Conf-770304--1

LA-UR - 77 - 909

TITLE: SOLAR PROTON FLUXES SINCE 1956

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SUBMITTED TO: PROCEEDINGS OF THE EIGHTH LUNAR SCIENCE CONFERENCE, HOUSTON, TX, MARCH 14-18, 1977

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UNITED STATES
ENERGY RESEARCH AND
DEVELOPMENT ADMINISTRATION
CONTRACT W-7405-ENG. 36

Solar proton fluxes since 1956

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Abstract--The fluxes of protons emitted during solar flares since 1956 were evaluated. The depth-versus-activity profiles of ^{56}Co in several lunar rocks are consistent with the solar-proton fluxes detected by experiments on several satellites. Only about 20% of the solar-proton-induced activities of ^{22}Na and ^{55}Fe in lunar rocks from early Apollo missions were produced by protons emitted from the sun during solar cycle 20 (1965-1975). The depth-versus-activity data for these radionuclides in several lunar rocks were used to determine the fluxes of protons during solar cycle 19 (1954-1964). The average proton fluxes for cycle 19 are about five times those for both the last million years and for cycle 20. These solar-proton flux variations correlate with changes in sunspot activity.

13 April 1977

INTRODUCTION

A significant portion of the induced radioactivities in the top few centimeters of the moon is produced by energetic particles emitted from the sun (the remaining cosmogenic radioactivity is produced as the result of the bombardment of the moon by galactic-cosmic-ray (GCR) particles (Reedy and Arnold, 1972)). The solar-induced activities of radionuclides with different half-lives allow comparisons of the average fluxes of solar-cosmic-ray (SCR) particles over different time periods. The depth-versus-activity profiles of 2.6-y ^{22}Na and 0.73-My ^{26}Al in lunar rocks and the equivalent-steady-state solar-proton fluxes which produced these radionuclides are very similar, indicating that the average flux of particles emitted from the sun over the last million years is not greatly different than that of those emitted recently (Finkel et al., 1971; Lavrukhina and Ustinova, 1971). The long-term flux of solar alpha particles determined from measurements of the activities of 80 000-y ^{59}Ni was also found to be comparable to the flux of alpha particles measured recently (Lanzerotti et al., 1973).

The conclusion that the average flux of SCR particles over the last million years is similar to that observed currently was not unexpected, since the sun was believed to be a very regular star. The numbers of spots on the surface of the sun vary with an eleven-year period, but it was generally accepted that the sun always had cycles similar to those observed now. However, Eddy (1976) has presented evidence that the sun has not always been regular. Observations of sunspots, auroral activities, and solar eclipses show that the sun was very inactive from 1645 to 1715 - the "Maunder Minimum." Measurements of ^{14}C activities in tree rings are consistent with the low solar activity for this period, and indicate that the sun was also inactive from about 1460 to 1550 (the "Sporer Minimum"), was very active from about 1100 to 1250, and probably had similar variations in activity frequently in the past (Eddy, 1976).

An extreme form of solar activity is the emission of energetic particles during the largest flares which occur on the sun. These SCR particles were first observed in the 1940's, but their fluxes have been determined quantitatively only since 1956 (Pomerantz and Duggal, 1974). The SCR-particle fluxes for events during solar cycle 20 (1965-1975) are known from direct satellite measurements made outside the Earth's magnetosphere (cf. King, 1974). Most of the SCR-particle flux values for solar cycle 19 (1954-1964) are based on indirect methods of observation, such as neutron-monitor counting rates and radiowave absorption in the ionosphere (Bailey, 1964; Webber et al., 1963; McDonald, 1963; Pomerantz and Duggal, 1974).

The present paper evaluates the integral fluxes of solar protons reported in the literature for flares during solar cycles 19 and 20, and checks to see if these fluxes are consistent with the radioactivities of spallogenic nuclides in the top layers of lunar samples. The solar-proton fluxes for solar cycle 20 are consistent with lunar radioactivity data; those for cycle 19 are not. The lunar radioactivity data for ^{22}Na, ^{55}Fe, and ^{3}H are used to derive the fluxes of solar protons for cycle 19. These solar-proton fluxes are compared with sunspot numbers for these cycles and with the average solar-proton fluxes over much longer time periods.

Accurate determination of the solar-proton fluxes for these two solar cycles would be useful in studying the variability of solar activity. The peak values of the Zurich smoothed sunspot numbers for these cycles were very different. Cycle 19 had the largest sunspot numbers ever observed - slightly over 200 for the peak value of the smoothed sunspot number. Cycle 20's peak sunspot number was 110 and the average of the peak sunspot numbers for all 20 cycles since 1750 is about 100.

The purpose of most compilations of integral solar-proton fluxes (e.g., Webber et al., 1963; King, 1974) is to provide a data base for studies of possible radiation effects for space missions. High doses of SCR-particles can damage electronic equipment in satellites, and very large solar flares emit enough energetic particles to pose a serious threat to the lives of humans exposed to them. Expanding and improving the quality of the data base of solar-proton fluxes would be useful in planning for future space missions.

Evaluation of Integral Proton Fluxes for Solar Flares since 1956

The proton fluxes for most solar flares during solar cycle 19 were first compiled by Webber et al. (1963). A slightly different tabulation by Webber is in McDonald (1963). Other compilations of integral fluxes (e.g., Weddell and Haffner, 1966; Modisette et al., 1965; and several in Warman, 1972) use the Webber et al. (1963) data for these flares, but some also give fluxes for some flares not reported in Webber et al. (1963). The adopted fluxes for solar cycle 19 are listed in Table 1 and shown in Fig. 1. Most are those of Webber et al. (1963); the rest are extrapolations of data reported at other energies or are the data of Weddell and Haffner (1966). The fluxes for the 13 February 1959 flare are based on data from Modisette et al. (1965). Bailey (1964) gives differential fluxes for energies above 10 MeV at the time of peak intensity for all of these flares except those on 13 June 1959, 2 September 1959, and 15 July 1961. Bailey's peak fluxes above 10 MeV are, on average, 2.5 times those in the sources adopted here. For each flare, the ratio of the peak flux of Bailey to that of the sources adopted here times the adopted integral flux above 10 MeV is shown in Fig. 1 as a circle. This disagreement for the peak fluxes illustrates the difficulty of obtaining SCR-particle fluxes from the indirect observations made during solar cycle 19.

The evaluated integral proton fluxes for the solar flares during cycle 20 are listed in Table 2 and shown in Fig. 2. The data for flares from May 1967 to May 1973 are based on the counting rate data obtained by the Solar Proton Monitor Experiment (SPME) of Bostrom et al. (1967-1973). The SPME was on the satellites IMP-4, IMP-5, and IMP-6, which were in highly eccentric Earth orbits. The SPME fluxes agree quite well with the proton fluxes obtained by other experiments on these IMPs (King, 1974). Except as noted, the adopted fluxes from the SPME were obtained by summing the hourly proton fluxes tabulated in various volumes of Solar Geophysical Data and subtracting the background counting rates. For the flares prior to May 1967, data from a number of sources were used to get the adopted fluxes (cf. Stassinopoulos and King, 1974, for some of the proton data on these early cycle 20 flares). The sums of the fluxes for cycle 20 solar protons up through 1972 as adopted here agree within 6% to the corresponding sums of King (1974). Several flares which emitted protons occurred late in 1973 and during 1974, but there are no reported data from the SPME on their proton fluxes. Very approximate proton fluxes were obtained for these flares from graphical data given in Solar Geophysical Data from measurements made over the Earth's polar caps by NOAA satellites, and the approximate integral fluxes for protons with energies greater than 10 MeV are shown in Fig. 2 as question marks.

Calculated SCR Production Rates of Short-Lived Radionuclides in the Moon

The depth-versus-activity profiles expected for several short-lived radionuclides (77-d ^{56}Co, 312-d ^{54}Mn, 2.6-y ^{22}Na, 2.7-y ^{55}Fe, and 12.3-y ^{3}H) were calculated using the above adopted solar-proton fluxes and the production-rate models of Reedy and Arnold (1972). For each radionuclide and proton energy, the integral flux data are converted to an equivalent-steady-state flux above energy E, J(>E), by the relation

$$J(>E) = \lambda \sum_{i=1}^{n} \Phi_i(>E) \exp(-\lambda \Delta t_i),$$

where $\Phi_i(>E)$ is the evaluated integral flux above energy E for flare i, λ is the decay constant for the specific radionuclide, and Δt_i is the time from the date of the flare to the date of interest (i.e., the date the sample was collected on the moon). Table 3 gives the calculated equivalent-steady-state fluxes for these radionuclides at the time of the Apollo 12 mission. About equal amounts of the solar-proton-induced activities of ^{22}Na and ^{55}Fe are made by solar protons from each solar cycle, the considerable decay over almost four half-lives for production by solar cycle 19 protons being compensated by the much larger fluxes of solar cycle 19 protons relative to those of cycle 20 prior to the Apollo 12 mission.

The cross sections and model of Reedy and Arnold (1972) were used to convert these and other equivalent-steady-state proton fluxes to depth-versus-activity profiles. The evaluated fluxes were assumed to be isotropic over all directions in space and the lunar rocks were assumed to be semi-infinite planes receiving 2π isotropic irradiations from space. These profiles were averaged over depths to convert them to activities for the layers analyzed in rocks 10017, 12002, and 14321, by Shedlovsky et al. (1970), Finkel et al. (1971), and Wahlen et al. (1972), respectively. The calculated solar-proton-induced activities for ^{56}Co and ^{54}Mn are given in Table 4 and those for ^{22}Na and ^{55}Fe are in Table 5.

Comparisons of Observed and Calculated SCR-Produced Radioactivity in Lunar Rocks

The activities of most cosmogenic radionuclides in the top few centimeters of lunar samples are produced by both GCR and SCR particles. Some radionuclides, such as ^{39}Ar, are made predominantly by GCR particles; at the other extreme, ^{56}Co is made almost entirely by solar protons, the GCR production rate of ^{56}Co in lunar samples being about one disintegration-per-minute per kilogram of sample (dpm/kg). The GCR-induced activities in the top layers of rocks 10017, 12002, and 14321 were determined using the calculated GCR activity-versus-depth production profiles of Reedy and Arnold (1972), the activities of the deepest sample in each rock being used to normalize these profiles. The SCR-induced activities in this deepest sample were determined by an iterative process where the GCR activity-versus-depth profile was varied until the SCR profile was smooth for all depths, including this deepest sample.

The SCR and GCR profiles for ^{56}Co, ^{22}Na, and ^{55}Fe are shown for rock 12002 in Figs. 3-5, respectively. The "observed" SCR activities of ^{56}Co and ^{54}Mn in these rocks are given in Table 4 and those of ^{22}Na and ^{55}Fe are in Table 5. In almost all cases, the factors by which the Reedy-Arnold GCR profiles were multiplied differed appreciably from unity. In rocks 10017, 12002, and 14321, the GCR factors for ^{22}Na were 0.68, 0.77, and 0.68, respectively, and for ^{55}Fe they were 1.10, 0.55, and 0.48. These factors are consistent with measured activities in cores at depths where SCR production is negligible. For ^{22}Na in the Apollo 15 and 17 deep drill cores, Rancitelli et al. (1975) obtained 0.82 and 0.84 for the average ratios of observed activities relative to the Reedy-Arnold production rates. The ratios of observed-to-calculated activities for ^{55}Fe in several deep Apollo 15 samples were similar to those used here (R. Finkel, priv. comm., 1973). For rocks 12002 and 14321, the ratios of observed-to-calculated ^{54}Mn activities were 1.19 and 1.32. The average of these two ratios, 1.25, was used for rock 10017. There are no measurements for ^{54}Mn in deep samples, but ^{53}Mn (whose cross sections are similar to those for ^{54}Mn, cf. Reedy and Arnold, 1972) has been measured in several deep cores by the La Jolla group, and they have adopted an observed-to-calculated GCR factor for ^{53}Mn of 1.40 (Kohl et al., 1977).

Lavrukhina and Ustinova (1971) analyzed the ^{22}Na data of Shedlovsky et al. (1970) for rock 10017. They used essentially the same GCR depth-versus-activity profile used here. Their equivalent-steady-state solar-proton flux above 20 MeV was 31 protons/cm^2 s; the one obtained here was about 36 protons/cm^2 s. This relatively small difference is possibly due to the cross sections used in unfolding the SCR-induced profile. Lavrukhina and Ustinova (1971) didn't describe the spectral shape of the solar protons or give proton fluxes at other energies, so some of the difference could also be due to the energy distribution of the protons used in the analysis.

The half-lives of ^{56}Co and ^{54}Mn are short enough that they were produced in these samples almost entirely by solar protons emitted from the sun during solar cycle 20. The relatively good agreement of the observed and calculated ^{56}Co activities indicates that the evaluated solar-proton fluxes for solar cycle 20 probably are accurate. The reasons for the poor agreement between the observed and calculated activities for ^{54}Mn are not known. The cross sections for the production of ^{54}Mn are generally less well known than those for the production of ^{56}Co. Another source of uncertainty in the ^{54}Mn interpretation is the correction for GCR-induced activity, since the ratio of the SCR- to GCR-induced activities for ^{54}Mn is lower than that for the other three radionuclides analyzed here. The deepest sample in 12002 (20-60 mm) has a noticeably lower activity (31 ± 5 dpm/kg) than that of the next deepest sample (39 ± 10 dpm/kg). Raising the ^{54}Mn GCR factor to 1.68 lowers the average ratio of observed-to-calculated SCR activities from 2.0 to 1.3, and produces a reasonably smooth fit for all the samples down to 20 mm depths, but requires that the deepest sample have a GCR-produced activity of 39 dpm/kg. Other investigators have reported good agreement between measured SCR-induced activities and those calculated using SPME fluxes (e.g, Rancitelli et al., 1974), so there is no reason to believe that the adopted proton fluxes for solar cycle 20 are significantly in error.

The discrepancies between the observed and calculated SCR-produced activities for ^{22}Na and ^{55}Fe are much larger - generally the activities calculated with the evaluated solar-proton fluxes being 0.2 to 0.5 of the observed SCR-produced activities in these rocks (cf. Table 5.) Since solar cycle 20 protons can only account for about 20% of the SCR-produced activities of ^{22}Na and ^{55}Fe in these rocks, the undercalculation of their activities is due mainly to an underestimation of the proton fluxes for solar cycle 19. Because of the small contributions by cycle 20 protons, the SCR-induced activities of these radionuclides can be used quite accurately to determine the solar proton fluxes for cycle 19

Determination of Solar Cycle 19 Proton Fluxes from ^{22}Na and ^{55}Fe Activity-Versus Depth Profiles

Because of the fairly good agreement between the observed and calculated activities of ^{56}Co in rocks from three different missions, it is assumed that the evaluated proton fluxes for solar cycle 20 are correct, and that the ^{22}Na and ^{55}Fe activities in these rocks not produced by solar cycle 20 protons were produced by solar cycle 19 protons. For each of these nuclides, the activities calculated with the evaluated fluxes of Tables 1 and 2 were subtracted from the observed SCR activities. The "excess" activity-versus-depth profiles for both radionuclides were well fit by an equivalent-steady-state proton flux with a J(>10 MeV) of about 50 protons/cm^2 s (4π) and an exponential-rigidity spectral shape of R_0 = 125 MV. For cycle 19 production of these radionuclides, the ratio of the extra-to-evaluated equivalent-steady-state proton fluxes are 2.0, 4.0, and 5.8 for energies above 10, 30, and 100 MeV, respectively. Table 5 and Figs. 4 and 5 show the calculated SCR activities including this extra proton flux for cycle 19. The agreement between observed and calculated activities for both ^{22}Na and ^{55}Fe is now excellent, the differences generally being less than 10%.

What cannot be determined from the ^{22}Na and ^{55}Fe data is the distribution of this extra proton flux among the flares which occurred during solar cycle 19. If all the extra flux occurred in the middle of the years 1956, 1959, or 1961, the integral number of protons in this extra flux would be about 2.2, 1.0, or 0.6 times that for distributing the extra proton flux proportionally among the evaluated fluxes. The factor of 2.0 for the extra-to-evaluated equivalent-steady-state flux above 10 MeV is similar to the factor of 1.5 for the extra flux implied by the peak fluxes of Bailey (1964) relative to those of the evaluated fluxes. The ratios of Bailey's peak fluxes to the evaluated peak fluxes are fairly constant throughout cycle 19. Almost half of the evaluated proton fluxes for cycle 19 occurred in 1959. Thus there is no evidence against assuming that this extra proton flux should be distributed among all the flares of cycle 19 in proportion to the evaluated fluxes of Table 1.

Comparisons of Observed and Calculated ^{3}H Activities

The radionuclide ^{3}H (half-life of 12.3 years) is produced relatively easily by solar protons. The ^{3}H activity-versus-depth profile in rock 12002 (D'Amico et al., 1971) shows a significant increase of ^{3}H activity in the 0-8 mm layer compared with that in the deeper layers. Other ^{3}H measurements generally show the same trend, although there is poor reproducibility for activities measured at any given depth. Some of the ^{3}H activities measured in lunar samples show unusual behavior, such as the wide variations in ^{3}H activities measured in the Apollo 17 deep drill core by Stoenner et al. (1974) and the occasional presence of ^{3}H released at fairly low temperatures (e.g., Fireman et al., 1973). The ^{3}H depth-versus-activity data for several samples were fit approximately with a GCR depth-versus-activity profile 1.4 times that of Reedy and Arnold (1972) and equivalent-steady-state fluxes of about 200, 70, 30, and 12 protons/cm^{2} s (4π) above 10, 30, 60, and 100 MeV respectively.

For energies above 10 MeV, the equivalent-steady-state fluxes for Apollo 12 calculated from the data in Tables 1 and 2 and from the extra cycle 19 flux are 43, 10.4, and 86, respectively. Thus about 70% of the SCR-induced activity of ^{3}H

was produced by protons from cycles 19 and 20. An average solar-proton flux of about 150 protons/cm^2 s above 10 MeV prior to 1954 would account for the rest of the observed ^3H activity. Solar cycles 17 and 18 had maximum sunspot numbers of about 100 and 150, so this average flux prior to 1954 is consistent with sunspot numbers for these cycles. However, because of the large uncertainty in the SCR-produced ^3H activities, nothing quantitative can be said about the solar-proton fluxes prior to 1954. The ^3H activity measurements do exclude the possibility that a significant fraction of the extra ^{22}Na and ^{55}Fe SCR activities was produced by very intense solar-proton fluxes prior to 1954, since such fluxes would have produced much more ^3H activity than was observed in lunar samples.

Discussion

The average fluxes of solar protons for solar cycle 20 (based on the evaluated data in Table 2), solar cycle 19 (Table 1 times the factors given above), and for the last million years (Wahlen et al., 1972) are listed in Table 6. Also given are the peak values of the Zurich smoothed sunspot numbers for solar cycles 19 and 20 and the average of the peak values for cycles 1 to 20.

The temporal distribution of the protons emitted from the sun over the last million years is not well known. The proton fluxes derived from radioactivity data for 0.73-My ^{26}Al and 3.7-My ^{53}Mn are similar (Wahlen et al., 1972). For their ^{53}Mn studies of gardening in the tops of cores, Kohl et al. (1977) used an average solar proton flux with J(>10 MeV) = 70 protons/ cm^2 s and a spectral shape of R_0 = 100 MV, both parameters similar to those derived from the ^{26}Al and ^{53}Mn depth-versus-activity profiles in lunar rocks. Bhandari et al. (1976) measured ^{26}Al activities for the surface and for a deep sample of four rocks with exposure ages from 0.5 to 3.8 million years and found little (less than ±25%) variation in the average solar-proton intensities. The depth-versus-activity profile of 5730-y ^{14}C was measured in rock 12002 by Boeckl (1972). Using the ^{14}C

production-rate calculations of Reedy and Arnold (1972), Boeckl obtained an average solar-proton flux over the mean life of ^{14}C which was about twice that over the last million years. The cross sections for the $^{16}O(p,3p)^{14}C$ reaction are not well known; hence there is more uncertainty in the proton fluxes derived from ^{14}C data than from data for the other radionuclides (whose production cross sections are better known).

The protons in solar flares which occurred as distant as five half-lives were important in producing the ^{22}Na and ^{55}Fe activities observed at the time of the early Apollo missions. The fact that the equivalent-steady-state fluxes for ^{22}Na and ^{26}Al were similar in Apollo 11 and 12 samples (Lavrukhina and Ustinova, 1971; Finkel et al., 1971) therefore is not sufficient evidence for proving the constancy of solar-proton fluxes. The average proton fluxes during solar cycle 20 are very similar to the average fluxes over the last million years, and the peak value of of sunspot numbers for cycle 20 is about the average of the peak values for all solar cycles since 1750. It should be noted that the majority of the solar protons for cycle 20 was emitted during the 4 August 1972 flare, and that the average proton fluxes for all flares prior to August 1972 would be much lower than those in Table 6. The average cycle 19 proton flux is about five times the average flux for both the last million years and for all of cycle 20, while the peak sunspot number of cycle 19 is only twice that for cycle 20 and for the first 20 cycles. Thus the average solar-proton fluxes correlate with sunspot numbers. Since the variation of solar-proton fluxes between cycles is greater than the variation of sunspot numbers, studies of solar-proton fluxes in the past using SCR-induced radioactivities should be a good method for the study of long term variations in solar activity.

Many investigators, such as King (1974), consider the August 1972 solar event as emitting "anomalously large" fluxes of protons. Since the proton fluxes previously adopted for solar cycle 19 are low by factors of 3 to 7, the intensities of solar protons in cycle 19 flares are much larger than previously believed, and some of the cycle 19 flares probably had solar-proton fluxes comparable to those of August 1972. Solar cycle 19 is usually dismissed as atypical (e.g., King, 1974). However, since the level of activity of an eleven-year solar cycle can not be predicted accurately ahead of time, long-term deep-space missions should be designed to withstand the radiation effects of flares like that of August 1972.

Acknowledgments--This research was supported by ERDA and by NASA work order W-14,084. The author thanks J. R. Arnold for useful discussions during this work, D. R. Criswell for the suggestion that lunar data be used to study possible radiation effects in space, and M. L. Wall and E. F. Willow for their aid in the preparation of this manuscript.

Figure Captions

Fig. 1. Zurich smoothed sunspot numbers (continuous solid curve) and the omnidirectional integral fluxes of protons above several energies emitted by flares during solar cycle 19. The fluxes for several flares which occurred close to each other have been combined. For each flare, the circle represents the product of the integral flux of protons with energies above 10 MeV as shown here times the ratio of the peak flare proton fluxes above 10 MeV of Bailey (1964) to that of the source adopted here.

Fig. 2. Zurich smoothed sunspot numbers (continuous solid curve) and the omnidirectional integral fluxes of protons above several energies emitted by flares during solar cycle 20. The fluxes for several flares which occurred close to each other have been combined. The question marks are very approximate values of the integral fluxes of protons above 10 MeV for several flares near the end of the solar cycle.

Fig. 3. The solar-proton-produced activities of ^{56}Co in rock 12002. The points are the measured activities of Finkel et al. (1971) less a GCR-produced activity of 1 disintegration-per-minute per kilogram of sample (dpm/kg). The solid curve (labeled SPME) is the production profile calculated with the solar-proton fluxes of Table 2.

Fig. 4. The solar-proton-produced activities of ^{55}Fe in rock 12002. The points are the measured activities of Finkel et al. (1971) less the GCR-produced activity (shown as a dotted line). The dashed curve (labeled WEBBER AND SPME) is the production profile calculated with only the solar-proton fluxes given in Tables 1 and 2. The solid curve is the calculated production profile including the extra proton fluxes for solar cycle 19 (cf. text).

Fig. 5. The solar-proton-produced activities of ^{22}Na in rock 12002. The points are the measured activities of Finkel et al. (1971) less the GCR-produced activity (shown as a dotted line). The dashed curve (labeled WEBBER AND SPME) is the production profile calculated with only the solar-proton fluxes given in Tables 1 and 2. The solid curve is the calculated production profile including the extra proton fluxes for solar cycle 19 (cf. text).

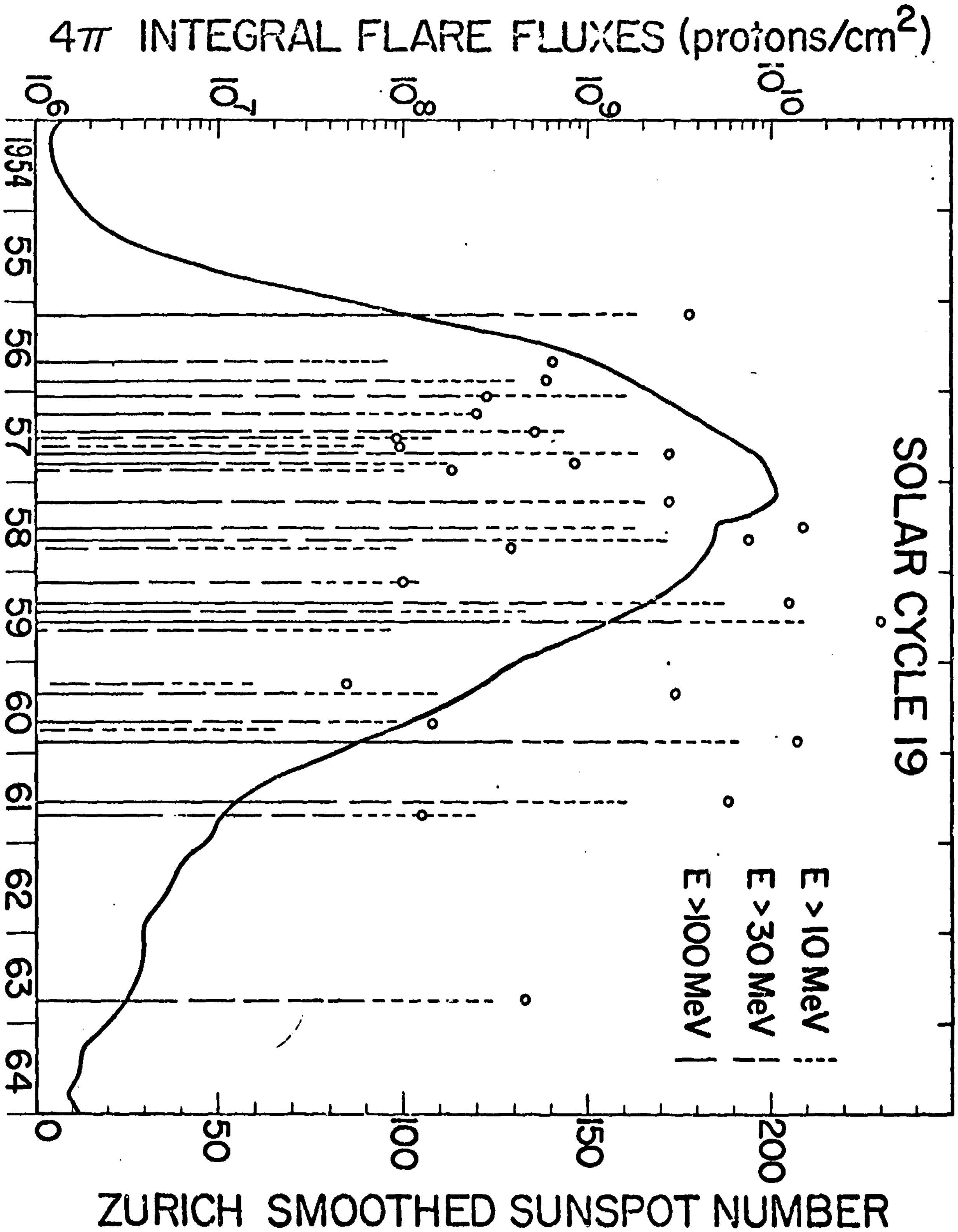
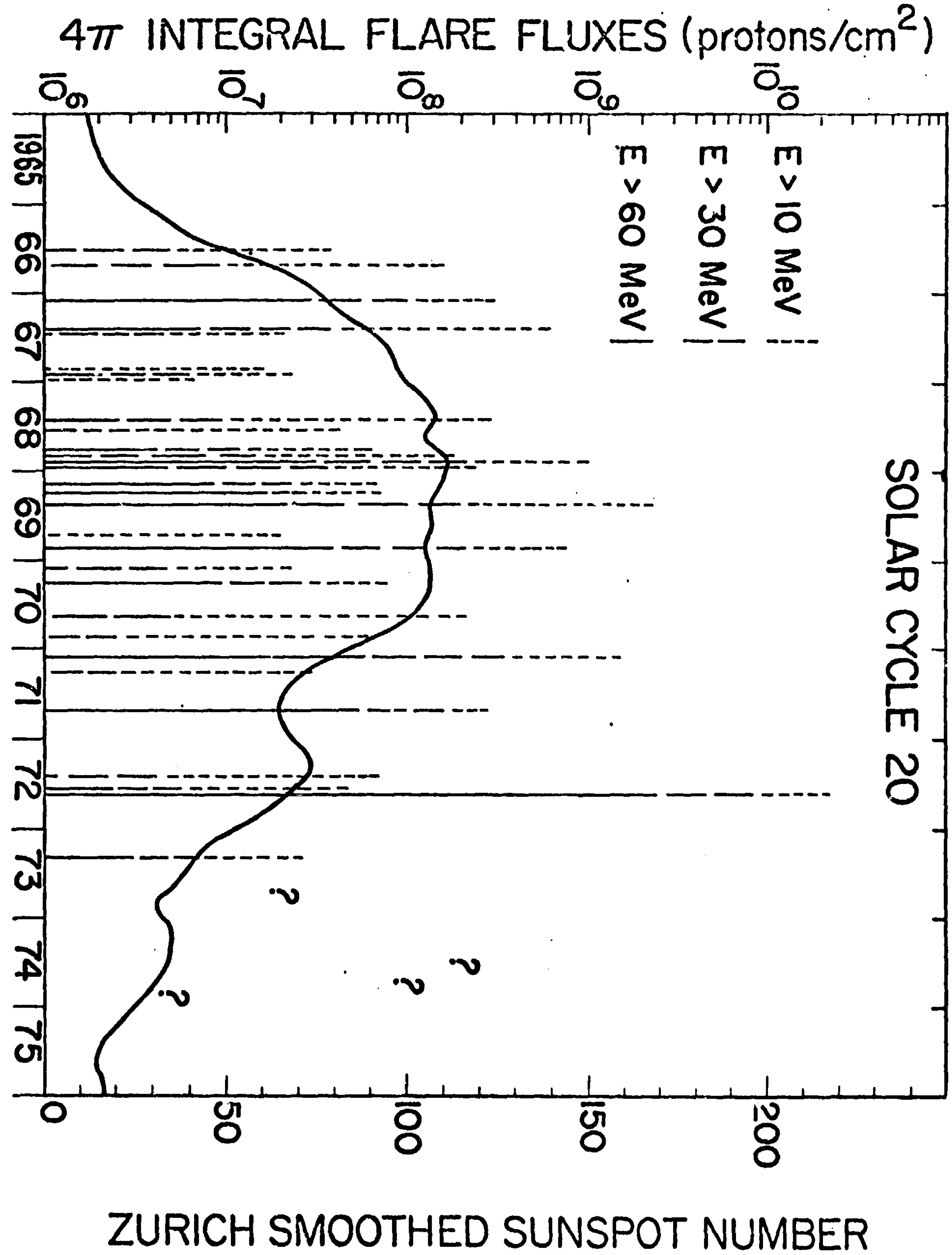

4π INTEGRAL FLARE FLUXES (protons/cm²)
10⁶
10⁷
10⁸
10⁹
10¹⁰
SOLAR CYCLE 19
E > 10 MeV
E > 30 MeV
E > 100 MeV
1954
55
56
57
58
59
60
61
62
63
64
0
50
100
150
200
ZURICH SMOOTHED SUNSPOT NUMBER

FIG. 1



4π INTEGRAL FLARE FLUXES (protons/cm²)
10⁶
10⁷
10⁸
10⁹
10¹⁰
E > 10 MeV
E > 30 MeV
E > 60 MeV
SOLAR CYCLE 20
1965
66
67
68
69
70
71
72
73
74
75
0
50
100
150
200
ZURICH SMOOTHED SUNSPOT NUMBER

FIG. 2

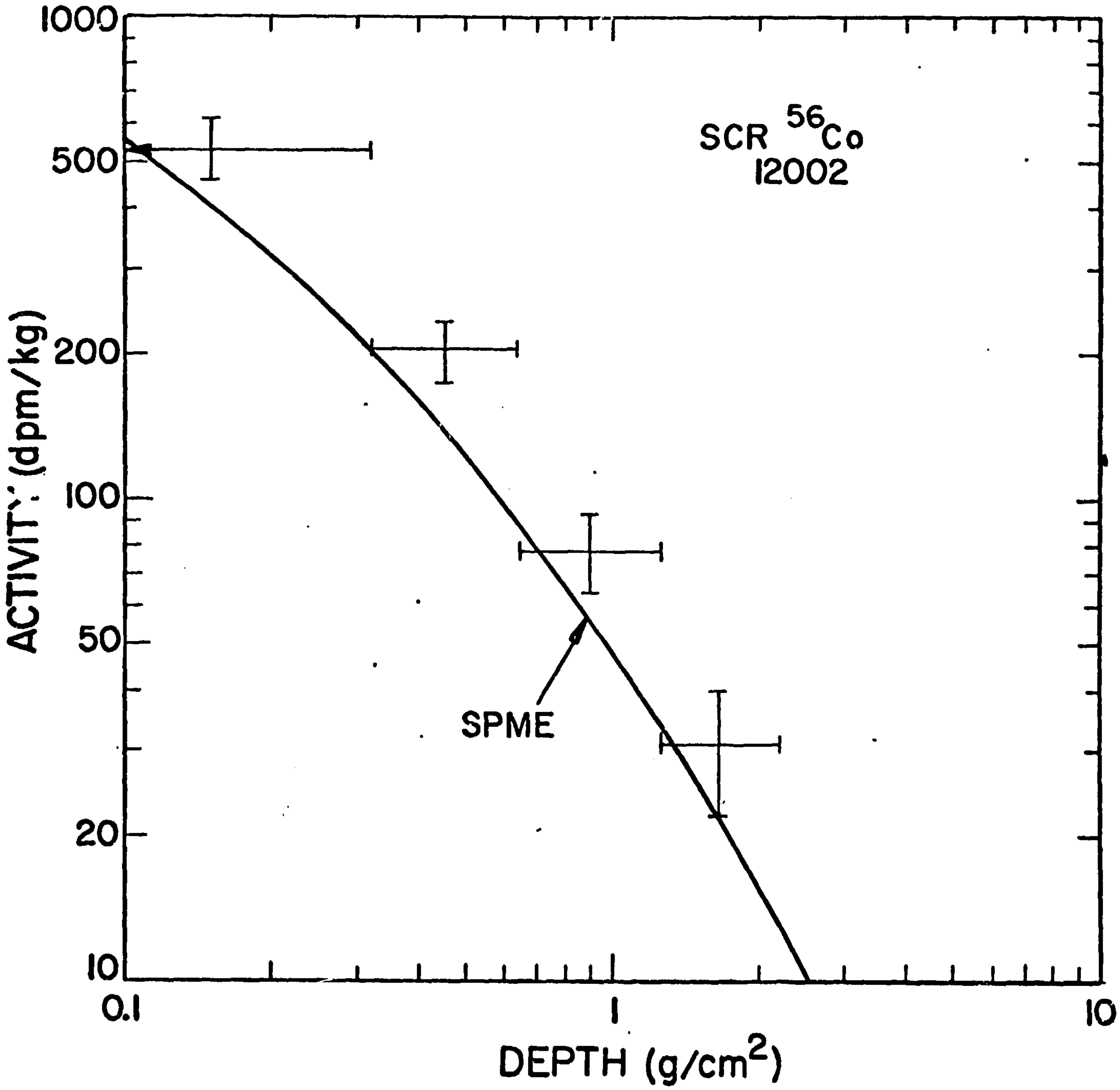
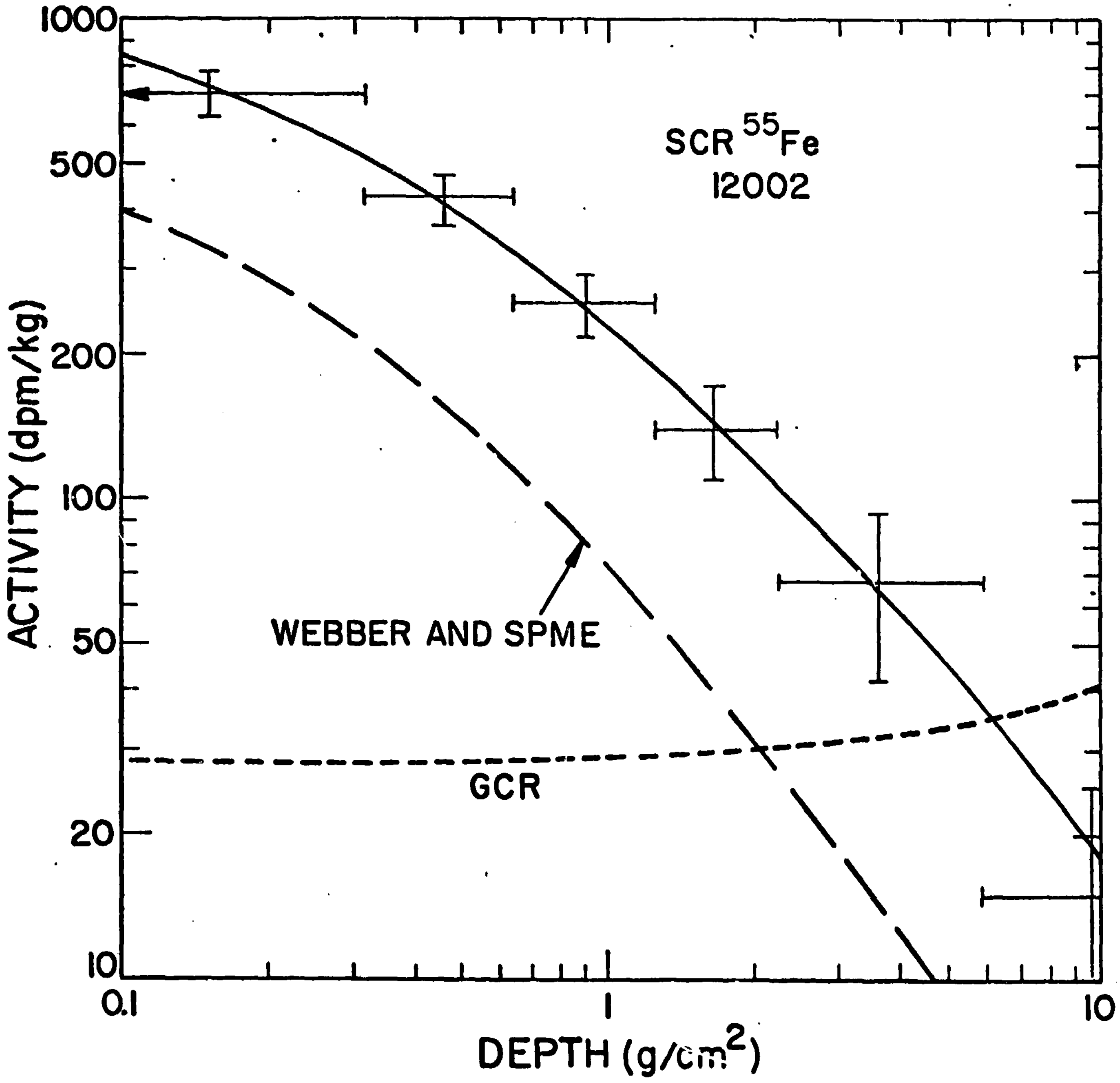
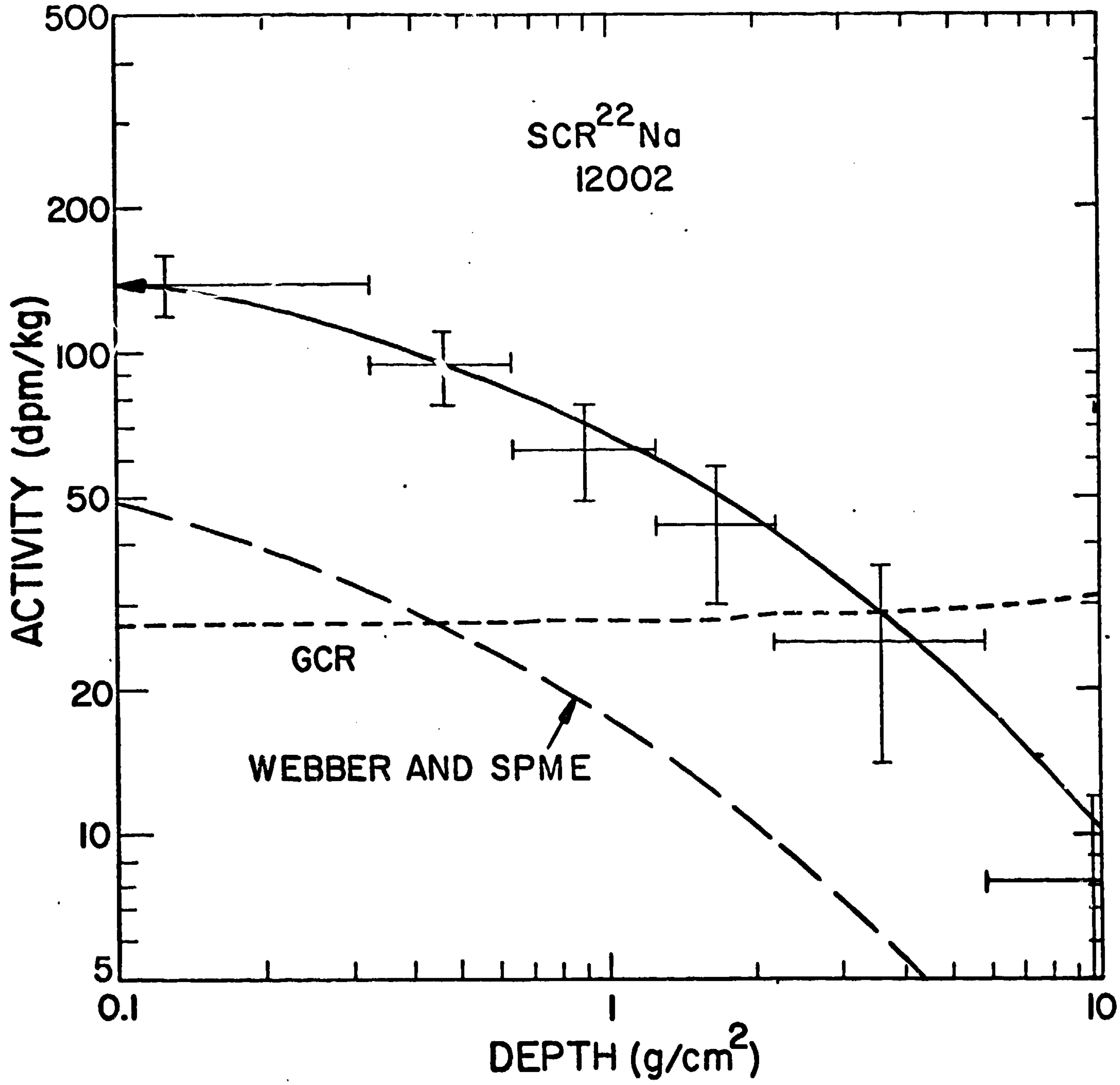

SCR ^{56}Co
12002
SPME
1000
500
200
100
50
20
10
ACTIVITY (dpm/kg)
0.1
1
10
DEPTH (g/cm^2)

FIG. 3



1000
500
200
100
50
20
10
ACTIVITY (dpm/kg)
SCR ^{55}Fe
12002
WEBBER AND SPME
GCR
0.1
1
10
DEPTH (g/cm^2)

FIG. 4



500
200
100
50
20
10
5
0.1
1
10
ACTIVITY (dpm/kg)
DEPTH (g/cm2)
SCR 22Na
12002
GCR
WEBBER AND SPME

FIG. 5

Table 1

Omnidirectional (4π) integral fluxes of solar protons from flares during solar cycle 19 (1954-1964) in units of 10^7 protons/cm^2 above energies of 10, 30, or 100 MeV.[a]

Flare Date	>10 MeV	>30 MeV	>100 MeV	Source[b]
2/23/56	180.	100.	35.	
8/31/56	8.	2.5	0.6	
11/13/56	40.[c]	10.	1.5	Weddell *et al* (1966)
1/20/57	160.[c]	20.	0.7	
4/3/57	24.[c]	5.	0.5	Weddell *et al* (1966)
6/21/57	73.[c]	15.	1.5	Weddell *et al* (1966)
7/3/57	14.[c]	2.	0.1	
8/29/57	116.[c]	12.	0.3	
8/31/57	39.[c]	8.	0.8	Weddell *et al* (1966)
9/2/57	26.[c]	5.	0.45	Weddell *et al* (1966)
10/20/57	17.[c]	5.	1.	
3/23/58	200.	25.	1.	
7/7/58	180.	25.	0.9	
8/16/58	40.	4.	0.16	
8/22/58	80.	7.	0.18	
8/26/58	150.	11.	0.2	
2/13/59	12.[c]	2.8	0.36[c]	Modisette *et al* (1965)
5/10/59	550.	96.	8.5	
6/13/59	45.[c]	8.5	0.7	Weddell *et al* (1966)
7/10/59	450.	100.	14.	
7/14/59	750.	130.	10.	
7/16/59	330.	91.	13.	
9/2/59	6.4[c]	1.2	0.1	
9/3/60	9.	3.5	0.7	
11/12/60	400.	130.	25.	
11/15/60	250.	72.	12.	
11/20/60	14.	4.5	0.8	
7/12/61	50.	4.	0.1	
7/15/61	7.2[c]	1.3	0.1	Weddell *et al* (1966)
7/18/61	100.	30.	4.	
9/10/61	19.[c]	4.	0.4	Weddell *et al* (1966)
9/26/63	29.[c]	6.	0.6	Weddell *et al* (1966)
Cycle Total	4368.6	941.3	135.25	

[a]Only flares with integral fluxes above 30 MeV greater than 10^7 protons/cm^2 are given.

[b]Data from Webber *et al* (1963) unless otherwise specified.

[c]Extrapolated from fluxes for other energies.

Table 2

Omnidirectional (4π) integral fluxes of solar protons from flares during solar cycle 20 (1965-75) in units of 10^7 protons/cm^2 above energies of 10, 30, or 60 MeV.[a]

Flare Date	>10 MeV	>30 MeV	>60 MeV	Source[b]
2/5/65	2.5	0.66	0.17	Webber (1966)
7/7/66	3.8	0.50	0.15	King (1974)
9/3/66	16.	0.9	0.1	Kinsey (1969)
1/28/67	30.	10.	3.	Kinsey (1969), Blake et al (1969)
5/25/67	54.	2.1	0.2	
5/28/67	7.2	1.7	0.53	
6/6/67	2.1	0.45	0.11	
12/3/67	2.3	0.62	0.21	
6/9/68	29.	0.95	0.26	c
7/6/68	4.2	0.29	0.15	
9/29/68	2.8	0.9	0.38	c
10/4/68	3.2	0.3	0.04	
10/31/68	6.1	0.4	0.054	
11/1/68	11.	0.83	0.069	
11/4/68	1.0	0.24	0.066	
11/18/68	100.	21.	3.1	c
12/6/68	24.	3.6	0.48	c
2/26/69	6.8	2.3	0.86	c
3/30/69	7.2	2.8	1.7	
4/12/69	230.	20.	2.2	c
11/2/69	75.	21.	4.0	c
1/31/70	2.3	0.48	0.135	
3/29/70	7.8	2.6	0.91	
8/15/70	21.	0.46	0.069	
11/6/70	6.1	0.25	0.059	
1/24/71	150.	33.5	5.9	c
4/6/71	3.0	0.25	0.04	
9/2/71	38.	16.	5.7	
5/29/72	7.1	0.42	0.12	
7/22/72	4.8	0.57	0.24	
8/4/72	2000.	800.	240.	d
8/7/72	240.	38.	6.	d
4/30/73	2.7	0.72	0.31	
Cycle Total	3101.0	984.8	277.31	

[a] Only flares with integral fluxes above 30 MeV greater than 2 x 10^6 protons/cm^2 are given.

[b] Data from the Solar Proton Monitor Experiment (SPME), Bostrom et al (1967-1973) unless otherwise specified.

[c] C. O. Bostrom (Pers. Comm.), based on SPME data.

[d] J. W. Kohl et al (1973), based on SPME data.

Table 3

Calculated equivalent-steady-state omnidirectional proton fluxes (in protons/cm^2 s) above several proton energies (in MeV) for various radionuclides at the time of the Apollo 12 mission.

	^{56}Co	^{54}Mn	^{22}Na	^{55}Fe	^{3}H
J(>10), cycle 19	0	0.36	23.1	24.6	43.0
J(>10), cycle 20	105.4	79.4	40.0	38.9	10.4
J(>30), cycle 19	0	0.09	5.09	5.40	9.27
J(>30), cycle 20	22.7	12.7	6.05	5.88	1.54
J(>60), cycle 20	4.24	2.34	1.14	1.11	0.30
J(>100), cycle 19	0	0.012	0.70	0.74	1.31

Table 4

Observed and calculated activities of solar-proton-produced ^{56}Co and ^{54}Mn in lunar rocks.

Rock	Depth (mm)	^{56}Co (dpm/kg) obs.[a]	calc.[b]	^{54}Mn (dpm/kg) obs.[a]	calc.[b]
10017	0-4	124±20	190	15±21	24
10017	4-12	<16	10	17±27	6
12002	0-1	523±70	480	77±19	50
12002	1-2	204±30	135	56±14	29
12002	2-4	79±15	57	31±14	17
12002	4-7	31±9	21	28±12	9
12002	0-7	141±12	113	40±5	20
12002	9-20	---	4	15±12	3
14321	0-2	219±45	229[c]	---	26[c]
14321	2-5	77±30	39	---	11
14321	0-5	132±37	113[c]	26±14	17[c]

[a]Measured activities of Shedlovsky *et al* (1970) for 10017, of Finkel *et al* (1971) for 12002, and Wahlen *et al* (1972) for 14321, less GCR contributions.

[b]Using the evaluated solar-proton fluxes of Tables 1 and 2.

[c]Calculated assuming that some surface material was lost prior to analysis, cf. Wahlen *et al* (1972).

Table 5

Observed and calculated activities of solar-proton-produced ^{22}Na and ^{55}Fe in lunar rocks.

Rock	Depth (mm)	^{22}Na (dpm/kg) obs.[a]	calc.[b]	calc.[c]	^{55}Fe (dpm/kg) obs.[a]	calc.[b]	calc.[c]
10017	0-4	60±15	25	86	396±93	167	410
10017	4-12	22±12	6.5	36	42±48	26	104
12002	0-1	139±20	45	132	703±72	347	749
12002	1-2	94±17	27	93	426±51	153	400
12002	2-4	63±14	18	70	256±38	81	246
12002	4-7	44±14	12	49	141±32	38	140
12002	0-7	70±5	21	73	294±17	111	294
12002	9-20	25±11	5	25	68±26	12	55
14321	0-2	91±15	36[d]	93[d]	294±42	142[d]	286[d]
14321	2-5	46±11	16	53	119±24	42	110
14321	0-5	64±13	24[d]	69[d]	187±32	81[d]	179[d]

[a]Same sources as data in Table 4.

[b]Using only the evaluated fluxes of Table 1 and 2.

[c]Using the evaluated fluxes, plus the extra flux for cycle 19 (cf. text).

[d]Calculated assuming that some surface material was lost prior to analysis, cf. Wahlen et al (1972).

Table 5

Average omnidirectional fluxes (in protons/cm^2 s) of solar protons above several energies, and peak values of sunspot numbers, for solar cycles 20 and 19 and for the last million years.

Energy	Cycle 20[a]	Cycle 19[a]	10^6 y[b]
> 10 MeV	89	378	85
> 30 MeV	28	136	31
> 60 MeV	8.0	59	11
>100 MeV	---	26	4
Sunspot Max.[c]	110	201	100[d]

[a] Proton fluxes for these cycles are averaged over 11 years. Cycle 19 includes the extra flux discussed in the text.

[b] From Wahlen et al (1972), based on data for 0.73-My ^{26}Al and 3.7-My ^{53}Mn.

[c] Peak values of the Zurich smoothed sunspot number (from various volumes of Solar Geophysical Data.)

[d] Approximate mean of peak sunspot number for solar cycles 1 to 20 (about 1750 to 1975).

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