by factors of 2 to 3 can occur during a normal solar cycle, in agreement with measurements of short-lived cosmogenic radionuclides in recent meteorite falls [Evans et al., 1982; Heusser et al., 1978], and even larger deviations can occur when solar modulation is much stronger or weaker than usual. High production rates of cosmogenic nuclides are expected to occur in interstellar space and near the sources of GCR particles. However, there are considerable uncertainties in the spectral shapes and intensitites of interstellar protons, so the production rates of cosmogenic nuclides in IS space have uncertainties of the order of a factor of 2. From their cosmogenic nuclides [Raisbeck et al., 1983], some cosmic spherules appear to have been small objects in space, although the evidence for a cosmic spherule irradiated out of the solar system [Raisbeck et al., 1985] is not strong.

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References

Audouze, J., Some aspects of the nucleosynthesis of the light elements, Prog. Nucl. Part. Phys. 6, 125-157, 1980.

Bhandari, N., Records of ancient cosmic radiation in extraterrestrial rocks, Proc. Indian Acad. Sci., Earth Planet. Sci., 90, 359-382, 1981.

Bhandari, N., S. K. Bhattacharya, and M. B. Potdar, Production profiles of radionuclides in chondrites and their solar cycle variation, in Lunar and Planetary Science X, pp. 107-109, Lunar and Planetary Institute, Houston, 1979.

Caffee, M. W., J. N. Goswami, C. M. Hohenberg, and T. D. Swindle, Pre-compaction irradiation of meteorite grains, in Lunar and Planetary Science XVII, pp. 99-100, Lunar and Planetary Institute, Houston, 1986.

Castagnoli, G., and D. Lal, Solar modulation effects in terrestrial production of carbon-14, Radiocarbon, 22, 133-158, 1980.

Eddy, J. A., The Maunder minimum, Science, 192, 1189-1202, 1976.

Evans, J. C., J. H. Reeves, L. A. Rancitelli, and D. D. Bogard, Cosmogenic nuclides in recently fallen meteorites: Evidence for galactic cosmic ray variations during the period 1967-1978, J. Geophys. Res., 87, 5577-5591, 1982.

Heusser, G., W. Hampel, T. Kirsten, and O. A. Schaeffer, Cosmogenic isotopes in recently fallen meteorites, Meteoritics, 13, 492-494, 1978.

Ip, W.-H., and W. I. Axford, Estimates of galactic cosmic ray spectra at low energies, Astron. Astrophys., 149, 7-10, 1985.

Kohl, C. P., M. T. Murrell, G. P. Russ III, and J. R. Arnold, Evidence for the constancy of the solar cosmic ray flux over the past ten million years: ^{53}Mn and ^{26}Al measurements, Proc. Lunar Planet. Sci. Conf. 9th, pp. 2299-2310, 1978.

Mason, B., Data of Geochemistry, Sixth Edition; Chapter B, Cosmochemistry; Part 1, Meteorites, U.S. Geological Survey Professional Paper 440-B-1, 1979.

Michel, R., P. Dragovitsch, P. Englert, F. Peiffer, R. Stück, S. Theis, F. Begemann, H. Weber, R. Signer, R. Wieler, D. Filges, and P. Cloth, On the depth dependence of spallation reactions in a spherical thick diorite target homogeneously irradiated by 600 MeV protons: Simulation of production of cosmogenic nuclides in small meteorites, Nucl. Instrum. & Methods in Phys. Res., in press, 1986.

Michel, R., G. Brinkmann, and R. Stück, Solar cosmic-ray-produced radionuclides in meteorites, Earth Planet. Sci. Lett., 59, 33-48, 1982; plus erratum in Earth Planet. Sci. Lett. 64, 174, 1983.

Michel, R., and R. Stück, On the production of cosmogenic nuclides in meteorites by primary galactic particles: Cross sections and model calculations, Proc. Lunar Planet. Sci. Conf. 14th, J. Geophys. Res., 89, Supplement, B673-B684, 1984

Raisbeck, G. M., F. Yiou, J. Klein, R. Middleton, Y. Yamakoshi, and D. E. Brownlee, ^{26}Al and ^{10}Be in deep sea stony spherules; Evidence for small parent bodies, in Lunar and Planetary Science XIV, pp. 622-623, Lunar and Planetary Institute, Houston, 1983.

Raisbeck, G. M., F. Yiou, and D. E. Brownlee, Unusually high concentration of ^{10}Be in a cosmic spherule: Possible evidence for irradiation outside the planetary solar system, Meteoritics, 20, 734-735, 1985.

Ray, J., and H. J. Völk, The retention of spallation products in interstellar grains, Icarus, 54, 406-416, 1983.

Reedy, R. C., Nuclide production by primary cosmic rays in very small objects, Meteoritics, 18, 383-384, 1983.

Reedy, R. C., Nuclide production by primary galactic-cosmic-ray protons, in Lunar and Planetary Science XVII, pp. 695-696, Lunar and Planetary Institute, Houston, 1986.

Reedy, R. C., and J. R. Arnold, Interaction of solar and galactic cosmic-ray particles with the moon, J. Geophys. Res., 77, 537-555, 1972.

Reedy, R. C., J. R. Arnold, and D. Lal, Cosmic-ray record in solar system matter, Science, 219, 127-135, 1983; and Annu. Rev. Nucl. Part. Sci., 33, 505-537, 1983.

Tuniz, C., C. M. Smith, R. K. Moniot, T. H. Kruse, W. Savin, D.K. Pal, G. F. Herzog, and R. C. Reedy, Beryllium-10 contents of core samples from the St. Severin meteorite, Geochim. Cosmochim. Acta, 48, 1867-1872, 1984.

Webber, W. R., and S. M. Yushak, A measurement of the energy spectra and relative abundance of the cosmic-ray H and He isotopes over a broad energy range, Astrophys. J., 275, 391-404, 1983.

Figure Captions:

Fig. 1. The omnidirectional fluxes as a function of kinetic energy of solar protons (x, for R_0 100 MV) and of galactic-cosmic-ray protons in the solar system (using equation (1)), for no modulation (M 0) and for three levels of modulation: solar maximum (M 950 MeV), the 11-year average (M 550 MeV), and solar minimum (M 350 MeV).

Fig. 2. The omnidirectional fluxes as a function of kinetic energy of galactic-cosmic-ray protons in interstellar space and a possible spectrum at the source of the GCR. (Note that the range of fluxes is slightly lower than that in Fig. 1.)

Table 1. Nuclide Production Rates by Primary Cosmic-Ray Protons in the Solar System, Assuming C2-Chondritic Chemistry.

	10^6 years Av. SCR	Solar Max. GCR	Solar Av. GCR	Solar Min. GCR	Typical Meteorite
Parameter	$R_0=100$	$M=950$	$M=550$	$M=375$	
Integral Flux[a]	70	1.21	1.80	2.39	
Nuclide	(atoms minute^{-1} kg^{-1})				
^{3}He	566.	189.	317.	458.	900.
^{10}Be	4.1	4.9	8.1	11.5	22.
^{21}Ne	395.	11.6	20.8	32.	150.
^{26}Al	344.	4.3	8.1	12.7	60.
^{36}Cl	0.9	1.8	3.1	4.5	7.
^{38}Ar	72.	3.3	5.5	8.0	20.
^{53}Mn	590.	7.6	13.6	21.	105.

[a] In protons cm^{-2} s^{-1}; solar protons for $E > 10$ MeV, GCR for $E > 1$ GeV.

Table 2. Nuclide Production Rates by Primary Galactic-Cosmic-Ray Protons in Interstellar Space, Assuming C2-Chondritic Chemistry.

	Castagnoli and Lal		Ip and Axford	Webber and Yushak	GCR Source $R^{-2.65}$
Parameter	$M = 100$	$M = 0$	-	$T_o = 300 \pm 100$	-
Integral Flux[a]	3.63	4.33	2.23	$3.40^{+0.51}_{-0.42}$	2.72
Nuclide	(atoms minute^{-1} kg^{-1})				
^{3}He	855.	1257.	755.	$1867.^{\times 1.61}_{\div 1.42}$	2568.
^{10}Be	21.	29.	16.	$38.^{\times 1.50}_{\div 1.36}$	38.
^{21}Ne	71.	117.	81.	$234.^{\times 1.91}_{\div 1.66}$	1007.
^{26}Al	31.	58.	44.	$136.^{\times 2.10}_{\div 1.71}$	845.
^{36}Cl	8.	11.	6.	$14.^{\times 1.43}_{\div 1.33}$	13.
^{38}Ar	16.	24.	16.	$43.^{\times 1.91}_{\div 1.56}$	163.
^{53}Mn	49.	90.	69.	$210.^{\times 2.14}_{\div 1.72}$	1367.

[a] In protons cm^{-2} s^{-1} for $E > 1$ GeV.

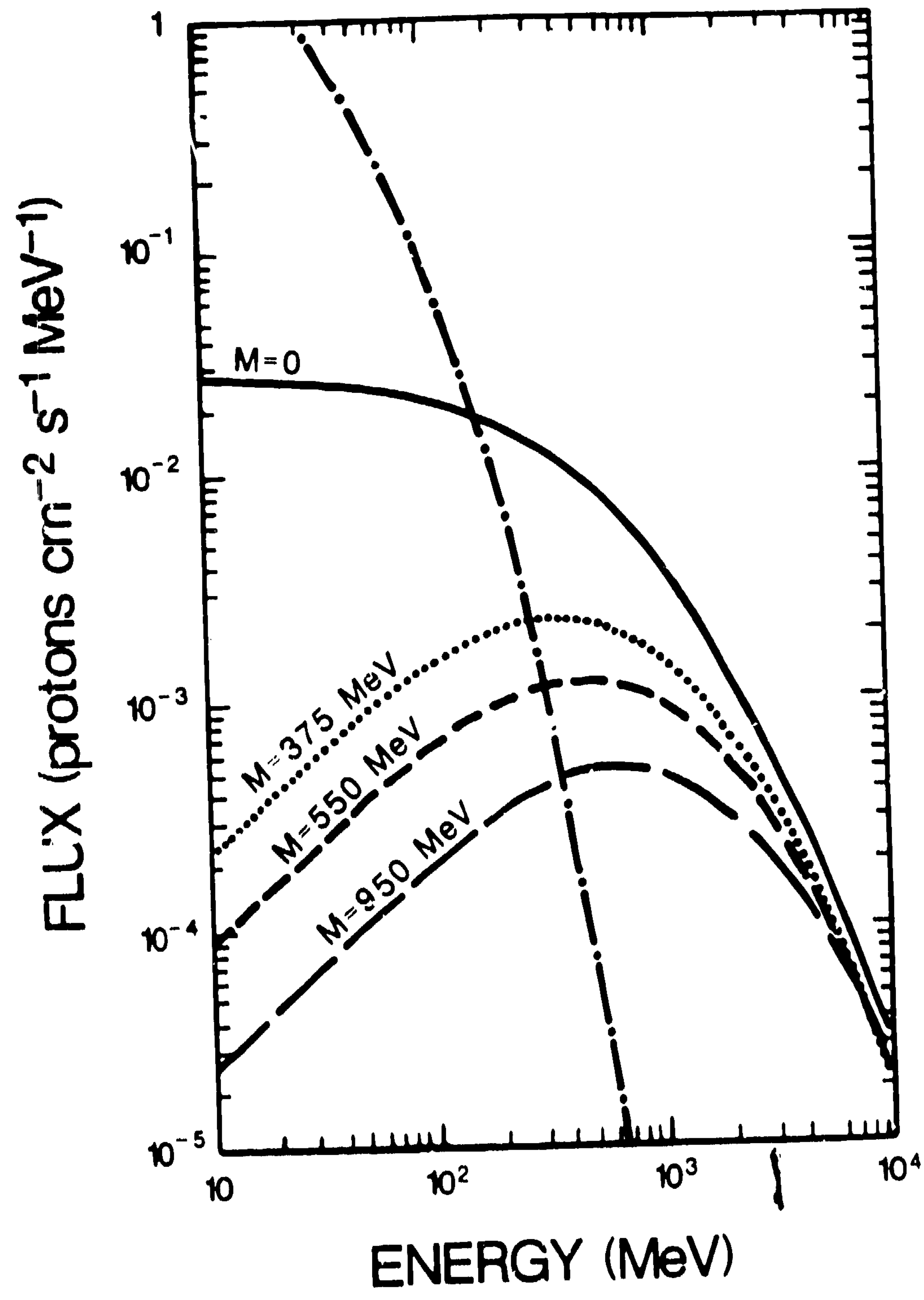
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
FLUX (protons cm^{-2} s^{-1} MeV^{-1})
M=0
M=375 MeV
M=550 MeV
M=950 MeV
10
10^2
10^3
10^4
ENERGY (MeV)

Figure 1

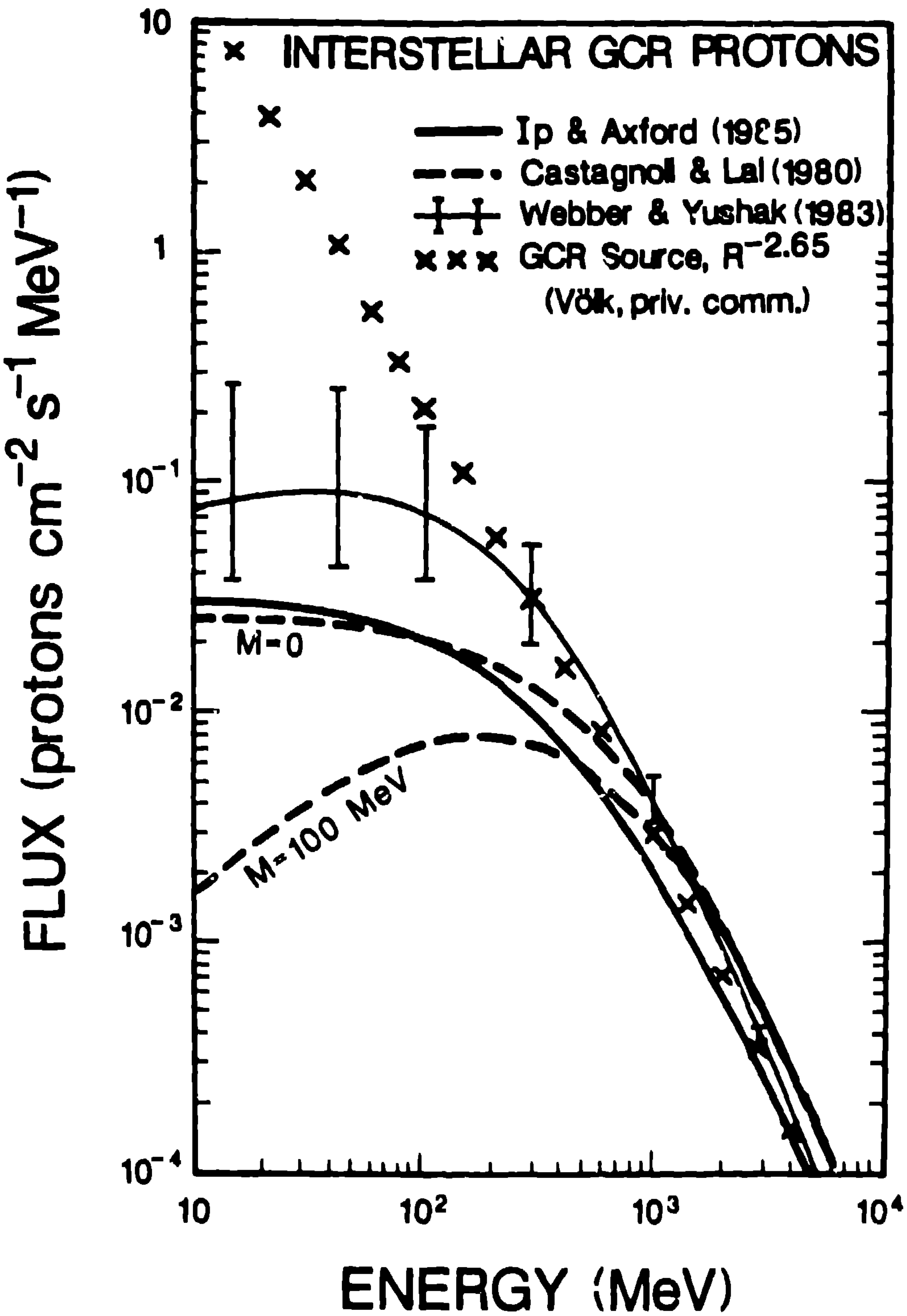
INTERSTELLAR GCR PROTONS
Ip & Axford (19E5)
Castagnoli & Lal (1980)
Webber & Yushak (1983)
GCR Source, R^-2.65
(Völk, priv. comm.)
M=0
M=100 MeV
FLUX (protons cm^-2 s^-1 MeV^-1)
ENERGY (MeV)
10
1
10^-1
10^-2
10^-3
10^-4
10
10^2
10^3
10^4

Figure 2