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STATISTICAL EVALUATION OF PROTON RADIATION FROM SOLAR FLARES

FINAL TECHNICAL REPORT

JPL CONTRACT 951293

29 JULY 1966

NORTH AMERICAN AVIATION, INC.
SPACE and INFORMATION SYSTEMS DIVISION

This work was performed for the Jet Propulsion Laboratory, California Institute of Technology, sponsored by the National Aeronautics and Space Administration under Contract NAS7-100.

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SPACE and INFORMATION SYSTEMS DIVISION

FOREWORD

This report describes the technical methods and results of effort on Contract 951293 with Jet Propulsion Laboratory, California Institute of Technology.

The authors appreciate the benefit of discussions with E. P. Divita of Jet Propulsion Laboratory. The assistance of Dorothy Steelman with the literature survey, data processing, and preparation of illustrations is gratefully acknowledged. R. Howard of Mount Wilson Observatory kindly permitted the reproduction of solar magnetograms.

SUMMARY

The occurrence probability of solar high energy proton radiation has been evaluated statistically as a function of radiation flux, solar activity level, and solar distance. The results are applicable to determining the solar proton radiation environment of spacecraft in interplanetary space between 1 and 2 astronomical units (AU) in the 1969 to 1975 time period.

Previous tabulations of solar proton event characteristics have suffered from incompleteness and inconsistencies. A literature survey permitted a new tabulation of solar flare times and positions, proton radiation event onset, rise and decay times, and proton fluxes above 10, 30, and 100 Mev at 1 AU. At least partial data of 76 proton radiation events were established from direct observations described in the literature. From these data, an analytical representation expressing the temporal variation of the proton flux as a function of proton energy and total flux per radiation event was derived. This representation was used to estimate flux data not available from experimental results. The annual fluxes and the frequency distribution of radiation events versus flux per event were then calculated.

To estimate the probability distribution of expected solar proton radiation levels from 1969 to 1975, the sunspot number in these years was predicted by extrapolating the Fourier transformation of the sunspot numbers from 1749 to 1964. The correlation coefficient of the annual proton flux versus energy with the sunspot numbers from 1956 to 1963 was calculated. It was then possible to calculate the most probable proton fluxes versus energy for each year from 1969 to 1975, as well as the confidence levels of these flux values. The occurrence frequency distribution of solar proton radiation events was also correlated with the sunspot number, and the results were used to predict the most probable number of proton events of various sizes for each year from 1969 to 1975.

The long-term average flux predictions were supplemented by establishing correlations between the occurrence probabilities of individual solar flares and observable predicable solar activity parameters. These parameters were (1) the area, duration, and luminosity of calcium plage regions; (2) the existence of stationary points of zero magnetic field in dipolar magnetic regions; and (3) decreases of the sea-level neutron flux that precede some solar flare proton radiation events.

Theoretical analyses were used to evaluate the temporal variation of the solar proton flux versus energy as a function of solar distance. These analyses assumed (1) acceleration of protons by hydromagnetic shock waves

induced in the solar corona by absorption of light emitted by a flare; (2) motion of protons in the quiescent interplanetary magnetic field; and (3) random walk of energetic protons captured in the disordered magnetic fields associated with local concentrations of plasma in interplanetary space.

Three aspects of the solar proton radiation environment permit evaluation of the probability distribution of the environment level experienced on a trajectory between 1 and 2 AU during the 1969 to 1975 time period. These aspects are the radiation event occurrence frequency distribution as a function of flux per event and stage of the sunspot number cycle, the analytical representation of the flux versus time and energy in an individual event at 1 AU, and the dependence of the environment on solar distance. Application of these aspects to mission environment analysis is illustrated for the example of an earth-Mars trajectory in 1971.

Recommendations for additional study include analysis of angular distributions of the radiation flux versus time and energy, evaluation of the environments of energetic solar electrons, alpha particles and heavy nuclei, and extension of the solar distance range to 0.3 and 5 AU.

CONTENTS

TABLES

ILLUSTRATIONS

I. INTRODUCTION

PREVIOUS RADIATION ENVIRONMENT MODELS

The design and operational philosophy of space vehicles and their components must be based on knowledge or assumptions concerning the environments that they are expected to encounter. The environment of charged particles, especially protons, at high kinetic energies is one to which many subsystems are sensitive. The significant proton radiation beyond the geomagnetic field is that originating at the sun; only protons associated with solar activity are discussed in this report. It is generally impossible to define this environment exactly, and models must be developed which express the probability of encountering various proton radiation levels.

Early attempts to provide models of the proton radiation environment were directed at establishing an upper envelope of the proton flux versus energy associated with a single solar flare (Reference 1). Later, the time-dependent flux versus energy distributions of several flare-associated increases of the proton radiation level were used to construct models of the proton flux as a function of energy and time after the flare (Reference 2). These models were also nearly envelopes of actual solar proton radiation events and did not represent the frequency of occurrence of events of various sizes. The desirability of establishing total flux encounter probabilities led to models (Reference 3) that expressed these probabilities as functions of proton energy and mission duration. The dependence of the expected environment on the stage of general solar activity and on solar distance are of great importance in planning and implementing future planetary exploration missions, and have not previously received quantitative consideration.

PROGRAM OBJECTIVE

The objective of this program is to evaluate the environment of high-energy proton radiation associated with solar flares in interplanetary space at distances from 1 to 2 astronomical units (AU) from the sun in 1969 to 1975. The results will be applicable to spacecraft environmental analysis and design.

TASK DESCRIPTION

In order to accomplish the general program objective, this effort was organized into six tasks with the following objectives:

1. Perform a literature survey of solar flare events for which protons have been observed, and prepare a table of characteristics of these events.

2. Establish statistical correlations between solar flare proton events and predictable solar phenomena.

3. Determine the occurrence probability of solar flare proton radiation characteristics.

4. Evaluate the spatial dependence of solar flare high-energy proton radiation characteristics.

5. Establish a method of evaluating the solar flare proton environment in space, and illustrate the method by application to a spacecraft trajectory in interplanetary space.

6. Prepare and submit reports as required, and provide for reviews of progress.

II. PROTON RADIATION EVENT TABULATION

LITERATURE SURVEY

While galactic (cosmic) radiation has been studied since 1913, the earliest measurements that suggested that the sun was a source of energetic particle radiation were made in 1942. The issue remained in doubt until 1956, when the unusual solar proton event of February 23 convinced even the skeptics. Since that date, approximately 100 events in which high-energy (Mev) protons were emitted from the sun have been recorded.

In order to prepare a table of the dates and characteristics of these events, a literature search was undertaken. In the initial stage, this search was based upon previous tabulations of solar proton events (References 4, 5, 6, and 7). These references not only led to a number of additional references relevant to solar proton events, but they also provided the bulk of the information for the list of the characteristics of the observed proton events.

The second stage of the literature search involved examining the indexes of standard technical journals in the field. The journals examined were:

(United States and Canada)

Journal of Geophysical Research (formerly Journal of Terrestrial Magnetism)

The Physical Review

Physical Review Letters

Canadian Journal of Physics

The Astronomical Journal

The Astrophysical Journal

Journal of Atmospheric and Terrestrial Physics

Science

Journal of the Royal Astronomical Society of Canada

(Western Europe)

Planetary and Space Sciences

Nature

Il Nuovo Cimento

Comptes Rendus

Space Science Reviews

Astronautica Acta

Space Research (COSPAR)

Monthly Notices of the Royal Astronomical Society

(Eastern Europe-English translations only)

Soviet Physics-JETP

Proceedings of the USSR Academy of Sciences

Geomagnetism and Aeronomy

Soviet Physics - Doklady

(Abstract Journals)

Physics Abstracts

Scientific and Technical Aerospace Reports (STAR)

International Aerospace Abstracts

As expected, the Journal of Geophysical Research yielded the most relevant information, followed by The Physical Review. For the early events (prior to 1956), The Physical Review was almost the sole source of information. The abstract journals were invaluable for locating articles written in languages other than English and reports not published in one of the standard journals.

Each journal was searched, starting with the most recent (generally December 1965 or January 1966) issue and going backward until it was apparent that further search had a very low probability of yielding anything.

For many of the journals, this cutoff point was January 1956, since those that failed to report the event of 23 February 1956 would not be expected to contain articles on earlier solar proton events. The Astrophysical Journal, The Astronomical Journal, and The Physical Review were searched back to 1950. The 19 November 1949 event was responsible for the first articles, although subsequent articles reported events that had been observed as early as 1942.

The references were divided into two groups — those concerned primarily with one event were categorized by month and year of that event (See Appendix A); those that referred to several events were categorized by the characteristic emphasized. Categories selected were:

Prediction of solar flares

Origin of solar flares

Source of solar flare particles and solar radio bursts

Propagation of solar flare particles

Spatial distributions of solar flare particles

Cosmic ray effects

Energy spectra of solar flare particles

Polar cap absorptions

Geomagnetic disturbances related to solar flares

Ionization and reactions in the earth's atmosphere

Miscellaneous

These lists of references appear in Appendix A. To prevent duplications and to facilitate study of the material, each list of references is presented in chronological order according to publication date.

DATA TABULATION

The first sources of information used in the table of solar flare and proton radiation event data (Table 1) were previously prepared tables of a similar nature (References 3, 4, 6, 8, and 9). The initial list prepared from

Table 1. Solar Flare and Proton Event Data

Solar Flare Data						Solar Particle Data				
Date Event No.	Time	Lat.	Long.	Plage	Imp.	Minimum Energy (Mev)	t (hours)	τ (hours)	$\hat{\phi}$ (p/cm^2-sec)	$\int \phi$ (p/cm^2)
2-28-42	1200	N 07	E 04		3	10			5,000*	1×10^9*
1						30	12*	25*	1,000*	1.5×10^8*
**						100	6-8*	15*	200*	1.5×10^7*
3-7-42	0442	N 07	W 90		?	10			7,000*	1.5×10^9*
2						30	12*	30*	1,500*	2×10^8*
**						100	8*	16*	250*	2×10^7*
7-25-46	1620	N 29	E 15		3+	10			10,000*	2×10^9*
3						30	10-15*	30*	2,000*	2.5×10^8*
**						100	8*	17*	400*	3×10^7*
5-11-49	2010	S 20	E 12		3+	10			1,000*	2×10^8*
4						30	10*	20*	200*	2×10^7*
**						100	5*	12*	30*	2×10^6*
11-19-49	1034	S 05	W 74		3	10			12,000*	3×10^9
5						30	12-15*	30*	3,000*	5×10^8*
**						100	8-10*	20*	600*	5×10^7*
1-27-51						10			2,000*	3×10^8*
6						30	10-12*	20-25*	300*	3×10^7*
**						100	6-8*	12-15*	50*	3×10^6*
5-16-51	1702	N 15	W 05		2	10			3,000*	5×10^8*
7						30	10-12*	25*	500*	5×10^7*
**						100	6-8*	15*	100*	5×10^6*
1-17-52						10			1,500*	2×10^8*
8						30	10*	20-25*	250*	3×10^7*
**						100	5-8*	10-15*	40*	3×10^6*

*Estimated value (see Sections II and IV).
**Characteristics estimated from balloon-borne ionization chambers and/or sea level neutron monitor data.
***Probably no patrol.

Table 1. Solar Flare and Proton Event Data (Cont)

Solar Flare Data						Solar Particle Data				
Date Event No.	Time	Lat.	Long.	Plage	Imp.	Minimum Energy (Mev)	t (hours)	τ (hours)	$\hat{\phi}$ (p/cm^2-sec)	$\int \phi$ (p/cm^2)
2-23-56 9	0340	N 22	W 74	3400	3+	10			10,000	1.8×10^9
						30	6-8	30	8,000	1.0×10^9
						100	3-4	16	5,000	3.5×10^8
8-31-56 10	1241	N 16	E 16	3643	3	10			300*	8×10^7*
						30	15*	36	150	2.5×10^7
						100	8-10*	20*	60	6×10^6
11-13-56 11	1501	N 16	W 10	3753	2+	10			4,000*	8×10^8*
						30	12*	25*	800*	1.0×10^8
						100	7*	16*	150*	1.5×10^7*
1-20-57 12	1120	S 25	W 30	3820	3+	10			30,000*	5×10^9*
						30	10*	24	2,000*	3×10^8
						100	8*	18*	100	1×10^7
4-3-57 13	0835	S 15	W 60	3907	3	10			2,400*	4×10^8*
						30	11*	23*	450*	5.0×10^7
						100	7*	15*	70*	5×10^6*
6-21-57 14	1780*	N 14	E 02		2	10			5,000*	1.0×10^9*
						30	12*	26*	1,000*	1.5×10^8
						100	7*	16*	200*	1.5×10^7*
7-3-57 15	0740	N 14	W 40	4039	3+	10			20,000*	2×10^8*
						30	2*	5*	2,000	2×10^7
						100	1-2*	3*	100	1×10^6*

Table 1. Solar Flare and Proton Event Data (Cont)

Solar Flare Data						Solar Particle Data				
Date Event No.	Time	Lat.	Long.	Plage	Imp.	Minimum Energy (Mev)	t (hours)	τ (hours)	$\hat{\phi}$ (p/cm^2-sec)	$\int \phi$ (p/cm^2)
7-24-57 16	1827	S 24	W 27	4070	2	10 30 100	 9* 5*	 20* 12*	600* 100* 15*	8×10^7* 7.5×10^6 7.7×10^5
8-9-57 17	0628	S 09	E 75	4099	2	10 30 100	 8* 5*	 18 12*	150* 20 2*	1.5×10^7* 1.5×10^6 1×10^5*
8-29-57 18	0555 1037	N 24 S 25	E 35 E 20	4124 4125	2 2	10 30 100	 25* 15*	 60 40*	10,000* 600 30	2×10^9* 1.2×10^8 3×10^6
8-31-57 19	0552 0552 1312	S 31 N 13 N 25	W 02 E 03 W 02	4125 4124 4124	2+ 2 3	10 30 100	 11* 7*	 25* 15*	3,000* 600* 100*	6×10^8* 8×10^7 8×10^6
9-2-57 20	1303 1316	N 10 S 34	W 26 W 36	4124 4125	1+ 2+	10 30 100	 11* 7*	 24* 15*	2,500* 400* 70*	4×10^8* 5.0×10^7 4.5×10^6
9-12-57 21	1516	N 11	W 18	4134	2	10 30 100	 8* 5*	 18* 11*	400* 60* 8*	6×10^7* 6.0×10^6 5×10^5
9-21-57 22	1338	N 10	W 06	4152	3	10 30 100	 10* 7*	 24 15-20*	600* 100 15*	1.5×10^7* 1.5×10^6 1×10^5*

Table 1. Solar Flare and Proton Event Data (Cont)

Solar Flare Data						Solar Particle Data				
Date Event No.	Time	Lat.	Long.	Plage	Imp.	Minimum Energy (Mev)	t (hours)	τ (hours)	$\hat{\phi}$ (p/cm^2-sec)	$\int \phi$ (p/cm^2)
9-26-57 23	2000*	N 22	E 15		3	10 30 100	 7* 4*	 15* 9*	50* 6* 1*	6×10^6* 4×10^5* 2.0×10^4
10-20-57 24	1642	S 26	W 45	4189	2+	10 30 100	 12* 8*	 30 20*	1,500* 500 140	2×10^8* 5×10^7 1×10^7
11-4-57 25	***					10 30 100	 8* 5*	 18 12*	350* 50 5*	1×10^8* 9×10^6 8×10^5*
2-9-58 26	2142	S 12	W 14	4404	2+	10 30 100	 8* 5*	 18 12*	5,000* 1,000 200*	5×10^7* 5×10^6 4×10^5
3-23-58 27	1005	S 14	E 78	4476	3+	10 30 100	 18* 8*	 40 20	8,000 1,200 100	2×10^9 2.5×10^8 1×10^7
3-25-58 28	0530 0603	N 17 S 15	E 25 E 50	4474 4476	2 2	10 30 100	 14* 9*	 30* 20*	18,000* 4,500* 900*	4×10^9* 6×10^8 7×10^7*
4-10-58 29	0100 0914	N 25 N 18	W 63 W 78	4485 4485	1 1+	10 30 100	 8* 5*	 18* 11*	350* 50 6*	5×10^7* 5×10^6 4×10^5*

Table 1. Solar Flare and Proton Event Data (Cont)

Solar Flare Data						Solar Particle Data				
Date Event No.	Time	Lat.	Long.	Plage	Imp.	Minimum Energy (Mev)	t (hours)	τ(hours)	$\hat{\phi}$(p/cm^2-sec)	$\int\phi$(p/cm^2)
7-7-58	0115	N 25	W 08	4634	3+	10			10,000	1.8×10^9
30						30	15*	32	1,500	2.5×10^8
						100	6-10*	16	100	9×10^6
7-29-58	0056	S 17	W 42	4659	2+	10			550*	8×10^7*
31	0303	S 14	W 44	4659	3	30	9*	20*	90*	8.5×10^6
						100	5-6*	12*	10*	7×10^5
8-16-58	0440	S 14	W 50	4686	3+	10			3,000	4×10^8
32						30	10	18	400	4×10^7
						100	6*	14*	20	1.6×10^6
8-21-58	1927	N 08	E 59		1	10			40*	4×10^6*
33						30	6-7*	14*	5*	3×10^5*
						100	4*	9*	<1*	1.9×10^4
8-22-58	1448	N 18	W 10	4708	3	10			6,000	8×10^8
34						30	10	20	600	7×10^7
						100	3	8-12	20	1.8×10^6
8-26-58	0027	N 20	W 54	4708	3	10			15,000	1.5×10^9
35						30	9	12	1,500	1.1×10^8
						100	5*	7*	50	2.0×10^6
9-22-58	0750	S 19	W 42	4765	2	10			600	9×10^7
36	1017	N 17	W 65	4756	2	30	15*	30	50	6×10^6
						100	8*	16*	1.5	1×10^5

Table 1. Solar Flare and Proton Event Data (Cont)

Solar Flare Data						Solar Particle Data				
Date Event No.	Time	Lat.	Long.	Plage	Imp.	Minimum Energy (Mev	t (hours)	τ (hours)	$\hat{\phi}(p/cm^2\text{-sec})$	$\int\phi(p/cm^2)$
5-10-59 37	2140	N 18	E 48	5148	3+	10 30 100	 20 12	 22 14	30,000 6,000 1,000	5.5×10^9 9.6×10^8 8.5×10^7
6-13-59 38	0400	N 17	E 57	5204	1+	10 30 100	 20* 12*	 40* 24	80* 9 1*	1×10^9* 8.5×10^7 7×10^6*
7-10-59 39	0240	N 20	E 66	5270	3+	10 30 100	 30 18	 40 20	15,000 4,000 1,200	4.5×10^9 1.0×10^9 1.0×10^8
7-14-59 40	0349	N 16	E 07	5269	3+	10 30 100	 16 12	 18 12	50,000 10,000 1,200	7.5×10^9 1.3×10^9 1.0×10^8
7-16-59 41	2145 2132	N 08 N 15	W 26 W 30	5269	3+ 3	10 30 100	 12 4	 30 18	18,000 6,000 1,500	3.3×10^9 9.1×10^8 1.3×10^8
8-18-59 42	1030	N 12	W 33		3	10 30 100	 27* 24	 30* 25*	150* 20 2*	2×10^7* 1.8×10^6 1×10^5*
9-2-59 43	2000*	N 12	E 60			10 30 100	 9* 6*	 20* 13*	800* 150* 20*	1×10^8* 1.2×10^7 1×10^6*

Table 1. Solar Flare and Proton Event Data (Cont)

Solar Flare Data						Solar Particle Data				
Date Event No.	Time	Lat.	Long.	Plage	Imp.	Minimum Energy (Mev)	t (hours)	τ(hours)	$\hat{\phi}$(p/cm²-sec)	$\int\phi$(p/cm²)
1-11-60 44	2100	N 23	E 03		3	10			25*	6×10^6*
						30	6	30	2.5	4×10^5
						100	4*	20*	0.2*	2.5×10^4*
3-29-60 45	0800*	N 11	E 30			10			400*	6×10^7*
						30	8*	18*	60*	6.0×10^6
						100	5*	11*	8*	5×10^5*
3-30-60 46	1540	N 12	E 12	5615	2	10			500*	7×10^7*
						30	7*	18*	60*	6.0×10^6
						100	4*	10*	6*	4×10^5
4-1-60 47	0858	N 12	W 10	5615	3	10			400	1.5×10^7
						30	2	6-12	200	5.0×10^6
						100	1	4	45	8.5×10^5
4-5-60 48	0245	N 10	W 61	5615	2+	10			150*	1.4×10^7
						30	3	12	20	1.1×10^6
						100	2*	8*	2*	7×10^4*
4-28-60 49	0130	S 05	E 34	5645	3	10			250	1.3×10^7
						30	3	8	120	5.0×10^6
						100	2	5	25	7×10^5
4-29-60 50	0220	N 12	W 20	5642	2	10			600*	7×10^7*
	0420	N 10	W 22	5642	3	30	9*	20*	100	7×10^6
	0554	N 14	W 20	5642	2	100	5*	11*	15*	6×10^5*

Table 1. Solar Flare and Proton Event Data (Cont)

Solar Flare Data						Solar Particle Data				
Date Event No.	Time	Lat.	Long.	Plage	Imp.	Minimum Energy (Mev)	t (hours)	τ(hours)	$\hat{\phi}$(p/cm^2-sec)	$\int\phi$(p/cm^2)
5-4-60 51	1020	N 14	W 90	5642	3+	10 30 100	 2-3 1	 8-14 4-6	150 100 40	1.2×10^7 6×10^6 1.2×10^6
5-6-60 52	1450	S 10	E 08	5653	3	10 30 100	 3 2*	 24 15*	300* 40 4*	4×10^7* 4×10^6 3×10^5*
5-13-60 53	0536	N 30	W 64	5654	3+	10 30 100	 3 2*	 15 10*	180 60 10	1.5×10^7 4×10^6 4.5×10^5
6-1-60 54	0844	N 28	E 46		3+	10 30 100	 2 1.5*	 20 12*	50* 5 0.4*	5×10^6* 4×10^5 3×10^4*
8-12-60 55	1940	N 22	E 27		3+	10 30 100	 10 7*	 50 35*	25* 3 0.3*	8×10^6* 6×10^5* 4×10^4*
9-3-60 56	0110	N 18	E 88	5838	3	10 30 100	 12-16 6-9	 32 26	450 200 60	9×10^7 3.5×10^7 7×10^6
9-26-60 57	0550	S 21	W 64	5858	2	10 30 100	 5* 3*	 10* 7*	300 40 4	2×10^7 2×10^6 1.2×10^5

Table 1. Solar Flare and Proton Event Data (Cont)

Solar Flare Data						Solar Particle Data				
Date Event No.	Time	Lat.	Long.	Plage	Imp.	Minimum Energy (Mev)	t (hours)	τ(hours)	$\hat{\phi}$(p/cm^2-sec)	$\int\phi(p/cm^2)$
11-12-60 58	1329	N 27	W 02	5925	3+	10 30 100	 10-16 8-10	 18-24 14-18	32,000 12,000 2,500	4×10^9 1.3×10^9 2.5×10^8
11-15-60 59	0221	N 30	W 32	5925	3+	10 30 100	 8-16 3-5	 16-20 8-12	22,000 8,000 2,400	2.5×10^9 7.2×10^8 1.2×10^8
11-20-60 60	2020	N 28	W 113	5925	3	10 30 100	 2-4 1	 10-16 4-6	2,200 1,000 400	1.4×10^8 4.5×10^7 8×10^6
7-11-61 61	1700	S 06	E 32	6171	3	10 30 100	 8-10 4	 22-26 18	120 30 3	1.7×10^7 3×10^6 3×10^5
7-12-61 62	1030	S 07	E 22	6171	3+	10 30 100	 8-12 6	 16-20 12	4,000 400 15	5×10^8 4×10^7 1×10^6
7-15-61 63	1440 1600 1512	N 14 S 07	E 13 W 20	6172 6172	3 2	10 30 100	 9* 5*	 20* 12*	800* 150* 20*	1×10^8* 1.3×10^7 1×10^6
7-18-61 64	1010	S 06	W 60	6171	3+	10 30 100	 6-10 2-3	 24 12	7,000 2,500 600	1×10^9 3×10^8 4×10^7

Table 1. Solar Flare and Proton Event Data (Cont)

Solar Flare Data						Solar Particle Data				
Date Event No.	Time	Lat.	Long.	Plage	Imp.	Minimum Energy (Mev)	t (hours)	τ(hours)	ϕ(p/cm^2-sec)	$\int\phi$(p/cm^2)
7-20-61 65	1620 1830	S 07	W 90	6171	3+	10 30 100	 4-6 1.5	 6-8 4	400 150 40	1.5×10^7 5×10^6 9×10^5
7-28-61 66	1920* 2180* 2145*	S 18 N 53 N 16	W 90 W 90 W 90	6175	1 1 1	10 30 100	 8* 5*	 18* 11*	400* 60* 7*	5×10^7* 4.4×10^6 4×10^5*
9-8-61 67	2200*	N 24	W 90		1	10 30 100	 8* 5*	 17* 11*	250* 40* 4*	3×10^7* 3.0×10^6 3×10^5*
9-10-61 68	2020	N 12	W 90	6212	1	10 30 100	 10 6-7*	 23* 14*	2,000* 350* 60*	3×10^8* 4×10^7 4×10^6*
9-28-61 69	2223	N 14	E 30	6235	3	10 30 100	 1.5 1	 12 8	500 150 36	5×10^7 6×10^6 1.1×10^6
11-10-61 70	1444	N 08	W 90	6264	2+	10 30 100	 9* 5-6*	 19* 12*	600* 90* 10*	8×10^7* 8×10^6 7×10^5*

Table 1. Solar Flare and Proton Event Data (Cont)

Solar Flare Data						Solar Particle Data				
Date Event No.	Time	Lat.	Long.	Plage	Imp.	Minimum Energy (Mev)	t (hours)	τ (hours)	$\hat{\phi}$ (p/cm^2-sec)	$\int\phi$ (p/cm^2)
2-23-62 71	1848	S 09	E 29	6351	1+	10 30 100	 2* 1*	 4* 2.5*	15* 1* <1*	1 x 10^6* 8 x 10^4* 4 x 10^3*
10-23-62 72	1708	N 02	W 71		2	10 30 100	 2 1.5*	 8 6*	16 4.5 0.5	6 x 10^5 1.2 x 10^5 1 x 10^4
2-9-63 73	***					10 30 100	 3* 2*	 7* 5*	6* 1* <1*	3 x 10^5* 2 x 10^4* 1 x 10^3*
4-15-63 74	1620	S 09	W 09	6766	2+	10 30 100	 7* 4*	 16* 10*	25* 2* <1*	5 x 10^6* 4 x 10^5* 3 x 10^4*
9-20-63 75	2351	N 10	W 09	6964	2+	10 30 100	 12* 8*	 30* 18*	10,000* 2,500* 500*	2 x 10^9* 3 x 10^8* 4 x 10^7*
9-26-63 76	0701	N 13	W 76	6964	3	10 30 100	 10* 7*	 25* 15*	3,000* 500* 100*	5 x 10^8* 6 x 10^7* 6 x 10^6*

these sources included some or all of the following data for each event and the flare most probably associated with each event:

Flare Data

Date of occurrence

Universal time of maximum

Heliographic latitude and longitude

Calcium plage region number, assigned by the McMath-Hulbert Observatory

Importance (1 - to 3 +)

Proton Radiation Event Data*

Onset plus rise time (t) in hours (from optical flash maximum to peak proton flux)

Characteristic decay time (τ) in hours (time in which proton flux decreases from peak to 1/e of peak)

Peak flux rate ($\hat{\phi}$) in p/cm^2 sec above energy E_o (Mev)

Integral flux ($\int\phi$) in p/cm^2 above energy E_o (Mev)

The solar proton data are generally given for particles above energies of 10, 30 and 100 Mev. However, frequently a complete set of the data for a given event (especially the early events) was not available. In particular, values of t (the onset plus rise time) and τ (the characteristic decay time) for protons above 10 Mev were not available for any of the events.

A secondary source of proton event information was Reference 10, which lists the integral fluxes for protons above 30 Mev for 52 events from 23 February 1956 to 10 November 1961. Of these events, fluxes for the following dates were not reported in the other compilations examined: 13 November 1956, 3 April 1957, 21 June 1957, 25 March 1958, 2 September 1959, 29 March 1960, 15 July 1961, 28 July 1961, 8 September 1961, 10 September 1961 and 10 November 1961.

Another very useful source of information for the early events was Reference 11, which, in addition to listing and providing information on nine events from 1947 to 1952, referenced earlier work pertaining to solar proton

*As observed at earth (1 AU)

events. Based on these articles, the following events were selected because the measurements (either by balloon-borne detectors or ground-based neutron monitors) indicated the presence of solar protons: 28 February 1942, 7 March 1942, 25 July 1946, 11 May 1949, 19 November 1949, 27 January 1951, 16 May 1951 and 17 January 1952. A problem arose in that the information desired for the table was not available directly. However, by comparing neutron monitor data (principally from Deep River, Canada) and ionization detector measurements (principally at Cheltenham, Maryland; Climax, Colorado; and Godhavn, Greenland) for these events with those for later events, estimates of the integral proton fluxes above 100 Mev were made.

The late 1962 and 1963 events presented a different kind of problem. The time required for data to be analyzed and reported in the literature appears to run from one to two years. Therefore, the only article of significance located for these events was that written by Geodeke and Masley (Reference 12). They report riometer attenuations at 30 Mcs for the following events: 23 February 1962, 23 October 1962, 9 February 1963 and 15 April 1963. The peak flux rate above 10 Mev was related to the maximum riometer attenuation by

$$\hat{\phi} > 10 \text{ Mev } (\text{p/cm}^2\text{-sec}) = 30 \ a^2 \quad (1)$$

where a is the attenuation in db. This relationship, obtained by fitting the data from Webber's table (Reference 4), is a reasonable average, although a factor of 3 variation is observed. By using this relationship, the peak flux rates above 10 Mev for these four events were estimated.

After these data were gathered, two problems presented themselves. One problem was to estimate the incomplete data for several of the events; the other problem was to reconcile differences in the data for those events which were reported by more than one source. The estimation of the missing data was carried out by use of the model event described in Section IV. Basically, this involved obtaining mathematical relationships that are reasonable approximations for those events for which all or most of the data are available and using these relationships to estimate the missing data from the available data. In this way, the entire event could be approximately reconstructed once a single flux, flux rate, rise, or decay time was known (provided the energy range represented was known). All of the missing data were estimated in this way. The estimated numbers are followed by an asterisk (*) in Table 1. The reconcilation of conflicts was sometimes carried out by use of the model event also. If a decision could not be made on the basis of reliability of measurement, reputation of author, or date of publication (later publications were favored), the data that best fit the other data (on the basis of the model) were used. The numbers finally selected are listed in Table 1.

In order to illustrate the techniques that were used to arrive at the numbers in Table 1, the event of 12 November 1960 will be considered. This event has been reported by many authors and discussed in some detail by Webber (Reference 13), Fitchel, Guss, and Ogilvie (Reference 14), Lewis et al (Reference 6), and several others. Unfortunately, the available measurements have not been collected by holding a symposium on the event, as was done for the July 1959 events (Reference 15).

One problem is to distinguish between primary references (in which authors report the results of direct measurements) and secondary refererces (in which authors report event characteristics based upon information obtained from the literature, private communication with other workers in the field, etc.). For example, various authors have used Webber's tabulations in their own publications. While secondary references are quite valuable in a study of this sort, it is important to prevent an artificial weighting of the results by citing a number of secondary references based upon one or a few primary references.

A brief summary of the reported characteristics of the event of 12 November 1960 is given in Table 2. These are either primary references or authoritative secondary references based upon a study of the available primary references. An integral flux of 1.2×10^9 p/cm^2 >30 Mev appears to be a common meeting ground, with the values of $\sim 2 \times 10^8$ being in units of p/cm^2-ster. Similarly, an integral flux of $\sim 3.5 \times 10^8$ p/cm^2 >100 Mev agrees with the published numbers. In a similar manner, peak flux rates of 12,000 p/cm^2-sec (>30 Mev) and 2,500 p/cm^2-sec (>100 Mev) were arrived at. Rise times of 10 to 16 hr (>30 Mev) and 8 to 10 hr (>30 Mev) and characteristic decay time of 18 to 24 hr (>30 Mev) and 14 to 18 hr (>100 Mev) were selected in a similar way.

In addition to the numbers reported in Table 1, several other references reporting characteristics of the 12 November 1960 event were found. Spectral shape information has been reported by de Feiter, Freon, and Le Grand (Reference 25), Kodama and Kitamura (Reference 26), Pomerantz, Duggal, and Nagashima (Reference 27), Conforto and Iucci (Reference 28), Lockwood and Shea (Reference 29), Roederer et al (Reference 30), and Ogilvie and Bryant (Reference 31). These references show that there seems to be a common meeting ground in the vicinity of an R^{-6} spectrum, although several authors point out that the spectral shape appeared to be too complex to be fit by a simple power law, either in rigidity or energy. The double peak in the neutron monitor data, reaching 2.1 times the normal sea-level counting rate, probably was related to this fact. The second peak has been interpreted as due to the influence of disturbed magnetic fields which "channeled" the solar plasma cloud to earth.

Table 2. Summary of 12 November 1960 Solar Proton Event Data

Ref.	t (hr)	τ (hr)	$\hat{\phi}$ (p/cm^2-sec)	$\int \phi$ p/cm^2
9	12-16 (>30 Mev) 8-10 (>100 Mev)	18-24 (>30 Mev) 14-18 (>100 Mev)	12,000 (>30 Mev) 2,500 (>100 Mev)	1.4 x 10^9 (>30 Mev) 3.5 x 10^8 (>100 Mev)
4	10 (>30 Mev) 8 (>100 Mev)	18 (>30 Mev) 14 (>100 Mev)	12,000 (>30 Mev) 2,500 (>100 Mev)	1.3 x 10^9 (>30 Mev) 2.5 x 10^8 (>100 Mev)
16				3.9 x 10^8 (>100 Mev) (includes 12-15 Nov) 4.7 x 10^9 (>30 Mev)
17			2,100 (>20 Mev) (p/cm^2-sec-ster)	2.2 x 10^8 (>20 Mev) p/cm^2-ster)
18				2-3 x 10^8 (>40 Mev) 4.8 -7.3 x 10^8 (>80 Mev) 2.6- 4.5 x 10^8 (>100 Mev)
19		10 (>30 Mev)	12,320 (>30 Mev)	
20	16 (>10 to 30 Mev)		5000 (>10 Mev) (p/cm^2-sec-ster) (21 db)	
21				1.6 x 10^8 $\frac{p}{cm^2}$ > *Mev
22				2.0 x 10^8 $\frac{p}{cm^2\text{-ster}}$ 20 Mev
23			1-10 x 10^3 $\frac{p}{cm^2\text{-sec-ster}}$	
24			50 $\frac{p}{cm^2\text{-sec-ster}}$ >80 Mev	αE -3 ± 0.3 at t = 30 hr

*Minimum energy not given.

A good summary of measurements made on this event is presented by Masley and Goedeke (Reference 32). However, it is our opinion that the 4π isotropy assumed throughout their analysis for the rocket and balloon altitude flux measurements is incorrect, especially since it results in a proton flux approximately six times that reported by other authors. This problem illustrates the difficulty of obtaining integrated flux numbers for the various events, since they must be inferred from indirect measurements (neutron monitors, riometers, etc.) and from a few flux rate measurements.

Since the numbers reported by Webber (Reference 4) agree with those selected for integral fluxes, peak flux rates, rise and characteristic decay times >30 and >100 Mev, his values were used for the integral flux and peak flux rate >10 Mev as well. However, had reported values for these parameters been unavailable, the technique for estimating them is straightforward. Based upon the available numbers, a value of A would have been chosen (Figures 19-22). For the event of 12 November 1960, A is $\sim 1.0 \times 10^8$, which leads to $\int \phi > 10$ Mev = 9×10^9 p/cm^2, and $\hat{\phi} > 10$ Mev = 36,000 p/cm^2-sec. These are the values that would have been used had not reliable published numbers ($\int \phi > 10$ Mev = 4×10^9 p/cm^2 and $\hat{\phi} > 10$ Mev = 32,000 p/cm^2-sec) been available. This not only illustrates how mission data were estimated but given an idea of the accuracy of the estimation technique used.

A number of very small events reported by Krimigis, Van Allen, and Frank (Reference 33), Van Allen (Reference 34), and Cline et al (Reference 35) have not been included in the table because of their size. Undoubtedly, there have been hundreds of such small events which have not be detected. However, it is the large events ($>10^7$ p/cm^2 >30 Mev) that control the annual proton fluxes and are of major interest from biological and material damage standpoints.

III. CORRELATIONS WITH SOLAR PARAMETERS

SELECTION OF CORRELATIONS

On the basis of the solar proton radiation event data presented in the preceding section, the future occurrence of events must be expected to be essentially random unless a means of predicting events can be established. It is clearly impossible to predict individual events farther into the future than the life-time of a typical active solar region, i.e., a few months. Since it is desired to evaluate the solar proton radiation environment in the 1969 to 1975 time period, an index of solar activity must be found which can be predicted several years in advance and which is strongly correlated with the mean flux of energetic protons associated with flares and with the frequency of solar proton radiation events.

Because of the generally cyclic but not fully periodic nature of solar activity, a reliable prediction of the future level of any activity index must be based on knowledge of past activity over many cycles. The sunspot number* is the only adequate activity index, having been observed continuously and uniformly since 1749, while other indices have been recorded only since 1913 or later. Sunspot data, therefore, exist for 19 complete cycles of mean duration 11.2 years, whereas no other activity data are consistently available for more than four cycles. As will be shown later, trends exist in the sunspot cycle which represent systematic changes over periods as long as 89 years; therefore, activity indices that have been recorded only for shorter periods are less capable of providing activity forecasts for future years.

The long-range prediction of mean levels of solar activity and flare-associated proton flux can be supplemented by methods applicable to the forecasting of individual proton radiation events from one to 35 days in advance. These methods are based on statistically significant relationships between observable characteristics of individual active regions and the future occurrence of solar flares at these regions. The utility of short-range forecasts of flares and, hence, of the likelihood of increases in the proton radiation environment level, for interplanetary missions lies in the ability to program and command evasive maneuvers (such as presentation of thick spacecraft sections toward the direction of approach of the most energetic protons) and the alteration of equipment operating modes (such as the telemetry cycle of a charged particle spectrometer). It is obvious that, in a flight

*The term "sunspot number" in this report refers to the monthly smoothed Wolf number (Zürich).

of several hundred days duration, at least one solar proton event will almost certainly occur. Short-range solar activity forecasts, therefore, are relevant to detailed spacecraft operations rather than to mission scheduling.

The characteristics of active solar regions selected as bases of flares prediction are the area, brightness, and luminosity of calcium plage regions and the presence of bipolar or complex magnetic regions in which the line separating areas of opposite polarity has no proper motion with respect to the solar photosphere (Reference 36).

Brightening in the chromospheric Ca II K_3 line is one of the earliest and most stable optical indications of the formation of an active region; therefore, plages promise a good opportunity for advance warning of flares. More transitory optical indices, such as the area of sunspot groups, do not afford sufficient stability for the reliable forecasting of activity more than a few (about three) days in advance (Reference 37).

Magnetic activity in a photospheric region often precedes optically observable activity and, as will be shown, allows the forecasting of flare occurrence probability with greater accuracy than is possible by means of plage observations alone.

An additional correlation, between solar proton events and previous slight decreases in the neutron flux near sea level, was investigated.

PROTON FLUX - SUNSPOT NUMBER

In order to evaluate the probability distribution of the mean flare-associated proton flux versus proton energy in 1969 to 1975, the correlation between this flux and the sunspot number must be established, and the probable sunspot number during these years must be estimated.

Sunspot Number Prediction

Although certain partial regularities, such as the basic cycle of mean duration 11.2 years, are evident in the temporal dependence of the sunspot number, the detailed behavior of this number is sufficiently complicated to require representation by a broad spectrum of component frequencies. If only the most important component frequencies such as those at 0.0112, 0.089, and 0.100 year^{-1} are used, the fluctuations in the sunspot number are still inadequately represented. Although there are presumably physical reasons underlying the sunspot cycle and its correlation with solar flare proton radiation occurrences, these reasons are too poorly understood to permit a theoretical and analytical approach to the problem of forecasting solar proton flux occurrence probabilities. It is necessary, therefore, to adopt a statistical approach which takes into account what may be truly random variations in the sunspot number and the solar flare proton flux level.

Let $R_M(t)$ be the monthly smoothed Wolf sunspot number at time t, where t = 0 on 1 July 1749 (Reference 38). The integral

$$\int_0^{t'} R_M(t)\, e^{-i\,2\pi ft}\, dt = \int_0^{t'} R_M(t)(\cos 2\pi ft - i\ \sin 2\pi ft)dt \tag{2}$$

has the amplitude which, when averaged over an infinite time interval, is equivalent to the sum of the Fourier sine and cosine integrals of $R_M(t)$ (Reference 39),

$$P(f) = \lim_{t' \to \infty} \frac{1}{t'} \left| \int_0^{t'} R_M(t)\, e^{-i2\pi ft} dt \right|^2$$

$$= \left[\int_0^{\infty} R_M(t) \sin 2\pi ft\ dt\right]^2$$

$$+ \left[\int_0^{\infty} R_M(t) \cos 2\pi ft\ dt\right]^2 \tag{3}$$

because of the orthogonality of the sine and cosine functions. The "power" P, i.e., the amplitude squared at frequency f, is defined as the frequency power spectrum of the sunspot number $R_M(t)$. Since R_M is known only during an interval of 216 years (actually a 215-year interval, 1749-1964, was used in this program), the limit in Equation 3 was approximated by an upper bound of $t' = 215$ years; therefore, the lower bound on f is 4.65×10^{-3} year^{-1}. An upper bound, $f_o = 0.2$ year^{-1}, was chosen because of the essential randomness of rapid fluctuations in R_M. The resulting spectrum of P(f) versus f is shown in Figure 1 (Reference 40), and the values and amplitudes of the 25 largest frequency components are presented in Table C2. Inspection of Figure 1 shows that any other components of the frequency power spectrum are negligible. Since $R_M(t'')$ is uniformly continuous piecewise on the interval ($1749.5 \leq t'' \leq 1976.0$), the only uncertainty in the use of Equation 4 is the one arising from the use of a finite number of components of the power frequency spectrum (Reference 39).

The sunspot number at time t" is the average of the frequency amplitude spectrum over the range of frequencies,

$$R_M(t'') = \left[\frac{1}{f_o} \int_{1/t'_m}^{f_o} P(f) \sin 2\pi f (t'' - t_o) df \right]^{1/2} \qquad (4)$$

where t'_m = 215 years and t_o is a time at which $R_M(t_o) = 0$. This value occurred only from February through December 1810, and so $t_o = 61.5 \pm 0.5$ year (after 1 July 1749). Then $R_M(t'') = 0$ at $t'' = 1810.5 \pm 0.5$, in accord with observation.

$R_M(t'')$ was calculated at each month from July 1749 through December 1969 by means of the computer program SPOTNO described and listed in Appendix C. The results were normalized so that the arithmetic mean deviation of predicted and observed maxima between 1749 and 1964 was zero. The time scale was translated so that the arithmetic mean deviation of predicted and observed dates of maxima between 1749 and 1964 was zero; this procedure is equivalent to the choice t_o = 65.2 year. In the normalization procedure, the un-normalized predicted maxima of $R_M(t'')$ have a mean value $\overline{R_M'}$ = 49.2, and the observed maxima of cycles 1 to 19 have a mean value $\overline{R_M}$ = 108.1. The calculated values of $R_M(t'')$ are then multiplied by the factor $(\overline{R_M}/\overline{R_M'}) = 2.20$. In the translation procedure, the unadjusted predicted maxima occur at times t'_i, i = 1 to 19, and the observed maxima occur at times t_i. The translation adds to each t'_i the amount δt = 0.47 year, so that

$$\sum_{i=1}^{19} (t_i' + \delta t - t_i) = 0$$

The dates and values of observed and predicted maxima of R_M are presented in Table 3. Observed and predicted values of R_M are shown in Figure 2 for recent cycles (15 through 19), and predicted monthly values during cycle 20 (January 1969 through December 1975) are also given. The distribution of deviations of observed and predicted maximum values of R_M is plotted in Figure 3 as a function of the standard deviation σ_R = 54.5. This distribution is fitted by a Gaussian distribution within statistical errors resulting from the population (19) of the sample of deviation values. The deviation of predicted from observed values of R_M is, therefore, random and not systematic. Comparison of predicted and observed sunspot numbers in the early part of cycle 20 (1964 to date) (Figure 2), shows reasonable agreement.

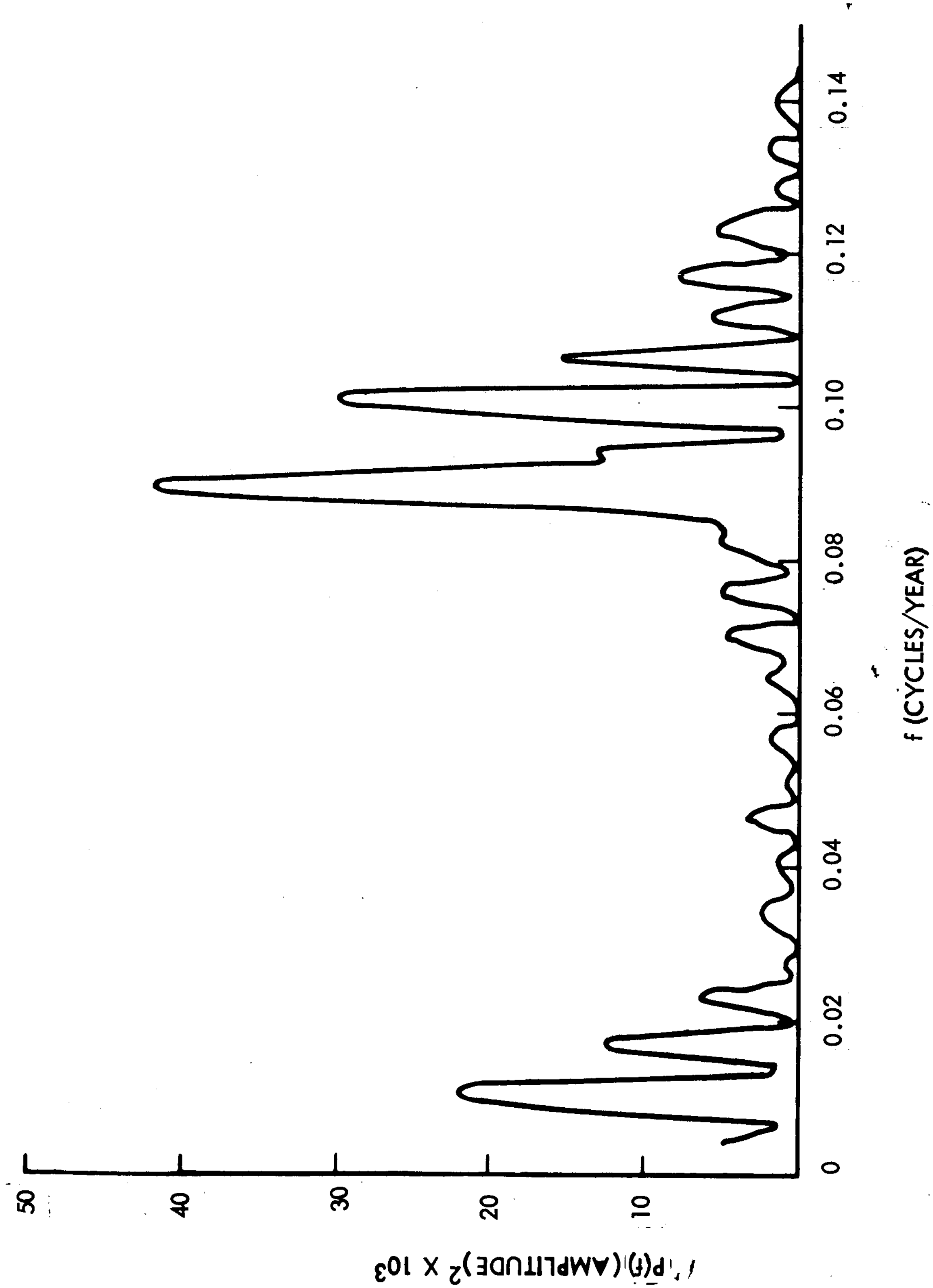

Figure 1. Sunspot Number Frequency Spectrum

An analysis (Reference 41) of the frequency distribution versus amplitude of sunspot number maxima led to the prediction of a maximum number of 135 in 1968, with probability 0.75 that this maximum will lie in the range $110 < R_M < 160$.

Using a correlation of R_M maxima with rise times from minimum to maximum, King-Hele (Reference 42) has predicted a maximum of $R_M = 140$ in February 1968; he does not give the standard deviations of these values.

As an alternate approach to development of a formal representation of the behavior of the sunspot number, an attempt was made to fit $R_M(t)$ by a polynomial

$$R_M(t) = \sum_{n=0}^{n} a_n (t-t_o)^n \tag{5}$$

by a least-squares technique. Since there are 19 observed maxima, a polynomial of degree 19 or greater is required. The behavior of such a polynomial is so sensitive to the terms of higher degree at large values of $(t-t_o)$ that the terms of low degree can not feasibly be evaluated with sufficient precision for accurate determination of $R_M(t)$ near $t = t_o$.

Proton Flux - Sunspot Number Correlation

The results presented in Section II provide values of the annual proton flux $\int \phi_Y$ (>E) at proton energies greater than E, at solar distance 1 AU. Figure 4 shows the annual flux above 10, 30, and 100 Mev and the annual smoothed Wolf sunspot number R_Y for 1955 through 1964. Use of annual proton flux values reduces fluctuations associated with single large or anomalous solar proton events such as that of 23 February 1956, without destroying the general correlation of the flux with the sunspot number.

The correlation coefficient of the annual smoothed Wolf sunspot number with the common logarithm of the annual proton flux is

$$C = \frac{\sum_{i=1}^{I} \left(R_{Yi} - \bar{R}_Y\right)\left(\int\phi'_{Yi} - \overline{\int\phi'_Y}\right)}{\left[\sum_{i=1}^{I} \left(R_{Yi} - \bar{R}_Y\right)^2 \sum_{i=1}^{I} \left(\int\phi'_{Yi} - \overline{\int\phi'_Y}\right)^2\right]^{1/2}} \tag{6}$$

Table 3. Monthly Smoothed Wolf Sunspot Numbers at Maxima

Observed			Predicted	
Cycle	Year	Number	Year	Number
1	1761.5	86.5	1759.4	70.1
2	1769.7	115.8	1770.4	90.6
3	1778.4	158.5	1781.4	71.2
4	1788.1	141.2	1791.7	16.5
5	1805.2	49.2	1802.2	74.4
6	1816.4	48.7	1812.1	110.6
7	1829.9	71.7	1827.3	140.0
8	1837.2	146.9	1837.8	165.3
9	1848.1	131.6	1847.9	140.0
10	1860.1	97.9	1859.1	110.6
11	1870.6	140.5	1869.0	74.4
12	1883.9	74.6	1884.3	16.5
13	1894.1	87.9	1894.7	71.2
14	1907.0	64.2	1905.7	71.6
15	1917.6	105.4	1916.2	99.5
16	1928.4	78.1	1927.4	91.0
17	1937.4	119.2	1937.5	115.0
18	1947.5	151.8	1947.4	105.4
19	1957.0	190.2	1955.8	103.4
20	--	--	1969.8 ± 0.7	135.2 ± 54.5

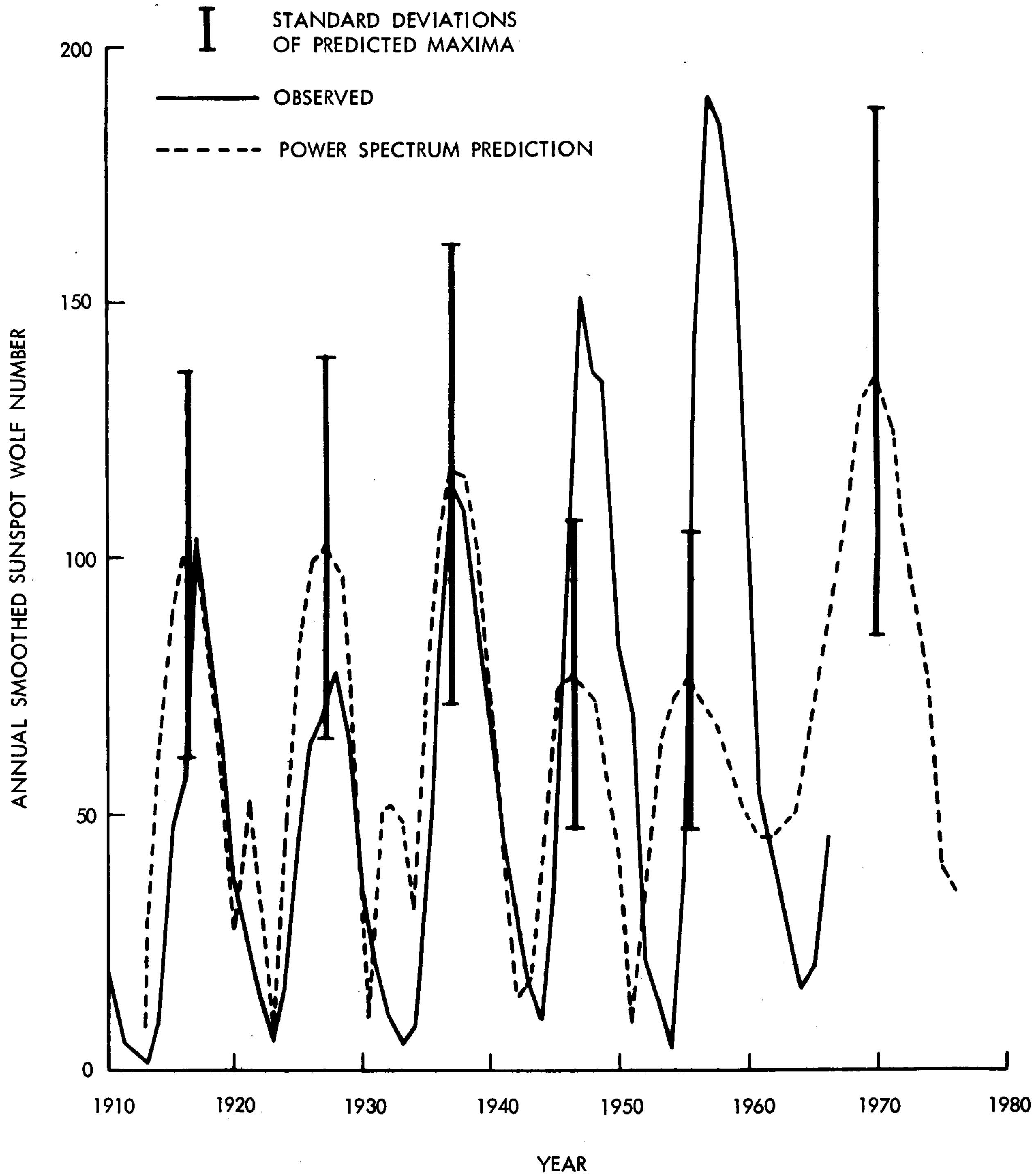

Figure 2. Observed and Predicted Sunspot Numbers

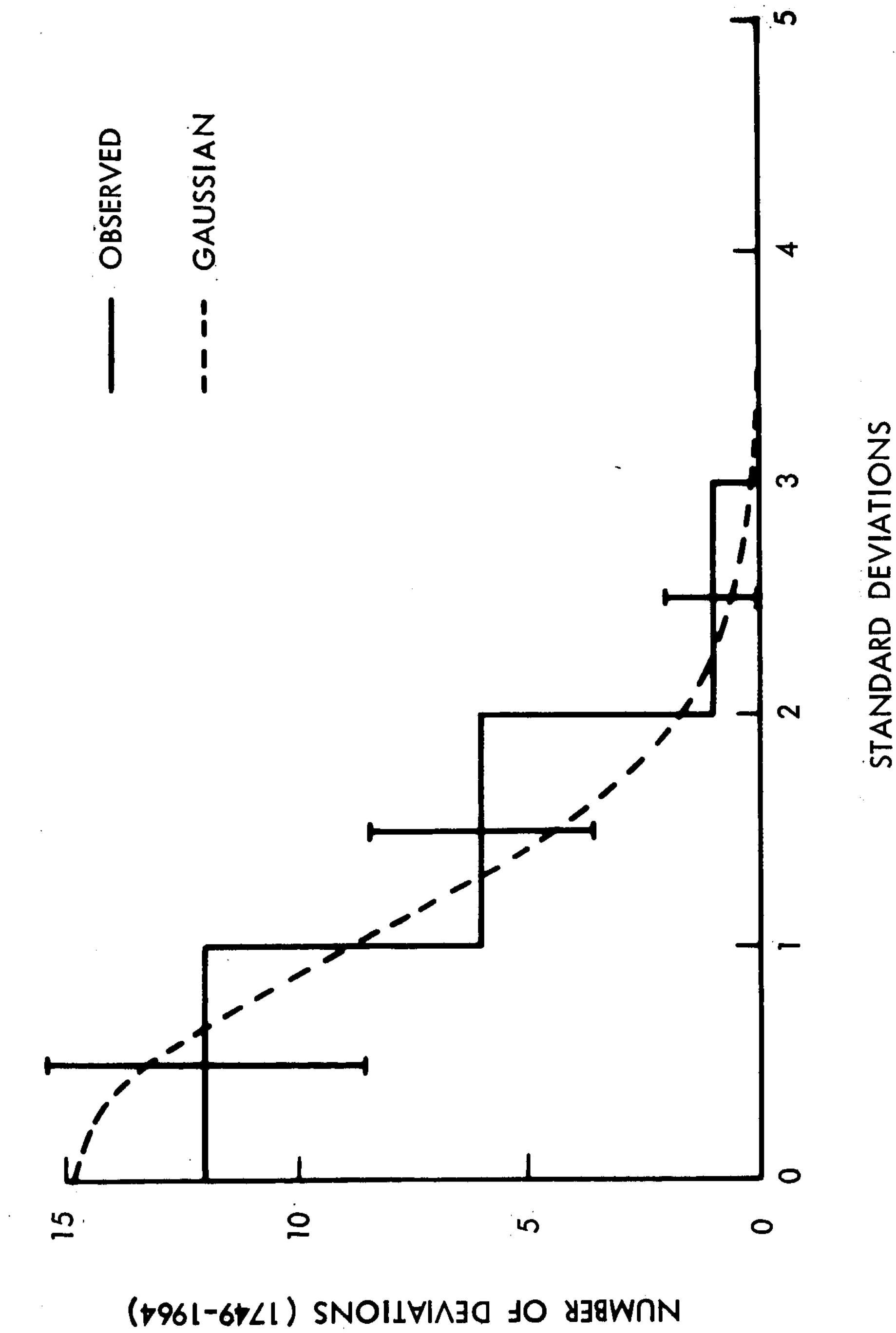

Figure 3. Distribution of Deviations of Predicted Maximum Sunspot Numbers

where I is the number of years sampled (10) and $\int\phi'_Y = \log_{10} \int\phi_Y$ was calculated for threshold energies of 10, 30, and 100 Mev. The results, presented in Table 4, are only slightly affected by omission of the 23 February 1956 event, the most unusual of the larger events in regard to its hard spectral distribution.

Table 4. Correlation of Proton Flux with Sunspot Number

Minimum Proton Energy	Correlation Coefficient
10 Mev	0.67
30 Mev	0.60
100 Mev	0.53

The ellipses in Figure 4 indicate the 95-percent confidence level that the flux in a given year from 1969 to 1975 will lie in the vertical range bounded by each ellipse at the abscissa corresponding to that year.* The most probable flux values lie on the major axis at these abscissae. These ellipses have equations of the form (Reference 43), adjusted for a sloping major axis,

$$\frac{R_Y^2}{\sigma_R^2} - \frac{2\,CR_Y \int\phi'_Y}{\sigma_R \sigma_\phi} + \frac{(\int\phi'_Y)^2}{\sigma_\phi^2} = (0.95)^2 \qquad (7)$$

where σ_R^2 is the sum of the variances of the sampled annual sunspot number R_Y (1956 - 1963) and of the predicted monthly numbers (Equation 4); σ_ϕ^2 is the variance of the annual proton flux. The mean values of R_Y and $\int\phi'_Y$ have not been subtracted from the R_Y and $\int\phi'_Y$ in computing σ_R^2 and σ_Y^2. The application of these results to the problem of evaluating the expected proton flux in the 1969-1975 time period is discussed further below and in Section IV.

Since the major axis of each ellipse is the locus of the most probable values of the annual flux above the corresponding energy,* and the probability distribution of $\log_{10} \int\phi_Y = \int\phi'_Y$ is assumed symmetrical about the most probable value, the probability is 0.5 that $\int\phi'_Y$ lies above the major axis. If a factor $p^2 < 1$ is used in place of $(0.95)^2$ on the right-hand side of Equation 7, the resulting ellipse represents the confidence level p of $\int\phi'_Y$.* As p^2 is varied in the range $0 < p^2 < 1$, a set of confocal ellipses with coincident major axes is generated.

*

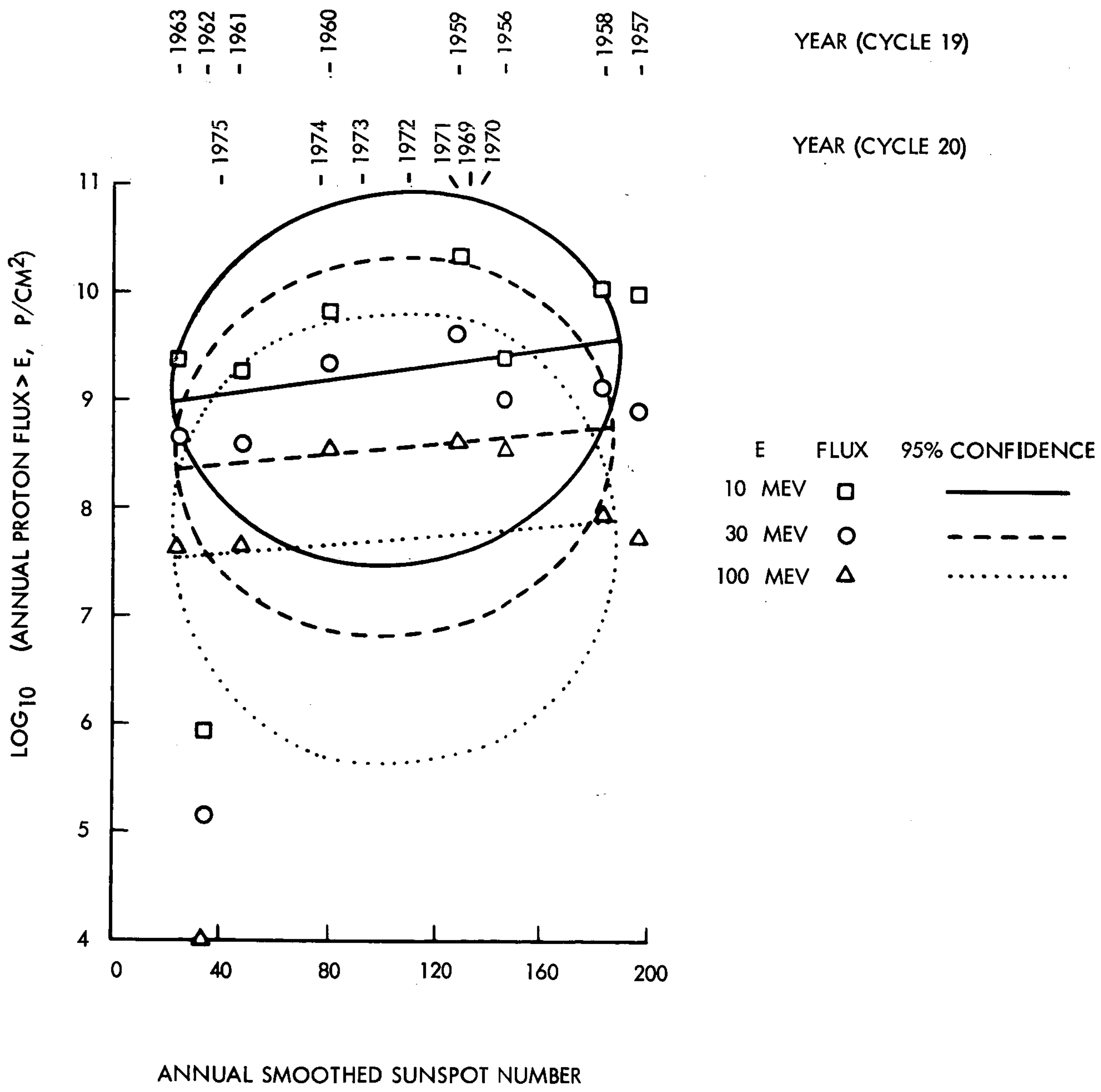

Figure 4. Annual Proton Fluxes Versus Sunspot Number

PROTON EVENT NUMBER - SUNSPOT NUMBER

There were 76 events reported in the literature in sufficient detail to warrant their inclusion in Table 1. It was necessary to correlate these data with the monthly smoothed Wolf sunspot numbers if the predicted sunspot numbers for the next solar cycle (cycle 20) are to be used as a basis for predicting future proton events.

In order to seek a correlation between the proton event data and the sunspot number, it seemed logical to arrange the proton event data in a pattern which provided only a small amount of bias with event size. This may be accomplished by constructing Table 5 from the data in Table 1. One count is entered in each column to the left of the column corresponding to a flux greater than the flux in a given event. The integral fluxes above 30 Mev were used since these data were the most numerous and probably the most reliable as well. It will be noted that the intervals are open-ended, i. e., an event with $\int \phi > 10^9$ p/cm^2 above 30 Mev would be recorded as a 1 in each column. Hence, even though only two events were recorded for 1942, each had $\int \phi > 10^8$ p/cm^2, and so were recorded in the first three columns of Table 5.

Based upon Table 5, a proton event number (PEN), analogous to the annual smoothed sunspot number R_Y, may be defined as

$$\mathrm{PEN} = \sum_{i}^{N} n_i \qquad (8)$$

where n_i is the number of columns in Table 5 in which the event would be listed, and N is the number of actual observed events in the year. Values of N are also given in Table 5. For the purposes of this analysis, it is assumed that R_Y and the PEN are related thus

$$(\mathrm{PEN})_Y = 0.1\ R_{Y-1} \pm 4.0 \qquad (9)$$

Since the estimated R_Y for 1969 is 135 ± 54, the estimated PEN for 1970 is 14 ± 5. The proton event numbers PEN for the years Y = 1940 to 1964 and the sunspot numbers R_Y are plotted versus time in Figure 5. It is to be noticed that for cycle 19 (the only one for which shape comparisons are possible) there is a time lag of about one year, as indicated in Equation 9, between the sunspot number (which reached a maximum in 1957-1958) and the proton event number (which reached a maximum in 1959). Callender, Manzano, and Winckler (Reference 44) measured an 18-month time lag in cosmic ray ionization. Until more definitive data become available, it is not possible to assume that such a time lag does not exist.

Table 5. Proton Event Frequency Versus Flux Above 30 Mev

Year	Number of Observed Events	Number of Events with $\int\phi$ >30 Mev Above Given Values (p/cm^2) $\int\phi > 10^7$	$\int\phi > 3 \times 10^7$	$\int\phi > 10^8$	$\int\phi > 3 \times 10^8$	$\int\phi > 10^9$	Total (PEN)
1942	2	2	2	2	0	0	6
1946	1	1	1	1	0	0	3
1949	2	2	1	1	1	0	5
1951	2	2	2	0	0	0	4
1952	1	1	1	0	0	0	2
1956	3	3	2	2	1	1	9
1957	14	8	7	3	1	0	19
1958	11	6	6	4	1	0	17
1959	7	6	5	4	4	2	21
1960	17	4	4	2	2	1	13
1961	10	4	3	1	1	0	9
1962	2	0	0	0	0	0	0
1963	4	2	2	1	1	0	6
Total	76	41	36	21	12	4	114

The time lag of approximately one year was obtained by comparing the standard deviations for the PEN from 0.1 R_Y for the following three cases.

Time Lag	Standard Deviation
0	4.2
1 year	4.0
2 years	7.4

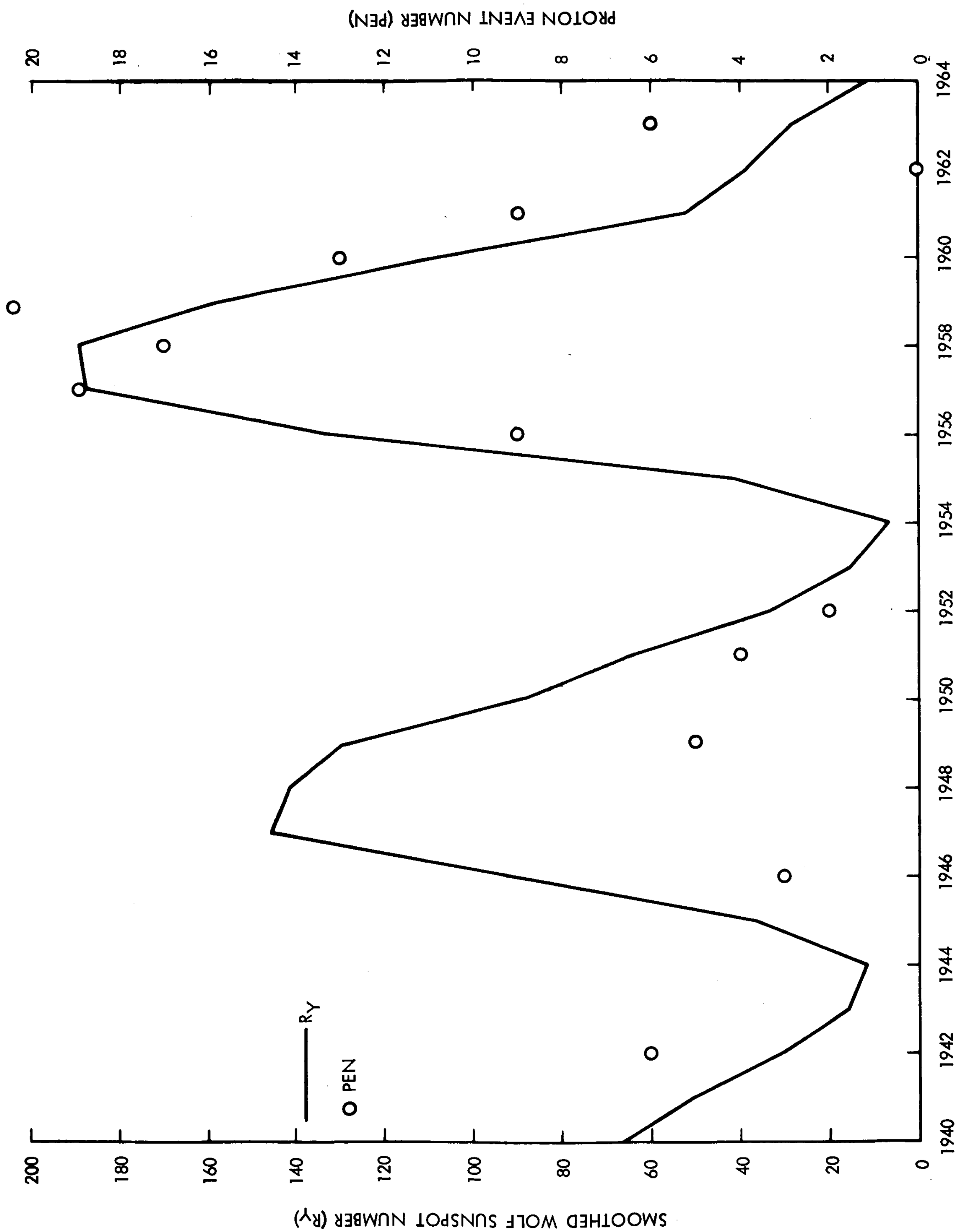

Figure 5. Proton Event Number and Sunspot Number, 1940-1964

Knowing the proton event number is not sufficient to calculate the total proton flux expected in any future year. A total of 14 events with $\int\phi = 10^7$ p/cm^2 >30 Mev would yield a PEN of 14 and a total flux of 1.4×10^8 p/cm^2 >30 Mev. However, the same PEN would result if there were two events of 10^9 p/cm^2 >30 Mev and one event of 5×10^8 p/cm^2 >30 Mev, but the total proton flux would be almost 20 times greater. This, together with the use of the PEN concept, is illustrated in Section V.

FLARE-ACTIVE SOLAR REGION

While the correlation between proton flux and the sunspot number is most valuable to interplanetary spacecraft radiation protection analysis, the ability to predict the probability of occurrence of solar flares during specific periods is also useful. Justification of the selection of characteristics of plage regions and magnetically active regions as indicators of future flare occurrence lies in the expectation that a strong correlation of flares with these indices will exist in future years. In order to evaluate the flare-plage correlation, let the plage areas, ages (numbers of disk passages), and luminosities as observed at central meridian passage (CMP) be assigned to intervals with indices i, j, k, respectively, defined in Table 6.

It must be emphasized that the correlations discussed here permit only the prediction of solar flare occurrence probabilities and not the occurrence or size of proton radiation events. A high probability of flare occurrence, however, is associated with a high probability of occurrence of enhanced levels of energetic proton radiation.

Table 6. Intervals of Parameters of Plage Regions

i	Area[1]	j	Age[2]	k	Luminosity[3]
1	<1000	1	1	1	1.0, 1.5
2	1000-2000	2	2	2	2.0, 2.5
3	2000-4000	3	3	3	3.0, 3.5
4	≥4000	4	4	4	4.0 - 5.0
		5	5		
		6	6		
		7	7		
		8	≥8		

[1] Millionths of solar hemisphere.
[2] Solar rotations.
[3] Units on McMath-Hulbert scale.

Let P_{ijk} be the number of plages in one year which had area in the ith interval, age in the jth interval, and luminosity in the kth interval. For example, P_{243} is the number of plages with area from 1000 to 1999 millionths of the hemisphere which were appearing on the visible hemisphere for the fourth time and had luminosity or intensity 3 or 3.5 on the McMath-Hulbert observatory scale. Let P'_{ijk} be the number of plages with similar characteristics, at each of which one or more flares occurred during the disk passage following the passage on which the given characteristics were observed. The flare-plage associations are those contained in Reference 45. In computing P'_{ijk}, only flares with corrected area 100 millionths of the solar hemisphere or greater are considered. Smaller flares have poorer correlation with plage characteristics and are not predictable with significant accuracy by the present method. If consideration were limited to flares larger than, for example, 200 millionths of the hemisphere, the smallness of the data sample would reduce statistical accuracy. The term "flare" will be understood in this section as one with corrected area at least 100 millionths of the hemisphere.

Let w_{ijk} be the probability that at least one flare will occur at any given plage region, during the disk passage following the one on which the CMP area, age, and luminosity of the plage were in intervals i, j, and k, respectively. A good estimate of w_{ijk} is given by (Reference 36)

$$w_{ijk} = P'_{ijk}/P_{ijk} \tag{10}$$

If the characteristics of a plage are observed at CMP, then w_{ijk} is known at least 21 days before the occurrence of any flare considered in association with this plage. If the region is formed west of the central meridian, this time is 14 days. The values of w_{ijk} for each combination of plage characteristics are listed in Appendix B for the years 1958 to 1964; these are assumed applicable to the years 1969 to 1975, respectively, in the next solar activity cycle.

Similarly, let P''_{ijk} be the number of plages in area interval i, age interval j, and luminosity interval k at which one or more flares occurred during the disk passage at which the plage was observed. Also let

$$w''_{ijk} = P''_{ijk}/P_{ijk} \tag{11}$$

Values of w''_{ijk}, tabulated in Appendix B, represent the probability of flare occurrence within seven days before or after the plage CMP date. If the plage is observed, for example, at the solar equator at 60 degrees east longitude, w''_{ijk} approximates the probability of flare occurrence at this plage during the remaining 11.5 days of its disk passage.

Expected Accuracy of Predictions

If a flare occurs at a given region, the prediction (expressed as a probability) is considered to have a fractional correctness of w_{ijk}. If no flare occurs at this region, the prediction has a fractional correctness of $(1-w_{ijk})$. In a given time interval, $\sum_{ijk} P_{ijk}$ predictions are made, one for each plage region.

The notation $\sum_{ijk} P_{ijk}$ represents the triple summation $\sum_{i=1}^{I} \sum_{i=1}^{J} \sum_{i=1}^{K} P_{ijk}$ over the i, j, and k intervals to which the plage area, age, and luminosity, respectively, can be assigned. Reference to Table 6 shows that i = 4, j = 8, k = 4 in the present analysis. The expectation that any prediction will prove to be "correct" in the way correctness has been defined above is the weighted average of the fractional correctness of all regions (Reference 36).

$$S = \frac{\sum_{ijk} P'_{ijk}\, w_{ijk}}{\sum_{ijk} P_{ijk}} + \frac{\sum_{ijk} (P_{ijk} - P'_{ijk})\,(1 - w_{ijk})}{\sum_{ijk} P_{ijk}}$$

$$S = \frac{\sum_{ijk} P_{ijk}\,(1 - 2\, w_{ijk} + 2\, w_{ijk}^{2})}{\sum_{ijk} P_{ijk}} \tag{12}$$

The expectation that a "false alarm" will result, i. e., that no flare will occur at the given region is

$$S_F = \frac{\sum_{ijk} \left[(P_{ijk} - P'_{ijk})\, w_{ijk}\right]}{\sum_{ijk} P_{ijk}} \tag{13}$$

$$S_F = \frac{1}{2}\,(1 - S) \tag{14}$$

If a prediction is neither correct nor a "false alarm," it represents a failure to predict a flare that does occur. The expectation of such a failure is

$$S_o = 1 - S - S_F = S_F \tag{15}$$

The expected accuracy of predictions of flare occurrence on the same disk passage as that at which the plage characteristics were observed can be represented by S'', S_F'' and S_o'', which are found by replacing P'_{ijk} with P''_{ijk} and w_{ijk} with w''_{ijk} in Equations 12, 14 and 15, respectively. Values of S and S'' are presented in Table 7 for the years 1958 through 1964. These values are assumed to hold for the corresponding years from 1969 through 1975, following an 11-year solar activity cycle. If the variables were uncorrelated, S or S'' would equal 0.5. The values of S apply only to flares at plages observable on the disk passage preceding the flare.

Table 7. Flare Prediction Accuracy

Year	Same Disk Passage (S'')	Next Disk Passage (S)
1958	0.716	0.674
1959	0.695	0.673
1960	0.713	0.888
1961	0.733	0.744
1962	0.717	0.717
1963	0.898	0.925
1964	0.899	0.960

Flare-Magnetic Field Correlation

Previous studies (References 36, 46) have established conditions on the solar magnetic field component normal to the photosphere, B_p, which are favorable to the occurrence of solar flares during the next disk passage of a magnetically active region. These simultaneous conditions are:

1. $|B_p| \lesssim 2$ gauss for 3 days or longer

2. $|\partial B_p/\partial t| \leqslant 1$ gauss/day

3. $|\nabla B_p| \geqslant 10$ gauss/heliographic degree

The gradient of B_p is understood to be the component normal to the line of sight of $\nabla (\vec{B} \cdot \vec{n})$ where $\vec{n}$ is a vector of unit length parallel to the line of sight. This association is most useful in cases where magnetic activity is evident before the formation of a calcium plage at a new region, and permits forecasting of flare occurrence probability at dates 21 to 35 days in advance at some regions at which the plage is "new" at the disk passage on which the flares occur.

To evaluate this correlation, the positions of flares at new calcium plages were translated to the dates at which magnetograms were obtained during the preceding solar rotation. The translation included effects of differential solar rotation and the inclination of the solar equator to the ecliptic plane. Table 8 presents the number and fraction of plages with age 1 rotation (i. e., new plages) in each year from 1960 through 1964; these plages

Table 8. Magnetic Field—Flare Association

Year	New Plages		Stationary Magnetic Null Points		Other New Flaring Regions
	Number	Fraction	Total	Flaring	
1960	123	0.291	90	72	23
1961	101	0.343	38	20	21
1962	162	0.535	22	14	15
1963-4	883	0.917	12	4	11

are the ones to which the magnetic field-flare correlation was applied. The table gives the number of cases in which the magnetic field conditions listed above occurred at the regions at which new plages were to appear on the solar rotation following the magnetic observation. Next is given the number of cases in which the existence of these magnetic conditions was followed by one or more flares on the next rotation. Finally the table indicates the number of new and flaring plage regions at which the magnetic conditions did not occur. Magnetograms prepared before 1960 (Reference 47) lack sufficient angular resolution for use in this analysis. The years 1963 and 1964, near a minimum stage of solar activity, were combined to provide a more significant statistical sample.

Accuracy of Combined Plage and Magnetic Correlations

Let N_M be the number of stationary magnetic null points in one year, i.e., the number of cases in which the previously described magnetic conditions occurred. Let N'_M be the number of such points near which flares were observed on the following solar rotation*. The combined accuracy of flare occurrence predictions based on association with plages and with magnetic field patterns is defined as

$$S^* = S\,(1 - \sum_{ik} P_{ilk}) / \sum_{ijk} P_{ijk} + N'_M \sum_{ik} P_{ilk} / N_M \sum_{ijk} P_{ijk} \tag{16}$$

where S is defined in Equation 12. The sum $\sum_{ik} P_{ilk}$ is the number of new plages (j = 1) in the yearly data sample. Values of S* are given in Table 9; the results in Tables 8 and 9 are assumed applicable to the years 1971 through 1975. In the absence of results for 1958 and 1959, it is assumed that the results for 1960 apply to 1969 and 1970.

The results shown in Table 9 indicate that flare occurrence probabilities can be predicted with reasonable confidence during years of high solar activity, but with only very limited validity during quiet years. The usefulness of this prediction technique in interplanetary radiation environment analysis has been discussed at the beginning of Section III.

Table 9. Accuracy of Combined Flare Prediction Method

Year	S*
1960	0.862
1961	0.590
1962	0.674
1963	0.38
1964	0.38

*"Near" is defined as within 10 heliographic degrees.

PROTON EVENT-NEUTRON MONITOR RATE

From one to fourteen days before some polar cap absorption (PCA) events, decreases of one to three percent have been observed in the neutron flux near sea level (References 48, 49). These so-called pre-decreases (pré-baisses) are to be distinguished from the larger Forbush decreases of typically 10 to 20 percent which accompany rather than precede some solar energetic proton events. Pre-decreases are probably caused by the exclusion from the earth of galactic charged particles by a plasma concentration that is associated with an active solar region and that lies to one side of the earth. Legrand's tabulation of pre-decreases from 26 February 1957 to 18 December 1957, when compared with the proton event list of Table 1, reveals the following association:

Total pre-decreases	12
Pre-decreases followed within 14 days by PCA event	6
Pre-decreases followed by geomagnetic storm but not PCA event	2
PCA events not preceded by decrease	2

The probability of a successful prediction of a polar cap absorption event is accordingly 0.50 ± 0.17, with 75 percent of proton events falling within the alert period from one to fourteen days after a pre-decrease. The validity of this method is rather limited, but it provides warnings during periods inaccessible by optical techniques because of the 14-day period required for passage of an active region across the solar disk.

IV. PROTON RADIATION OCCURRENCE PROBABILITY

MODEL EVENT AT 1 AU

In order to obtain a model solar proton event at 1 AU from the sun, it was necessary to establish correlations in the data that were available. The available data consisted of onset plus rise times for protons above 30 and above 100 Mev, characteristic decay times for the same protons, and peak flux rates and integral fluxes for protons above 10, 30, and 100 Mev. These data are listed in Table 1. It was these data that were examined for patterns that would permit the construction of a model event at 1 AU.

A previous study (Reference 50) has been carried out along these lines, which involved forming the following ratios which are subject to estimated standard deviations as shown:

$$\frac{\Sigma \int \phi > 10 \text{ Mev}}{\Sigma \int \phi > 30 \text{ Mev}} = 5.14 \pm 0.27 \sim E^{-1.51} \tag{17}$$

$$\frac{\Sigma \int \phi > 30 \text{ Mev}}{\Sigma \int \phi > 100 \text{ Mev}} = 6.55 \pm 0.65 \sim E^{-1.57} \tag{18}$$

$$\frac{\Sigma \hat{\phi} > 10 \text{ Mev}}{\Sigma \hat{\phi} > 30 \text{ Mev}} = 3.4 \pm 0.3 \sim E^{-1.12} \tag{19}$$

$$\frac{\Sigma \hat{\phi} > 30 \text{ Mev}}{\Sigma \hat{\phi} > 100 \text{ Mev}} = 4.0 \pm 0.4 \sim E^{-1.16} \tag{20}$$

In the above expressions, $\int \phi$ is the total proton flux (p/cm^2) above the indicated energy and $\hat{\phi}$ is the peak flux rate (p/cm^2-sec). The summations were carried out in each case over all events for which the data required in both the numerators and denominators were available. In other words, in the first ratio, only those events were included for which both the integral fluxes above 10 Mev and the integral fluxes above 30 Mev were available. From these ratios, it was determined that the average integral energy spectrum weighted by flux per event varied as $E^{-1.55 \pm 0.10}$, and the weighted peak flux rate varied as $E^{-1.15 \pm 0.09}$ (see Reference 50).

At this point, recourse was made to a mathematical expression used to fit the Bailey Model Event (References 2, 51). That expression was of the form

$$\phi\,(E > E_o,\ t) = \frac{At\ e^{-\alpha E_o^n t}}{E_o^m} \qquad (21)$$

where t = time after the flare (hours) and E = energy (Mev). A, α, m, and n were taken as constants. It is seen that the time integral of this expression from t = 0 to t = ∞ is:

$$\int \phi\,(E > E_o) = \frac{A}{\alpha^2\ E_o^{m+2n}} \sim \frac{1}{E_o^{1.55\pm0.10}} \qquad (22)$$

The peak flux rate, obtained when $t = \frac{1}{\alpha E_o^n}$, is

$$\hat{\phi}(E > E_o) = \frac{Ae^{-1}}{\alpha E_o^{m+n}} \sim \frac{1}{E_o^{1.15\pm0.09}} \qquad (23)$$

Thus, the first four ratios (Equations 17 through 20) formed from the data can be approximately fit, providing m = 0.75±0.15 and n = 0.4±0.1. The parameter α was evaluated by setting the time interval from t = 0 to t = $(1/\alpha E^n)$ equal to the size-weighted onset plus rise time. These onset plus rise times are shown in Figures 6 and 7 and were averaged, obtaining 12±7 hours (for protons above 30 Mev) and 7±5 hours (for protons above 100 Mev). Thus, α = 0.022±0.002 and the rise time does vary approximately as $E^{-0.4}$.

The characteristic decay time as given by Equation 21 is not a constant, since the linear factor of t tends to offset the exponential. If, however, the time required for the peak flux rate to decrease a factor of e is used, the characteristic decay time obtained is ~2.15 times the onset plus rise time. This yields characteristic decay times of ~25±12 hours (for protons above 30 Mev) and ~15±2 hours (for protons above 100 Mev). As Figures 8 and 9 show, these are in reasonable agreement with the size-weighted data. It will be noted that t and τ are plotted to the nearest hour.

The following expressions may be derived from Equation 21.

$$\phi\,(E > E_o,\ t) = \frac{At\ e^{-0.022 E_o^{0.4} t}}{E_o^{0.75}} \quad (p/cm^2\text{-hr}) \qquad (24)$$

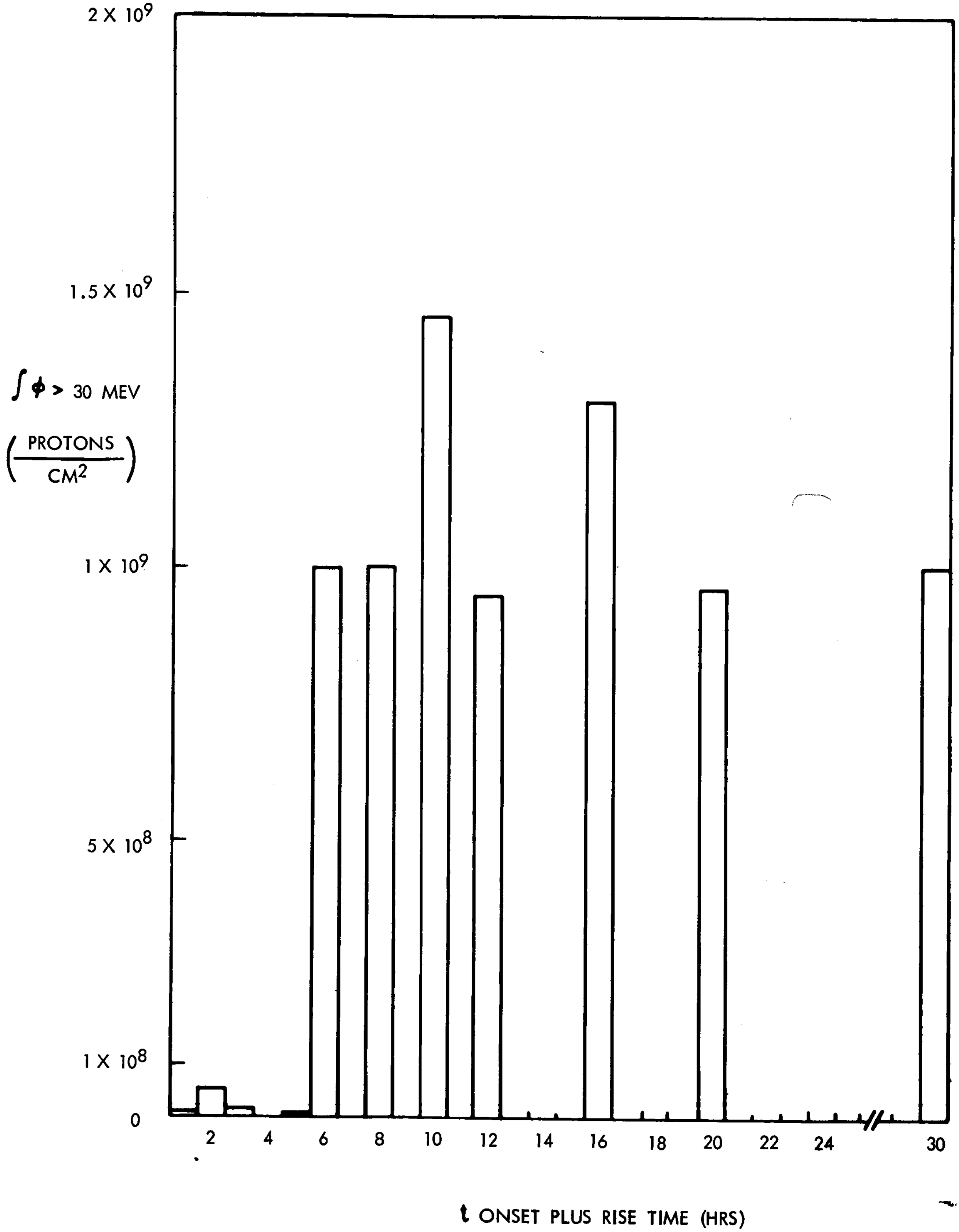

Figure 6. Onset Plus Rise Times Weighted for Flux Above 30 Mev

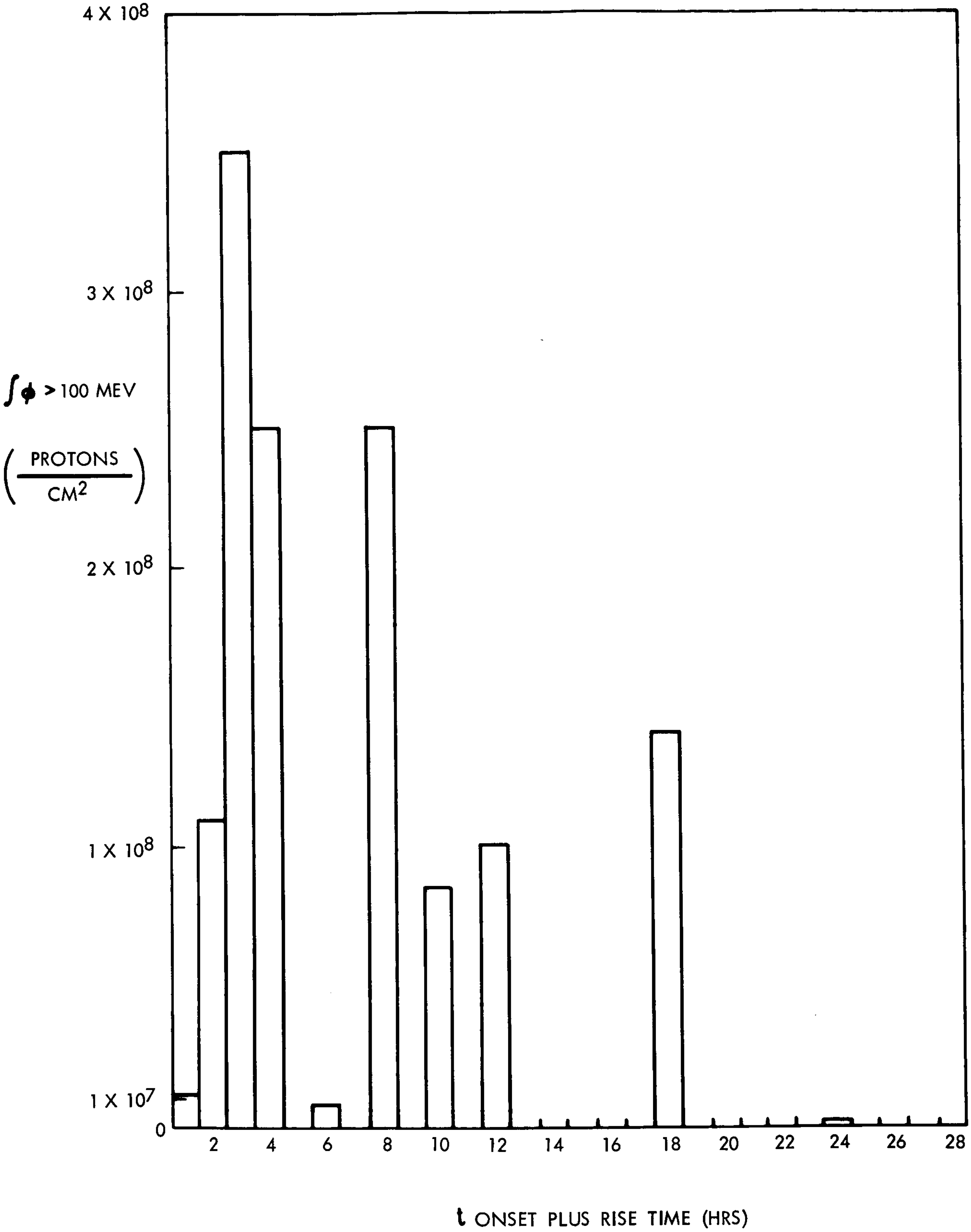

Figure 7. Onset Plus Rise Times Weighted for Flux Above 100 Mev

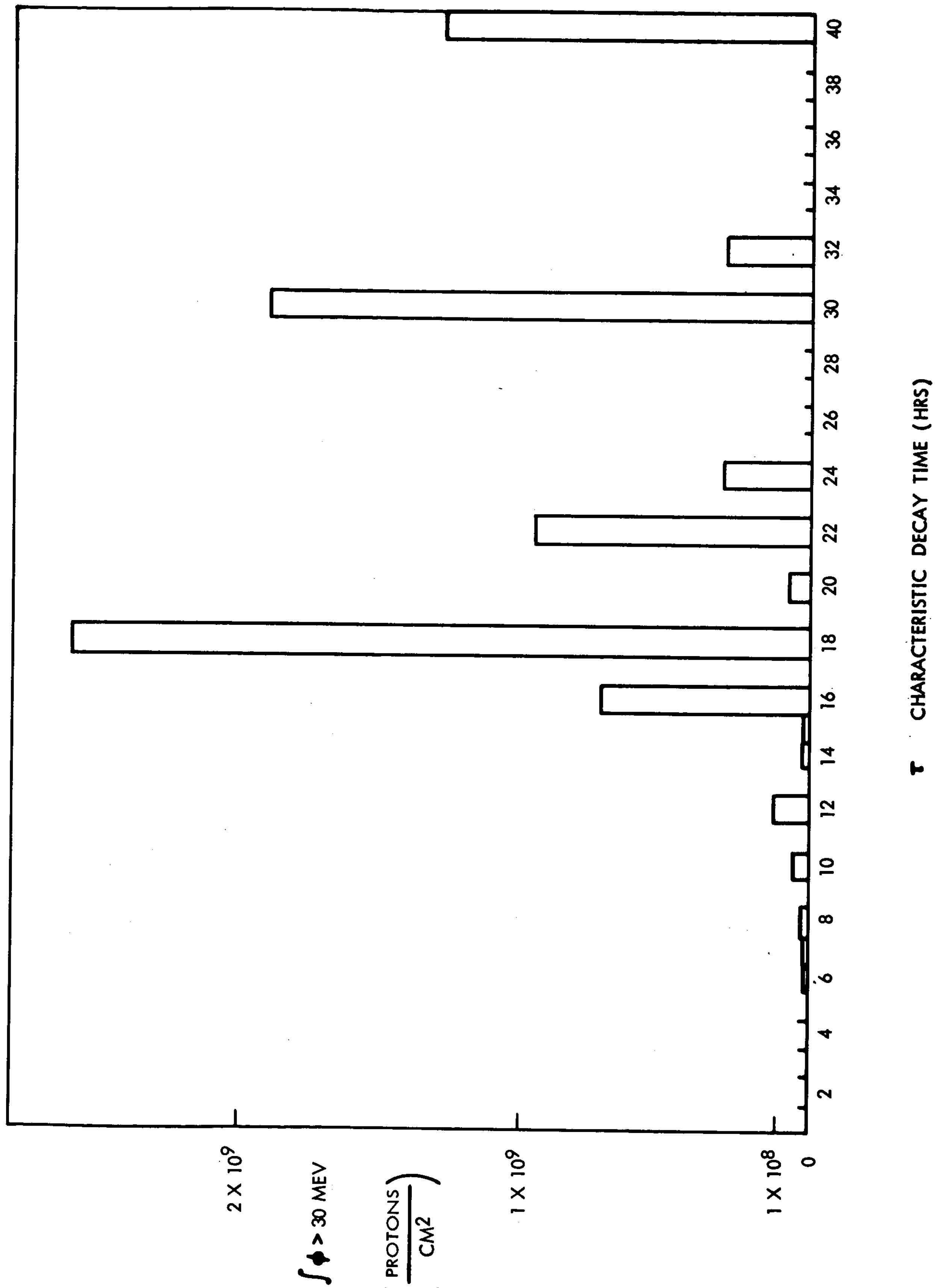

Figure 8. Characteristic Decay Times Weighted for Flux Above 30 Mev

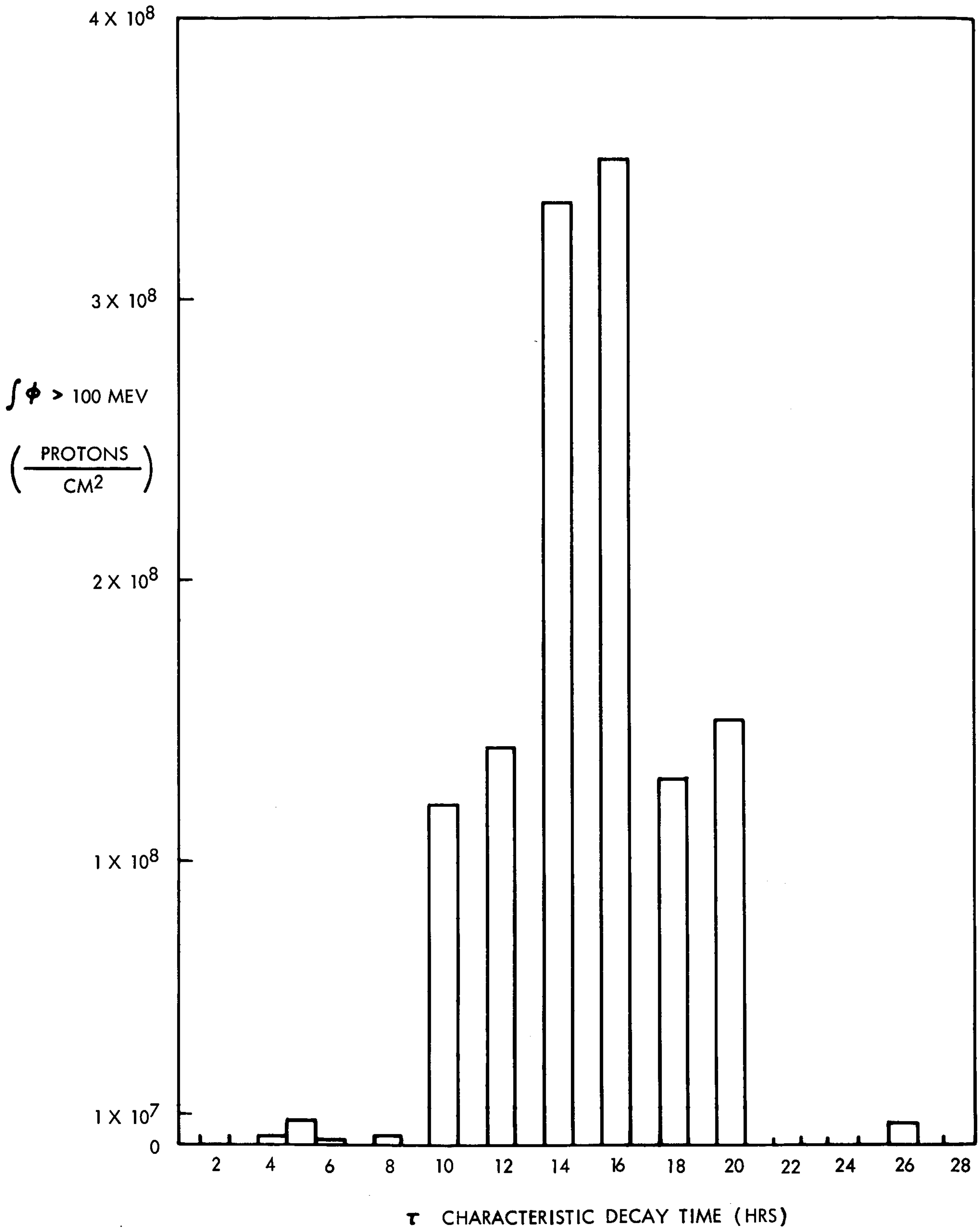

Figure 9. Characteristic Decay Times Weighted for Flux Above 100 Mev

$$\phi\,(E, t) = \frac{At\, e^{-0.022E^{0.4}t}}{E^{1.75}}(0.75 + 0.0088\, t\, E^{0.4})\ (p/cm^2\text{-hr-Mev}) \quad (25)$$

$$\phi\,(E) = \frac{3200\, A}{E^{2.55}}\ (p/cm^2\text{-Mev}) \quad (26)$$

$$\int\phi\,(E > E_o) = \frac{2100A}{E_o^{1.55}}\ (p/cm^2) \quad (27)$$

$$\hat{\phi}\,(E > E_o) = \frac{17A}{E_o^{1.15}}\ (p/cm^2\text{-hr}) \quad (28)$$

$$t_{rise}\,(E > E_o) = \frac{45}{E_o^{0.4}}(hr) \quad (29)$$

$$\tau_{decay}\,(E > E_o) = \frac{100}{E_o^{0.4}}\ (hr) \quad (30)$$

where A is a normalization constant determined from $\int\phi$ by Equation 27.

These expressions were derived as part of a series of radiation shielding studies carried out previously (Reference 50). Their use in the present study was hampered by their applicability to only the largest events. In order to obtain a model applicable to events of any size, modifications were required. In order to determine the sort of modifications required, the data were examined for characteristics that could be correlated with event size. Two trends were noted. The slopes of the integral energy spectra (Figure 10) and the peak flux spectra (Figure 11) tend to become less steep, and the ratio of integral flux to peak flux rate increases (Figures 12, 13, and 14) as the event size increases. Specifically, the integral energy spectrum appears to vary from $\sim E^{-1.6}$ for large events ($\int\phi$ >30 Mev above 10^9 p/cm^2) to $\sim E^{-2.6}$ for small events ($\int\phi$ >30 Mev below 10^8 p/cm^2). The relationship of integral flux to peak flux rate appears to be approximately (for all energies)

$$\int\phi \sim 2.5 \times 10^4\, \hat{\phi}^{\,1.177} \quad (31)$$

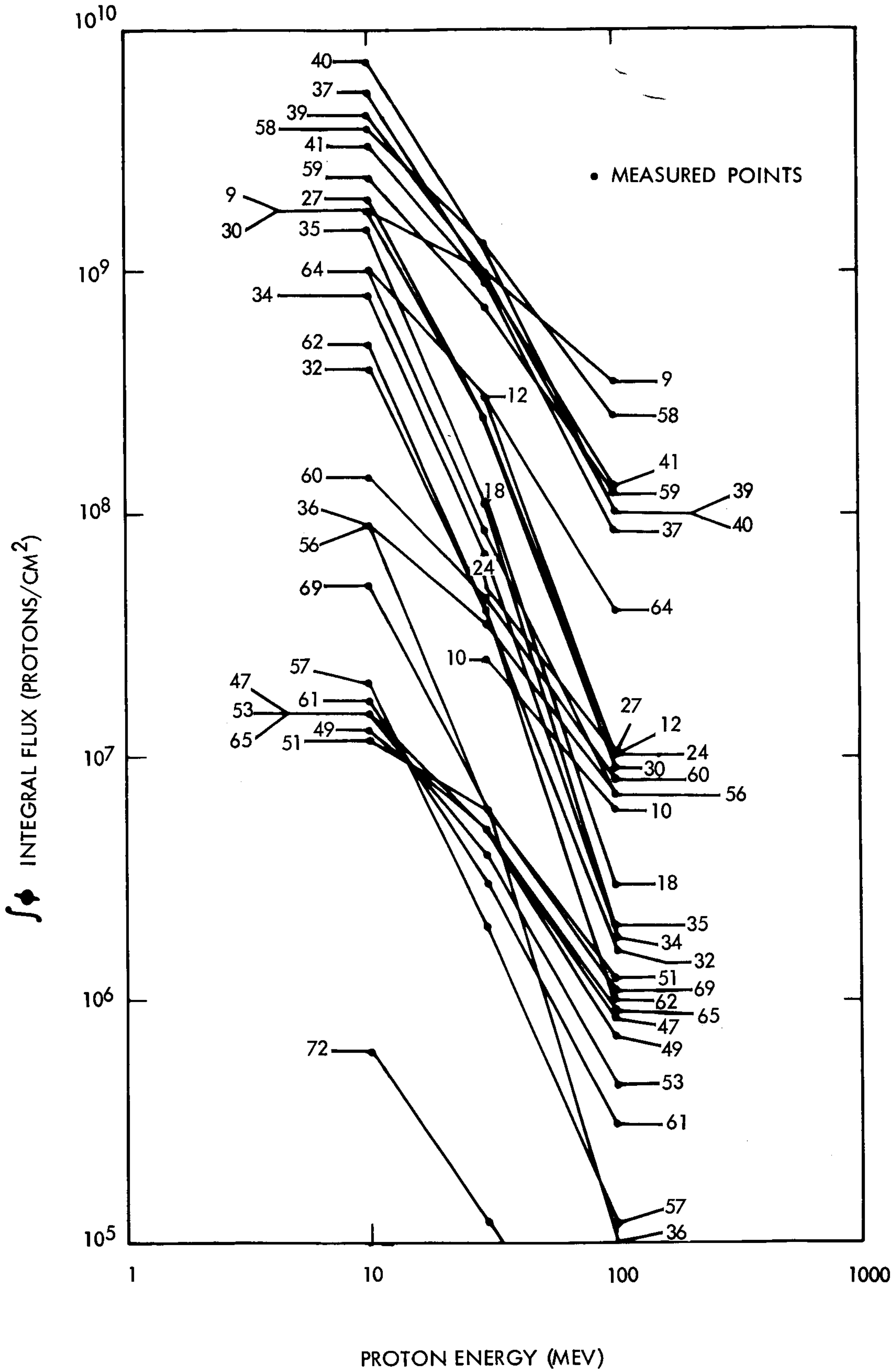

Figure 10. Integral Fluxes of Several Proton Events

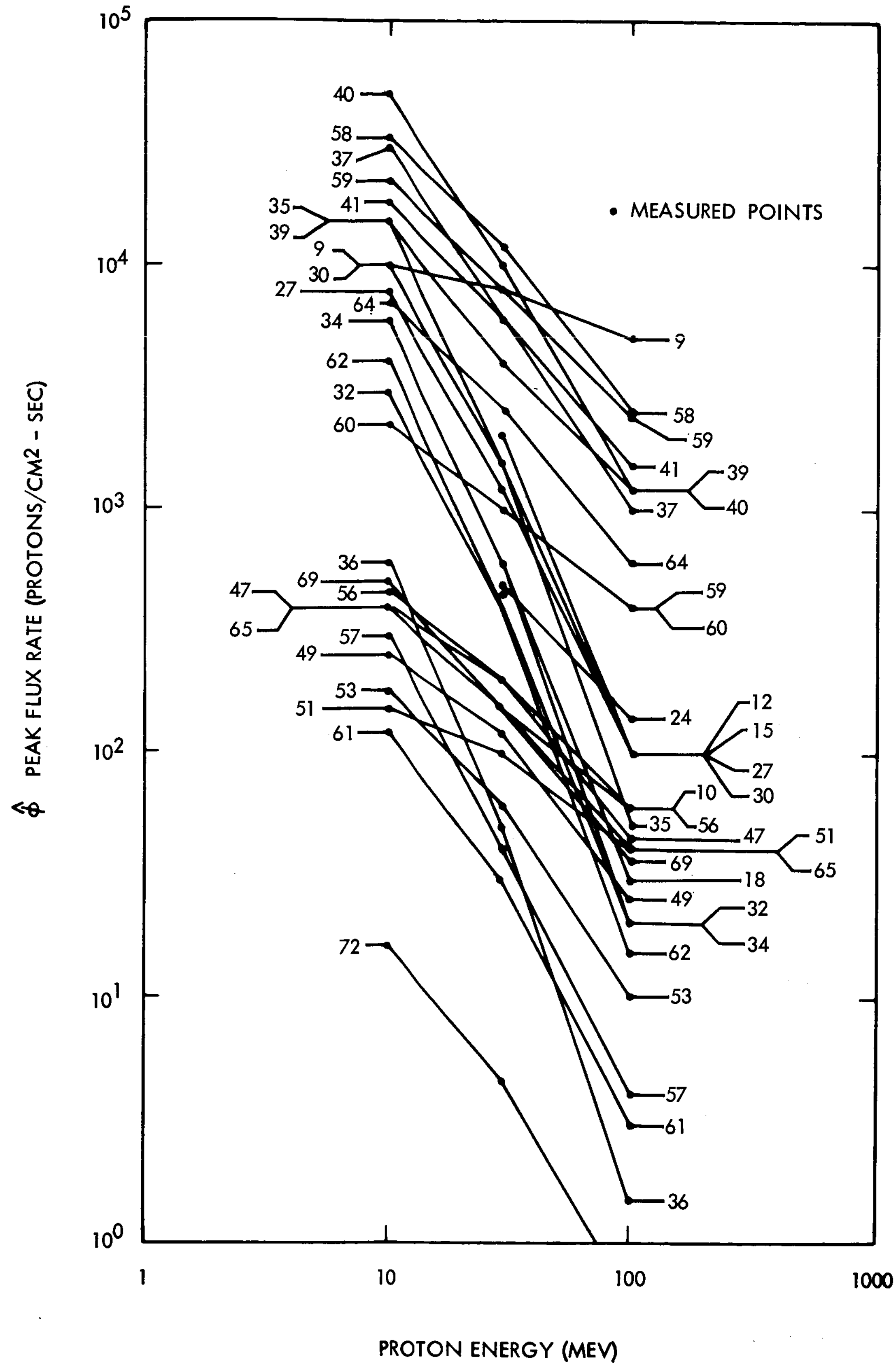

Figure 11. Peak Flux Rates of Several Proton Events

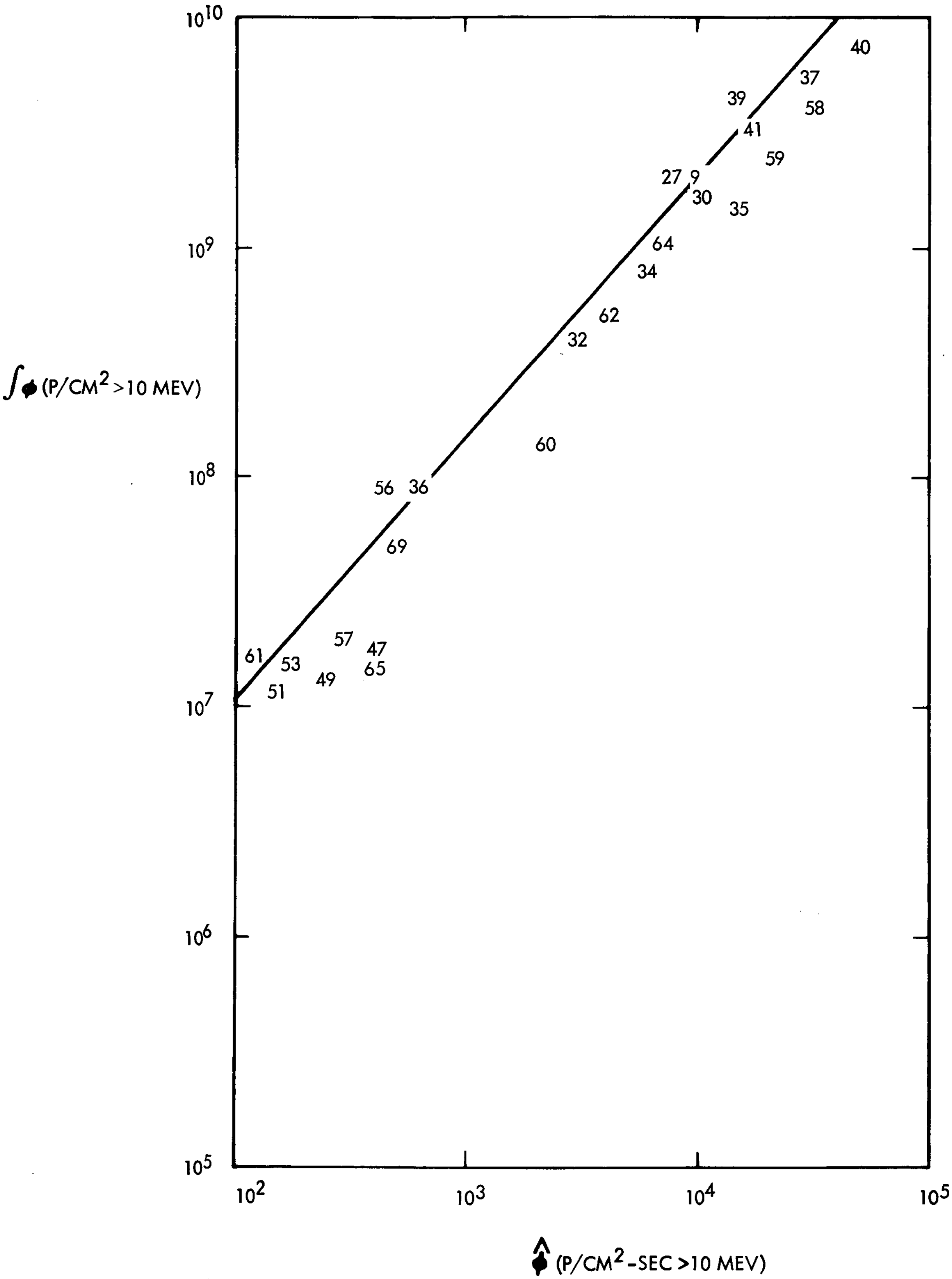

Figure 12. Integral Flux Versus Peak Flux Rate Above 10 Mev

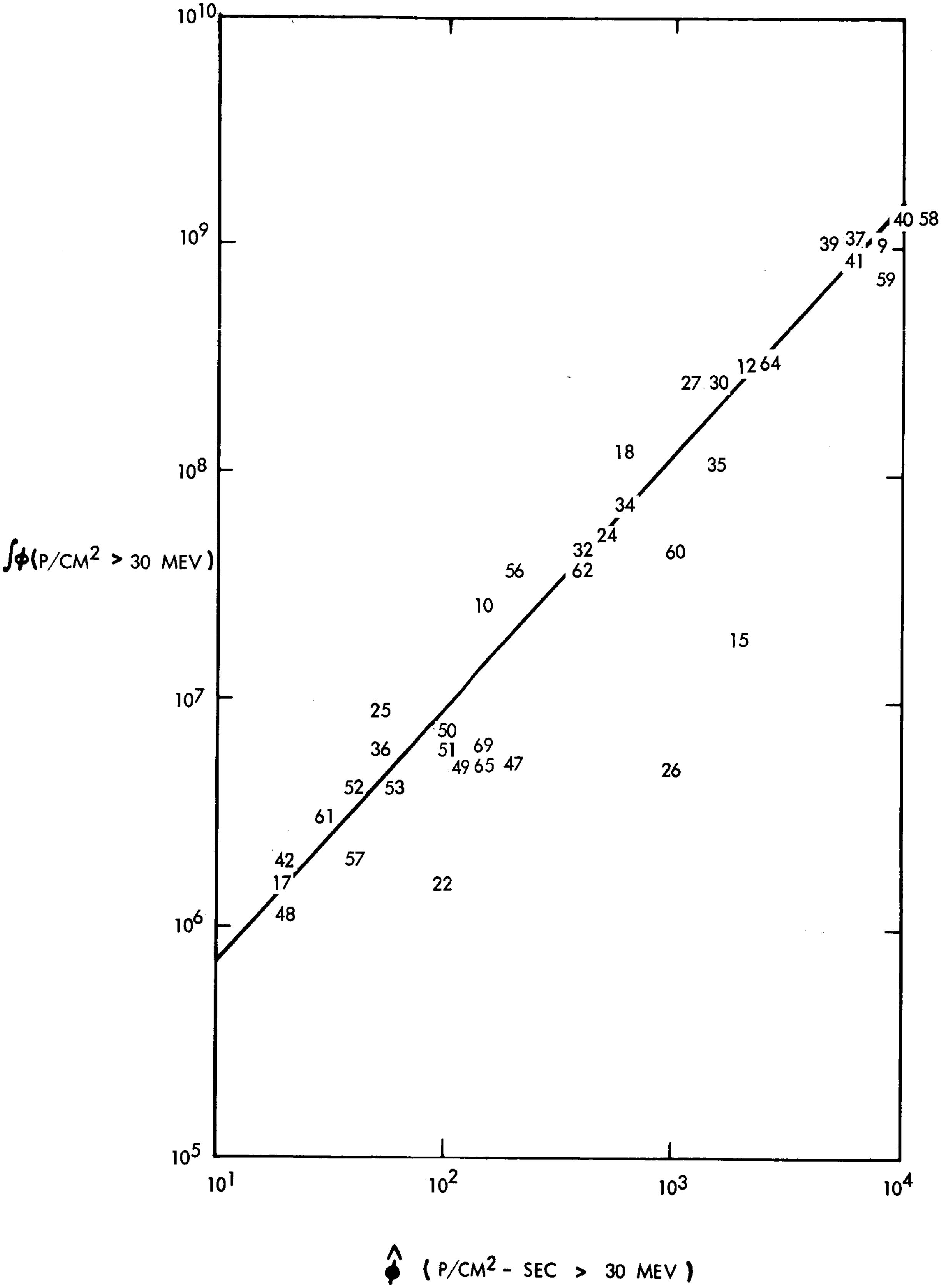

Figure 13. Integral Flux Versus Peak Flux Rate Above 30 Mev

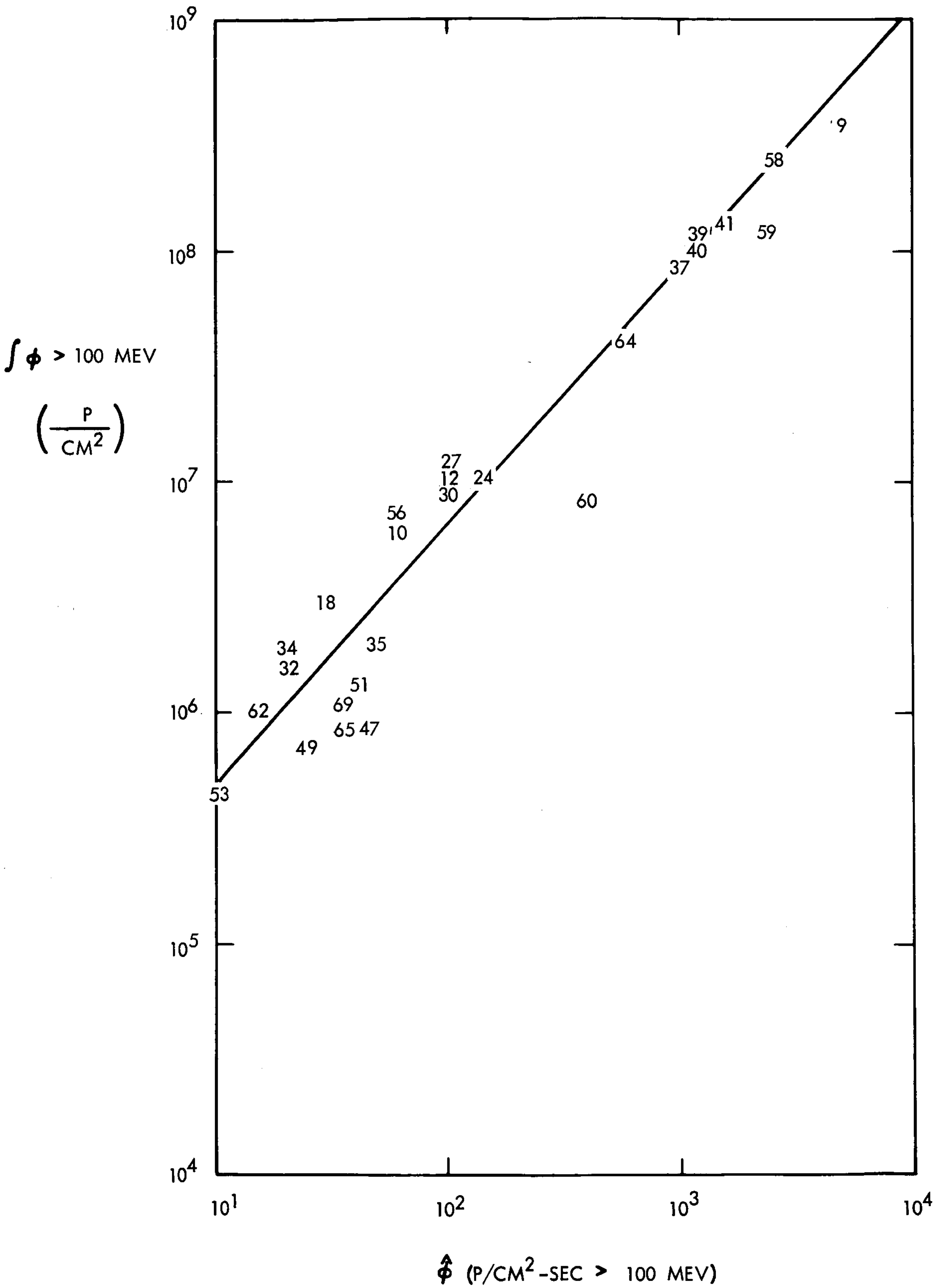

Figure 14. Integral Flux Versus Peak Flux Rate Above 100 Mev

In order to incorporate these trends into Equation 21, it was necessary to make α and m functions of event size (determined by the normalization factor A). The desired behavior can be approximated by the following relationships:

$$\alpha = A^{-0.224\pm0.01} \tag{32}$$

(from Equation 31) and

$$m = 16A^{-0.16\pm0.02} \tag{33}$$

which accounts for the $E_o^{-1.6}$ to $E_o^{-2.6}$ behavior. Substituting these into Equations 24 to 30 yields

$$\phi\,(E > E_o,\, t) = \frac{At\, e^{-\left(\frac{E_o^{0.4}\, t}{A^{0.224}}\right)}}{E_o^{16A^{-0.16}}}\ (p/cm^2\text{-hr}) \tag{34}$$

$$\phi\,(E,t) = \frac{At\, e^{-\left(\frac{E^{0.4}\, t}{A^{0.224}}\right)}\left(0.4\, t\, A^{-0.224} E^{0.4} + 16A^{-0.16}\right)}{E^{16A^{-0.16}+1}}\ (p/cm^2\text{-hr-Mev}) \tag{35}$$

$$\int\phi\,(E > E_o) = \frac{A^{1.45}}{E_o^{16A^{-0.16}+0.8}}\ (p/cm^2) \tag{36}$$

$$\phi\,(E) = \frac{16A^{1.29} + 0.8A^{1.45}}{E^{16A^{-0.16}+1.8}}\ (p/cm^2\text{-Mev}) \tag{37}$$

$$\hat{\phi}\,(E > E_o) = \frac{0.37\, A^{1.224}}{E_o^{16A^{-0.16}+0.4}}\ (p/cm^2\text{-hr}) \tag{38}$$

$$\tau_{decay}\,(E > E_o) = 2.15\, t_{rise}\,(E > E_o) = \frac{2.15\, A^{0.224}}{E_o^{0.4}}\ (hr) \tag{39}$$

The solid curves in Figures 12, 13, and 14 were calculated using these expressions. It is seen that they fit the data fairly well.

As an additional check on Equation 39, the rise (actually onset plus rise) and characteristic decay times as a function of the integral flux were compared with the formula. This is essentially the same as comparing the ratio of integral flux to peak flux rate, but the data exhibit more scatter (see Figures 15 through 18). Nevertheless, the calculated curves fit the data about as well as any other set of single-valued curves.

In order to facilitate the use of this model in estimating the missing event data, a series of graphs was made in which various parameters (peak flux rate, integral flux, rise and decay times) were plotted as functions of the normalization factor A. These graphs are shown in Figures 19 through 22 and were quite useful since A is not linearly proportional to any single event parameter (see Equations 34 through 39).

By the use of Equations 34 through 39 (Figures 19 through 22), the missing data in Table 1 were estimated. These estimated numbers are indicated by asterisks (*) and were not plotted as data points in Figures 6 through 18.

The advantage of using an analytical model (Equations 34 through 39) rather than a numerical fit to the existing data (Figures 10 through 18) is that it is possible to generate all the characteristics of a solar proton event in a consistent pattern once a single parameter (e.g., t, τ, $\int\phi$ or $\hat{\phi}$) is known.

EVENT FREQUENCY DISTRIBUTION

As expected, ~~both the number and size of proton events ar~~e function~~s~~ of solar activity. The correlation~~s~~ of rate event flux ~~and frequency~~ with the sunspot number has ~~have~~ been discussed in the previous section. In order to select events whose total flux ($\Sigma\int\phi$) and proton event number (PEN) add up to the totals expected on the basis of sunspot correlations, it is necessary to have an event frequency distribution to choose from. The most obvious distribution is by event size. In Figure 23, the number of proton events is shown as a function of integral flux above 10, 30, and 100 Mev. The 76 events of Table 1 were grouped into categories of $>10^{10}$ p/cm^2, 3 - 10 x 10^9 p/cm^2, 1 - 3 x 10^9 p/cm^2, 3 - 10 x 10^8 p/cm^2, etc. It is seen that the distributions are not in disagreement with the Gaussian distributions indicated by broken curves in Figure 23; the 1σ widths and means of the Gaussian curves are also shown in this figure. The lack of events larger than those observed is due presumably to their absence, while the lack of events smaller than those observed is due to observational difficulties. It is expected that if the proton event size distributions were completely known, they would be monotonic in nature, increasing as the event size decreased. However, these missed small events will not affect the annual proton fluxes appreciably.

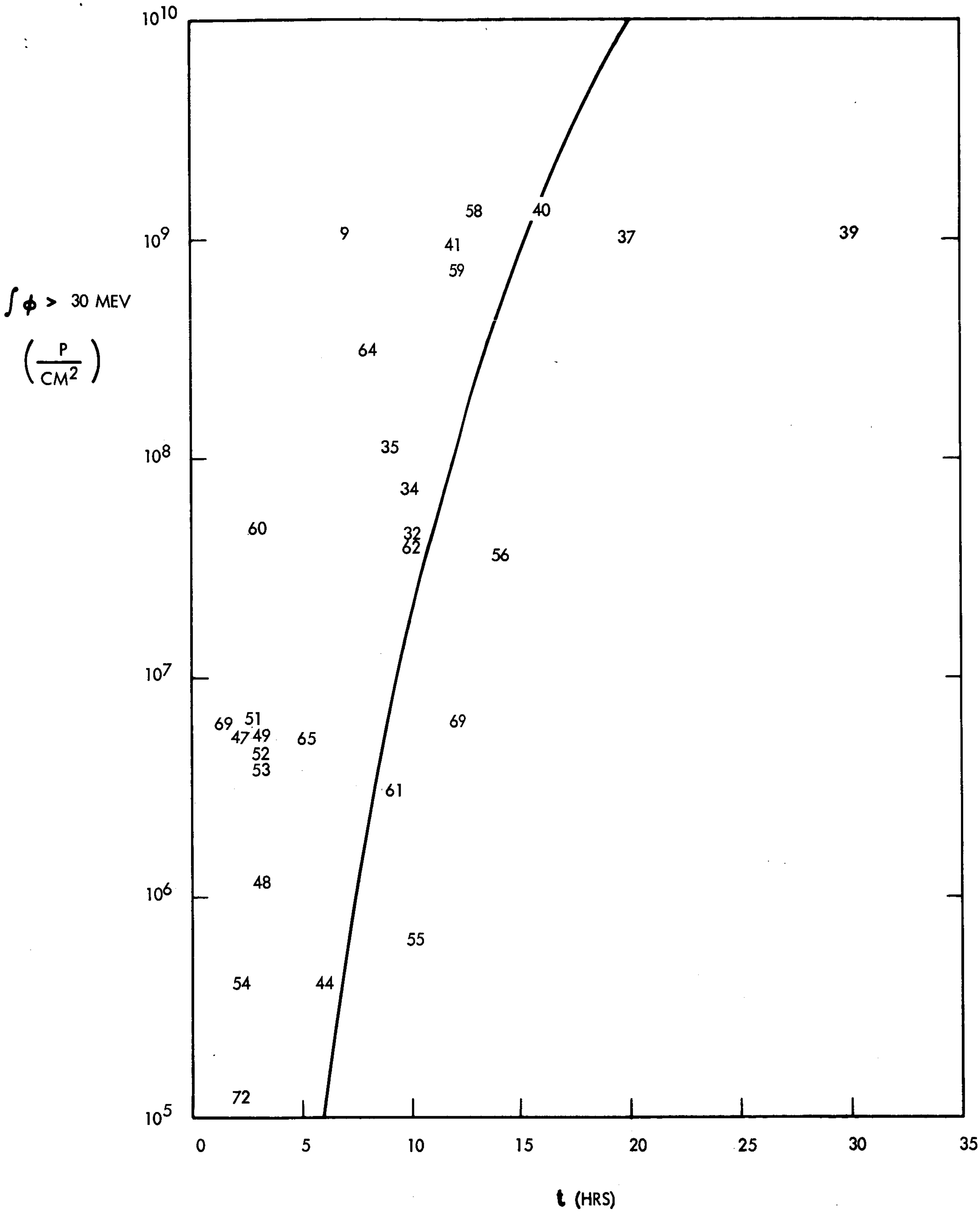

Figure 15. Integral Flux Above 30 Mev Versus Onset Plus Rise Time

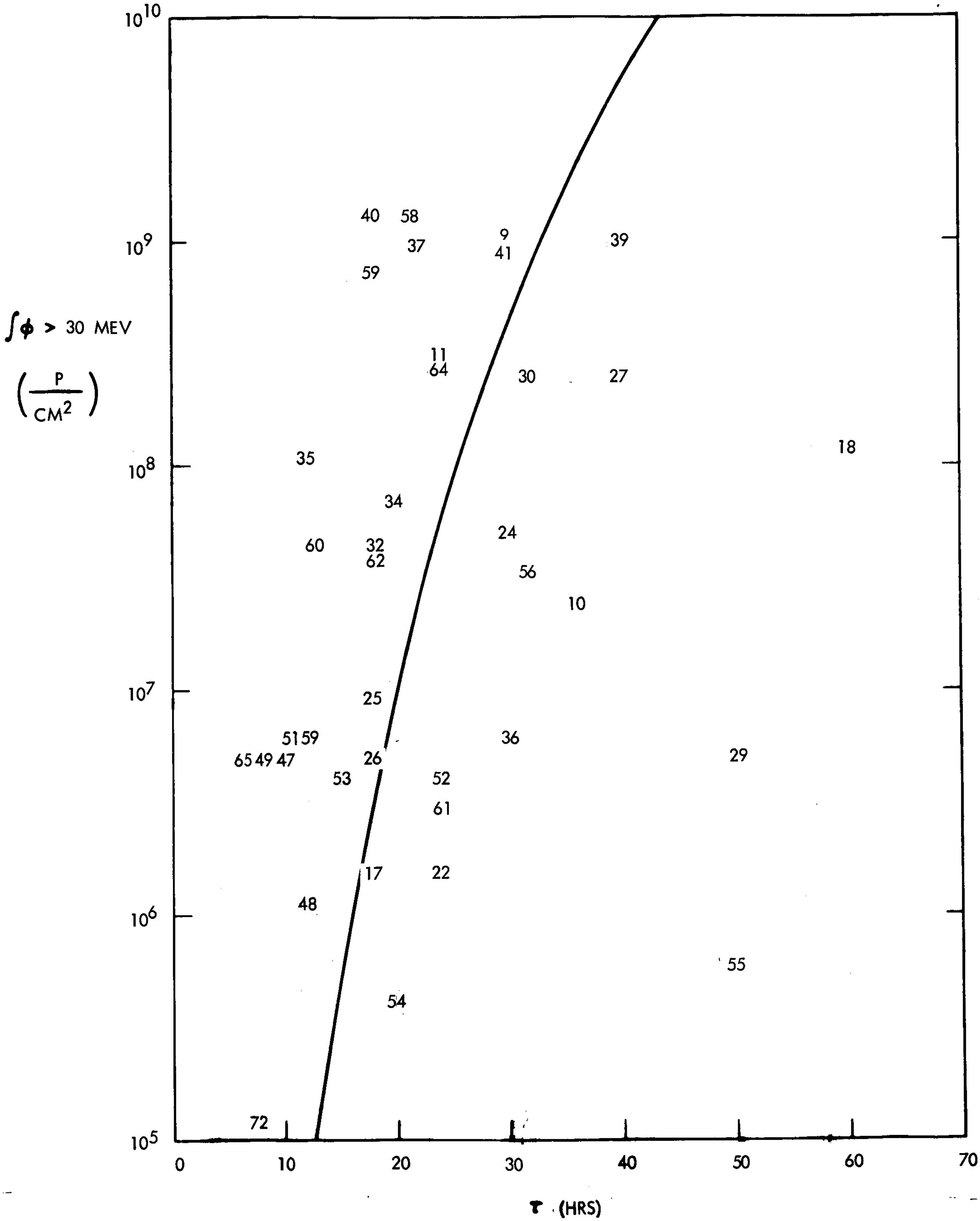

Figure 16. Integral Flux Above 30 Mev Versus Characteristic Decay Time

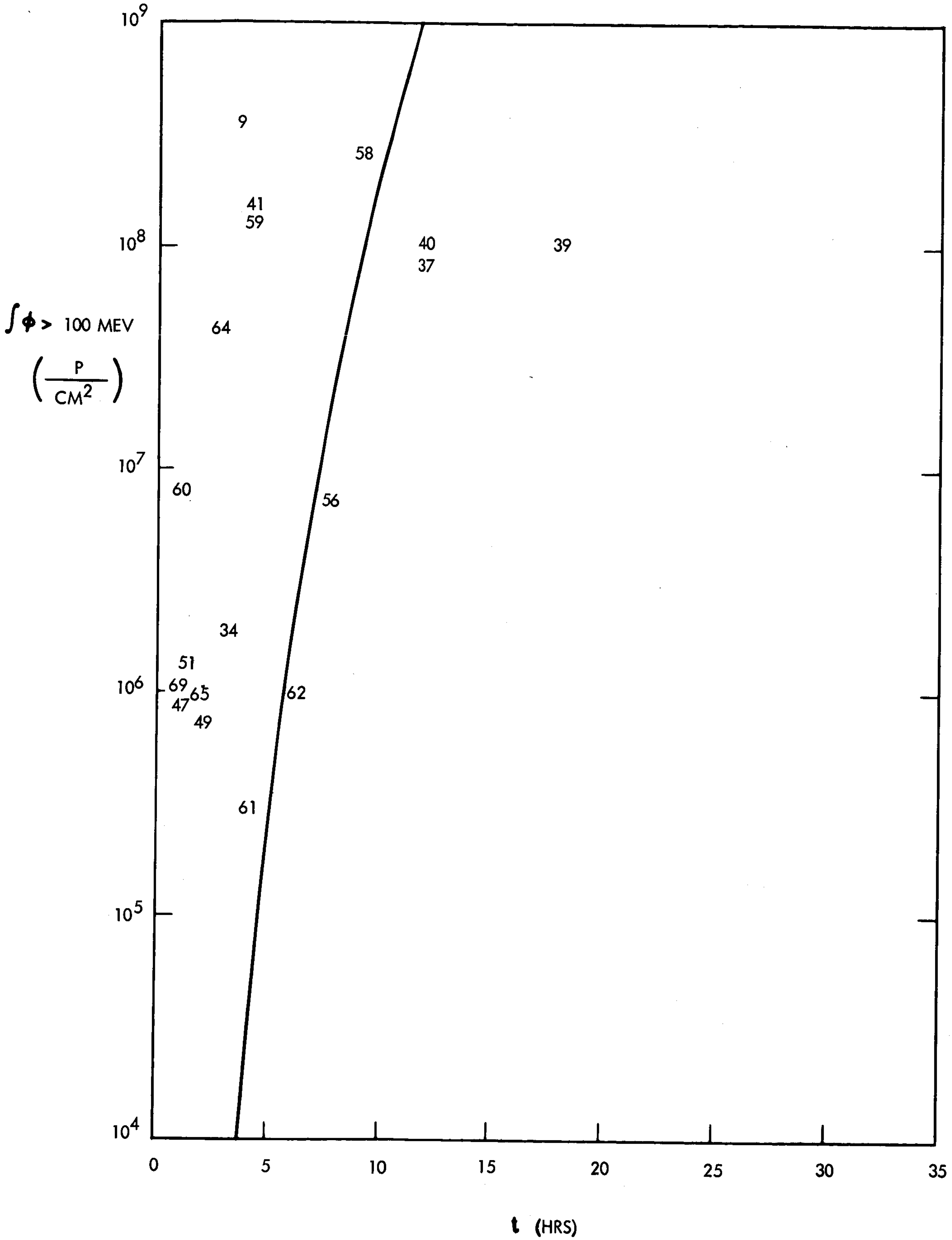

Figure 17. Integral Flux Above 100 Mev Versus Onset Plus Rise Time

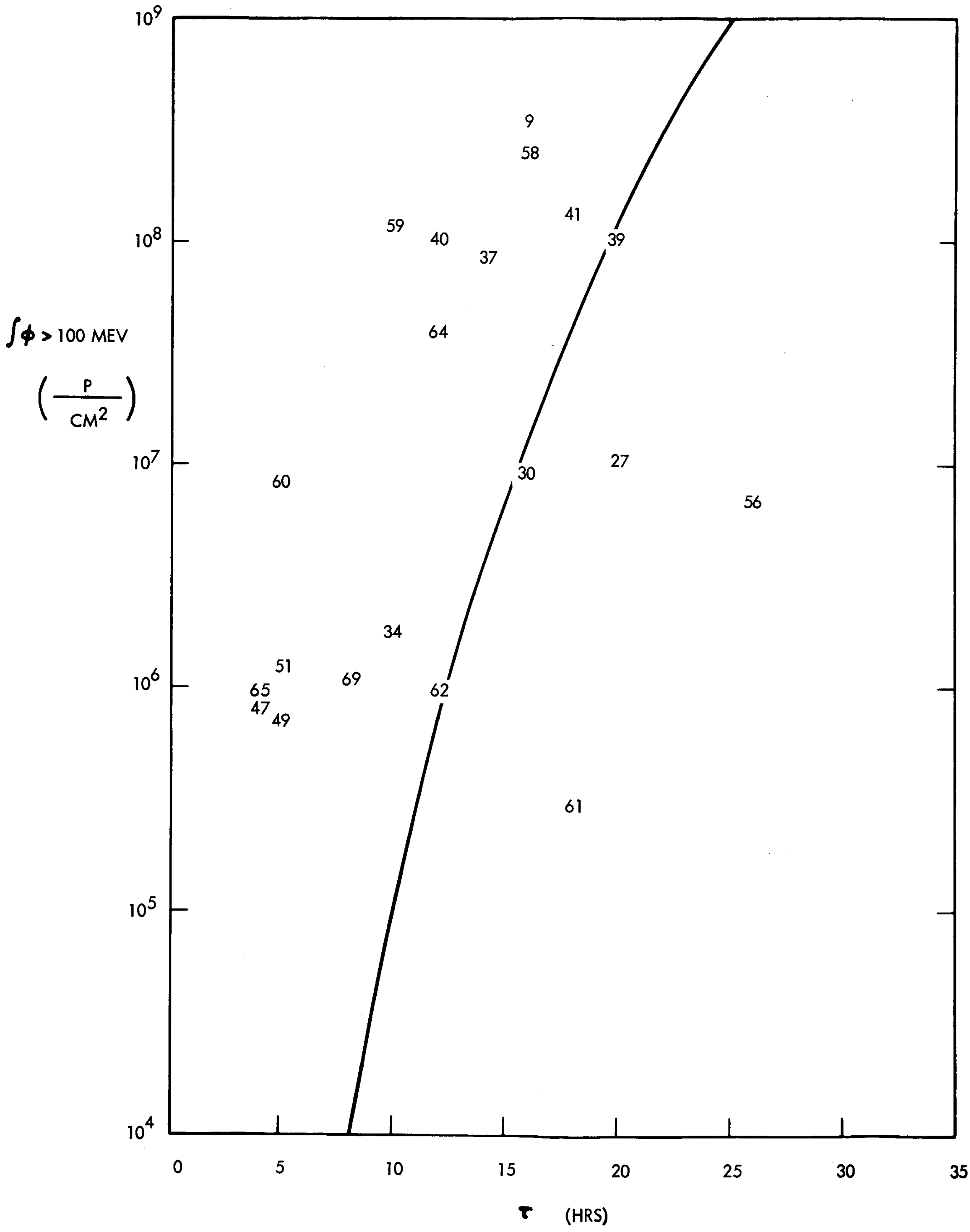

Figure 18. Integral Flux Above 100 Mev Versus Characteristic Decay Time

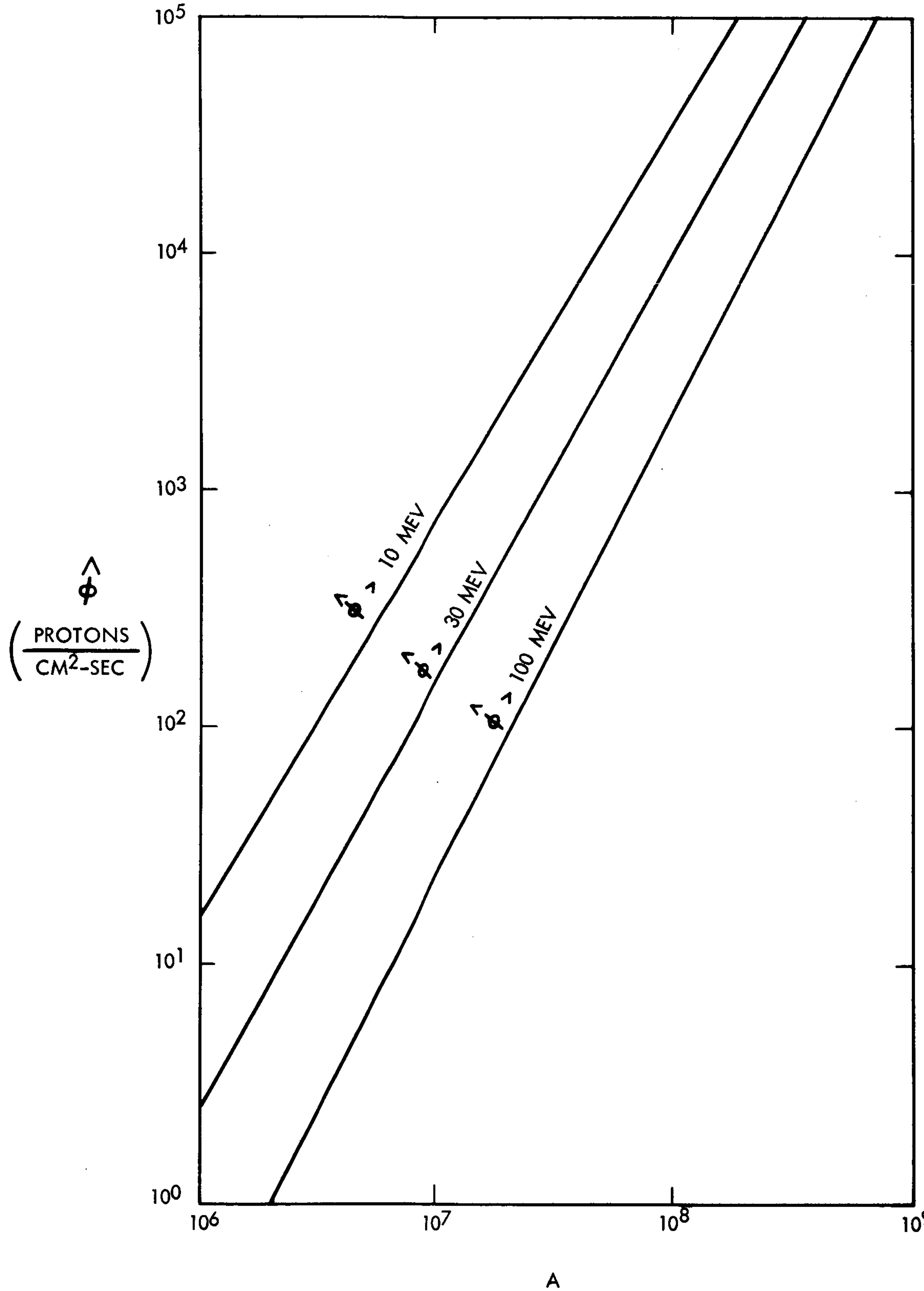

Figure 19. Calculated Peak Flux Rates Versus Parameter A

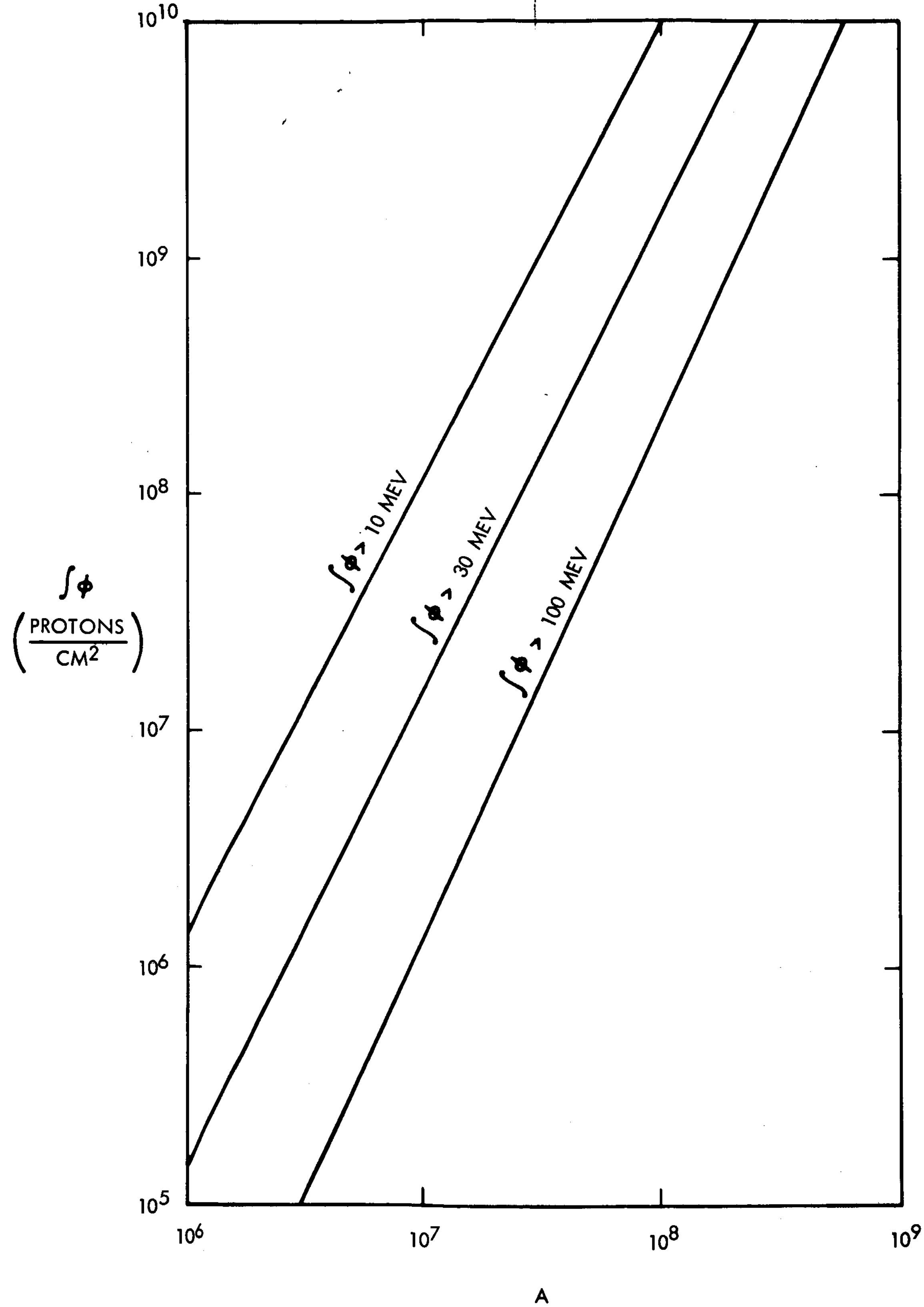

Figure 20. Calculated Integral Flux Versus Parameter A

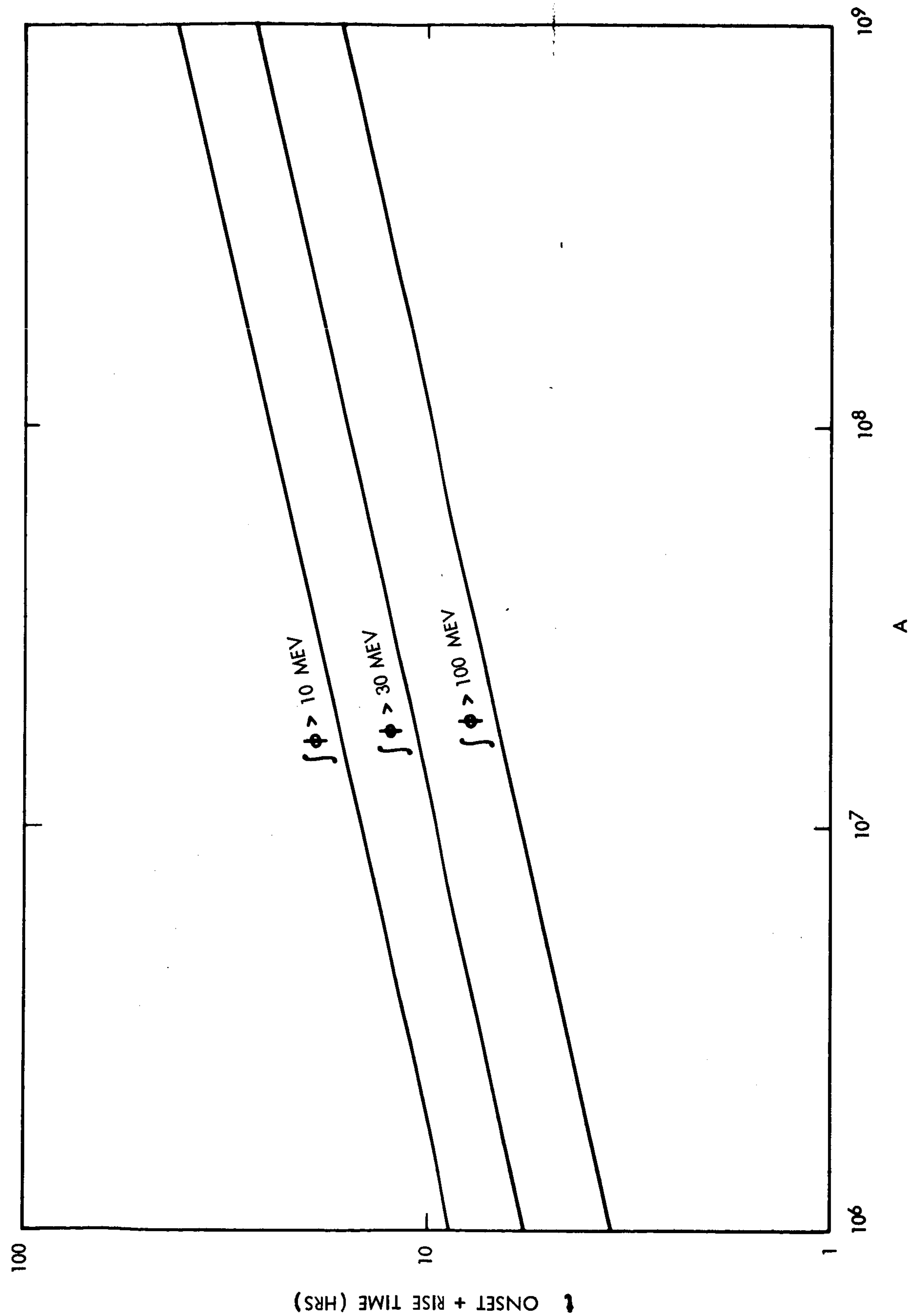

Figure 21. Calculated Onset Plus Rise Time Versus Parameter A

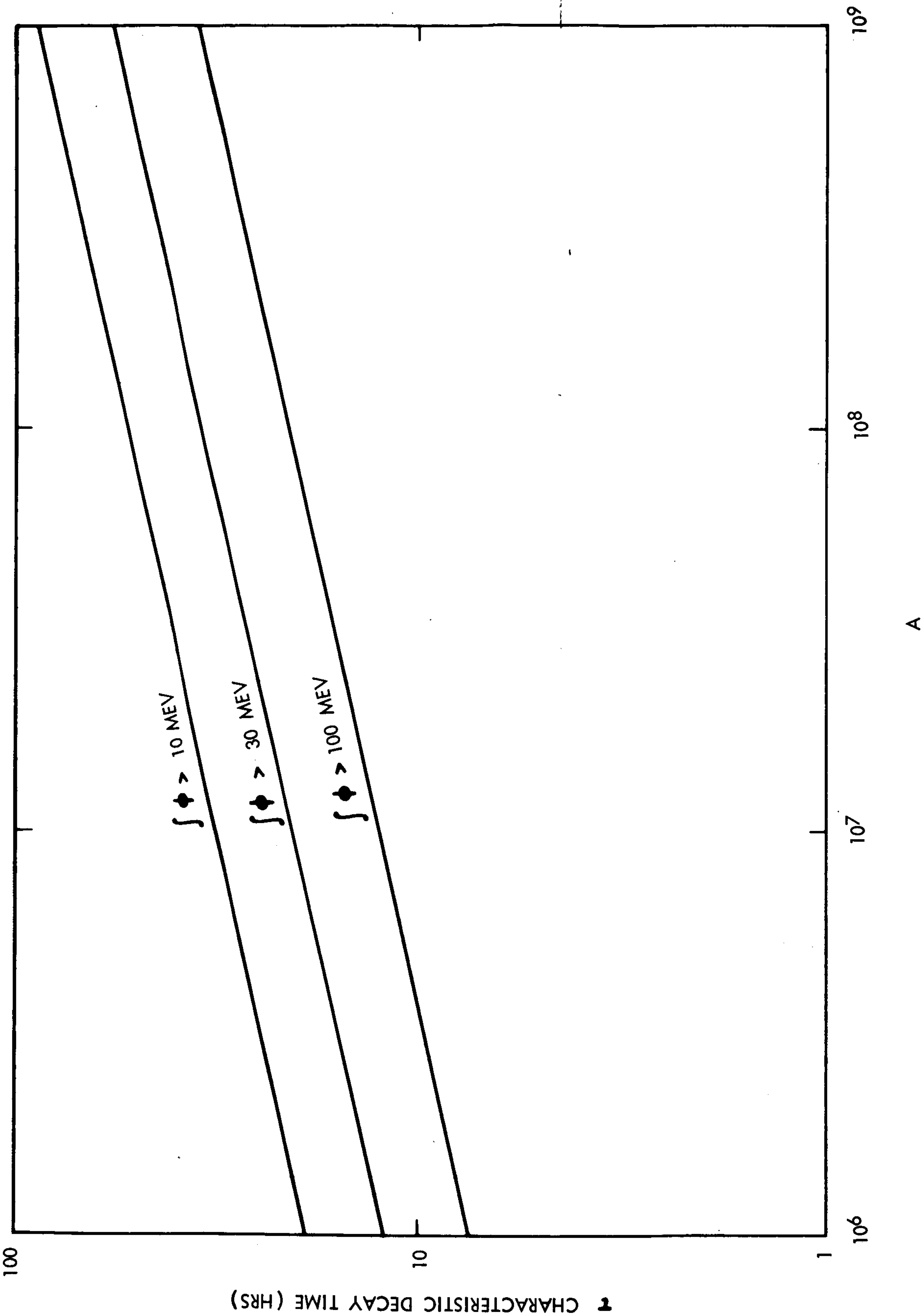

Figure 22. Calculated Characteristic Decay Time Versus Parameter A

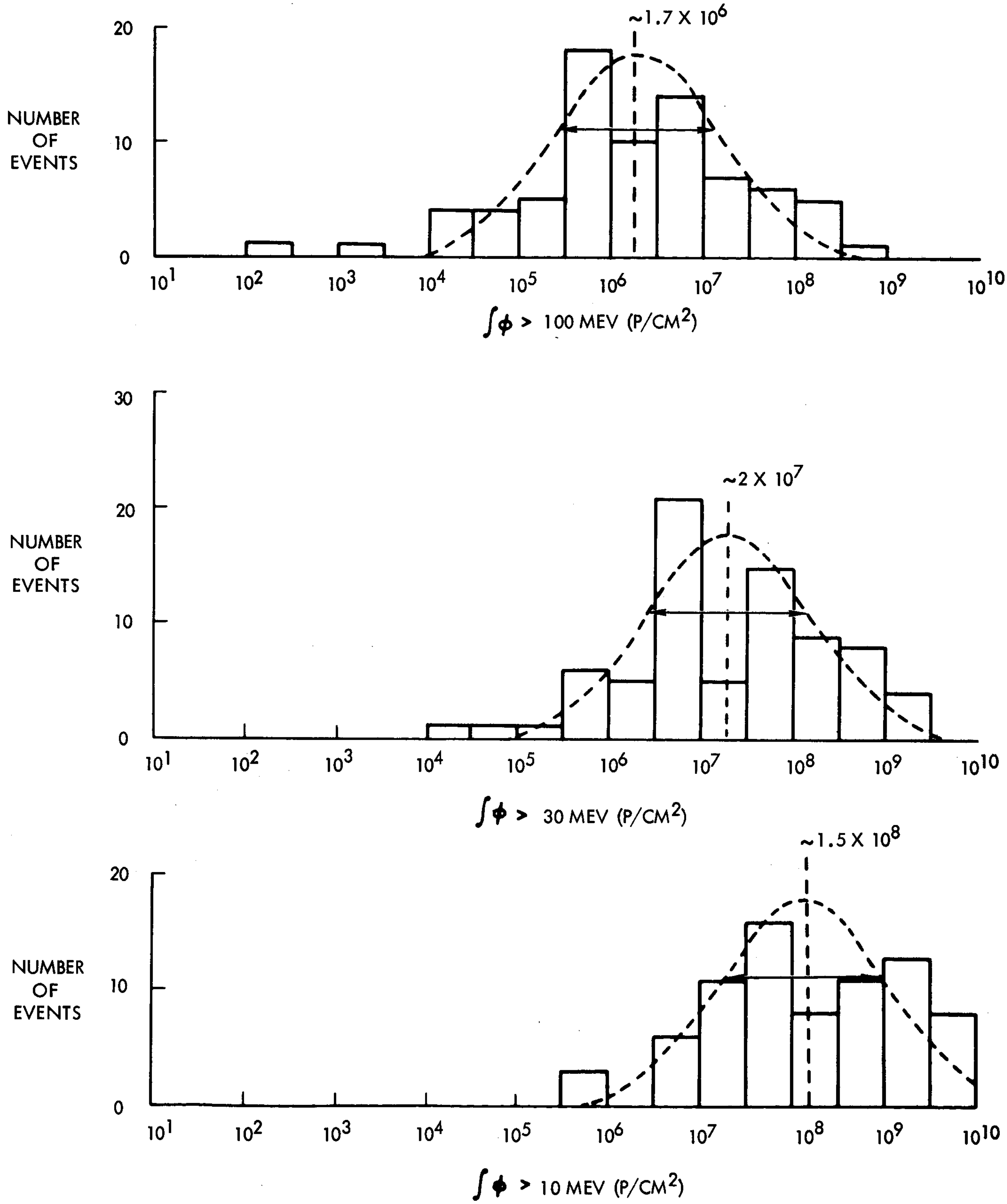

Figure 23. Distributions of Integral Flux Per Event

The most probable size of an observed event is:

$$\int \phi > 10 \text{ Mev} = \sim 1.5 \times 10^8 \text{ p/cm}^2$$

$$\int \phi > 30 \text{ Mev} = \sim 2 \times 10^7 \text{ p/cm}^2$$

$$\int \phi > 100 \text{ Mev} = \sim 1.7 \times 10^6 \text{ p/cm}^2$$

These numbers have estimated 1σ limits of a factor of ±2.

A second type of event frequency distribution concerns the number of events per month. The 72 events listed in Table 1 represent a time interval of 22 years (~264 months) (1942 through 1963), but to conclude that there has been an average of 72/264 events per month would be erroneous because many of the early events undoubtedly have been missed. From 1956 on, the probability of missing an event $\gtrsim 10^4$ p/cm^2-sec > 30 Mev has been fairly small, and 68 such events have been observed. Proceeding in this manner, the monthly probabilities of events as a function of event size over the 96 months from 1956 through 1963 can be obtained. The results are listed in Table 10. The differential percentages are listed at the left side of each column, the integral percentages are listed at the right. The maximum possible number in any column is 71 percent (68 events/96 months), and it is seen that the 50-percent probability/month event is rather small ($\sim 5 \times 10^6$ p/cm^2 > 30 Mev). The integral monthly probabilities (for events with $\int \phi$ above given values) are plotted in Figure 24.

It must be remembered that the monthly probabilities are averaged over the years 1956 through 1963. If the entire solar cycle 19 were included (~130 months), the monthly probabilities would probably have been decreased by ~25 percent, since the missing portions are near the solar minima. For the peak years of 1958-1960, the monthly probabilities would be increased. However, the limited data available do not permit this sort of analysis with much confidence.

The proton events are not distributed uniformly throughout the months, but they tend to occur in certain months. The monthly distributions for all 76 events listed in Table 1 are given in Table 11. The events missed prior to 1956 will not tend to bias the entire sample, as they would have the monthly probabilities computed above. The same data, expressed in percentages of the totals, are shown in Figure 25. It is seen that July has been by far the most active month, with 18.5 percent of the events, 24.5 percent of the proton event number (PEN), and 33 percent of the integral flux ($\int \phi$) above 30 Mev. December has apparently been the least active month, with 0 percent in all categories. However, this distribution must be viewed with

Table 10. Monthly Probabilities of Event Size for 1956-1693

Event Size (p/cm^2)	$\int \phi > 10$ Mev (Events/Month)	$\int \phi > 30$ Mev (Events/Month)	$\int \phi > 100$ Mev (Events/Month)
$> 1 \times 10^{10}$	0	0	0
$3 - 10 \times 10^9$	7.3	0	0
$> 3 \times 10^9$	7.3	0	0
$1 - 3 \times 10^9$	10.4	4.2	0
$> 1 \times 10^9$	17.7	4.2	0
$3 - 10 \times 10^8$	9.4	7.3	1.0
$> 3 \times 10^8$	27.1	10.5	1.0
$1 - 3 \times 10^8$	6.3	6.3	5.2
$> 1 \times 10^8$	33.4	16.8	6.2
$3 - 10 \times 10^7$	16.7	12.5	4.2
$> 3 \times 10^7$	50.1	29.3	10.4
$1 - 3 \times 10^7$	11.5	4.2	5.2
$> 1 \times 10^7$	61.6	33.5	15.6
$3 - 10 \times 10^6$	6.3	21.8	11.5
$> 3 \times 10^6$	67.9	55.3	27.1
$1 - 3 \times 10^6$	0	5.2	9.4
$> 1 \times 10^6$	67.9	60.5	36.5
$3 - 10 \times 10^5$	3.1	6.3	18.7
$> 3 \times 10^5$	71.0	66.8	55.2
$1 - 3 \times 10^5$	0	1.0	5.2
$> 1 \times 10^5$	71.0	69.8	60.4

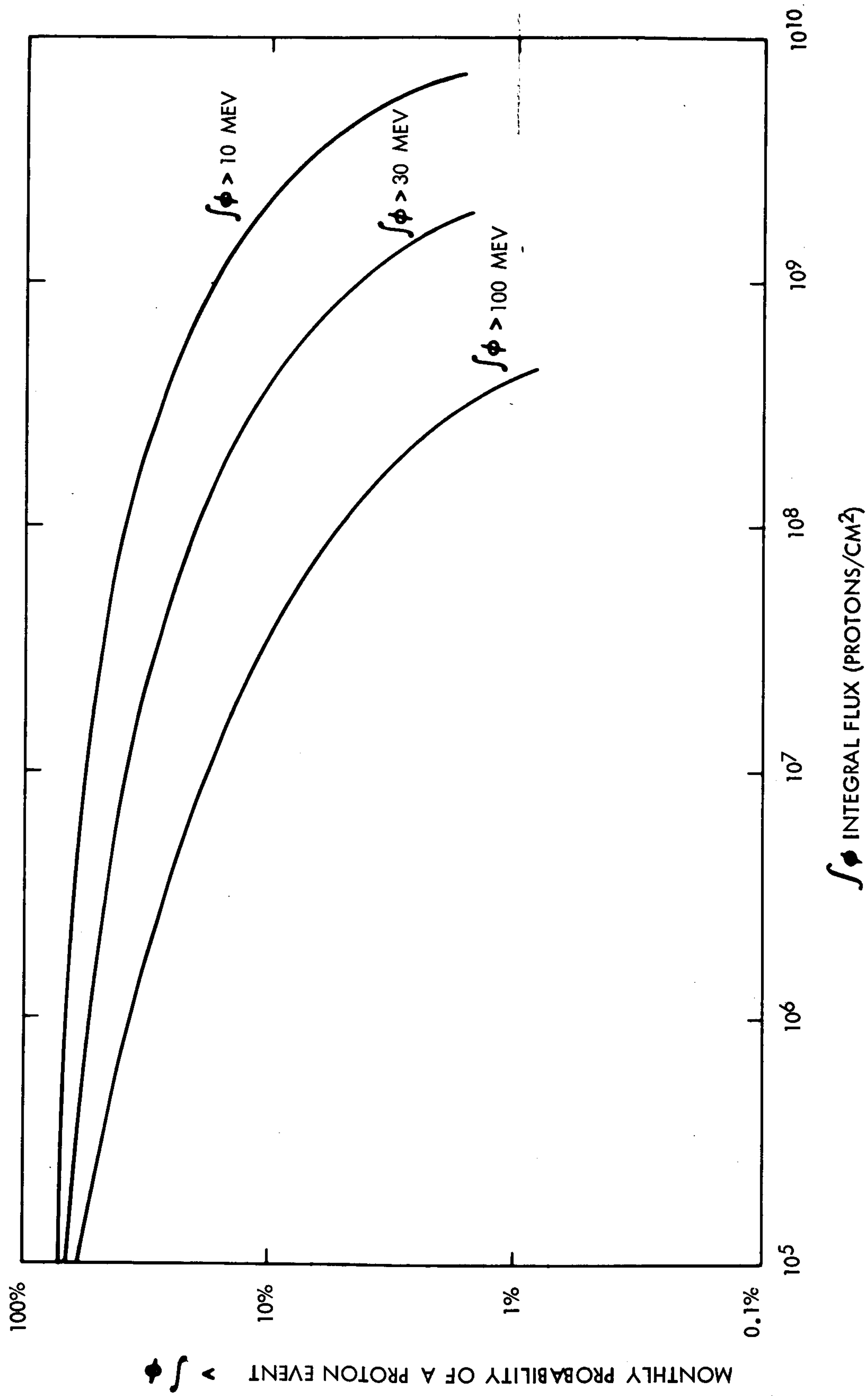

Figure 24. Monthly Proton Event Occurrence Probability

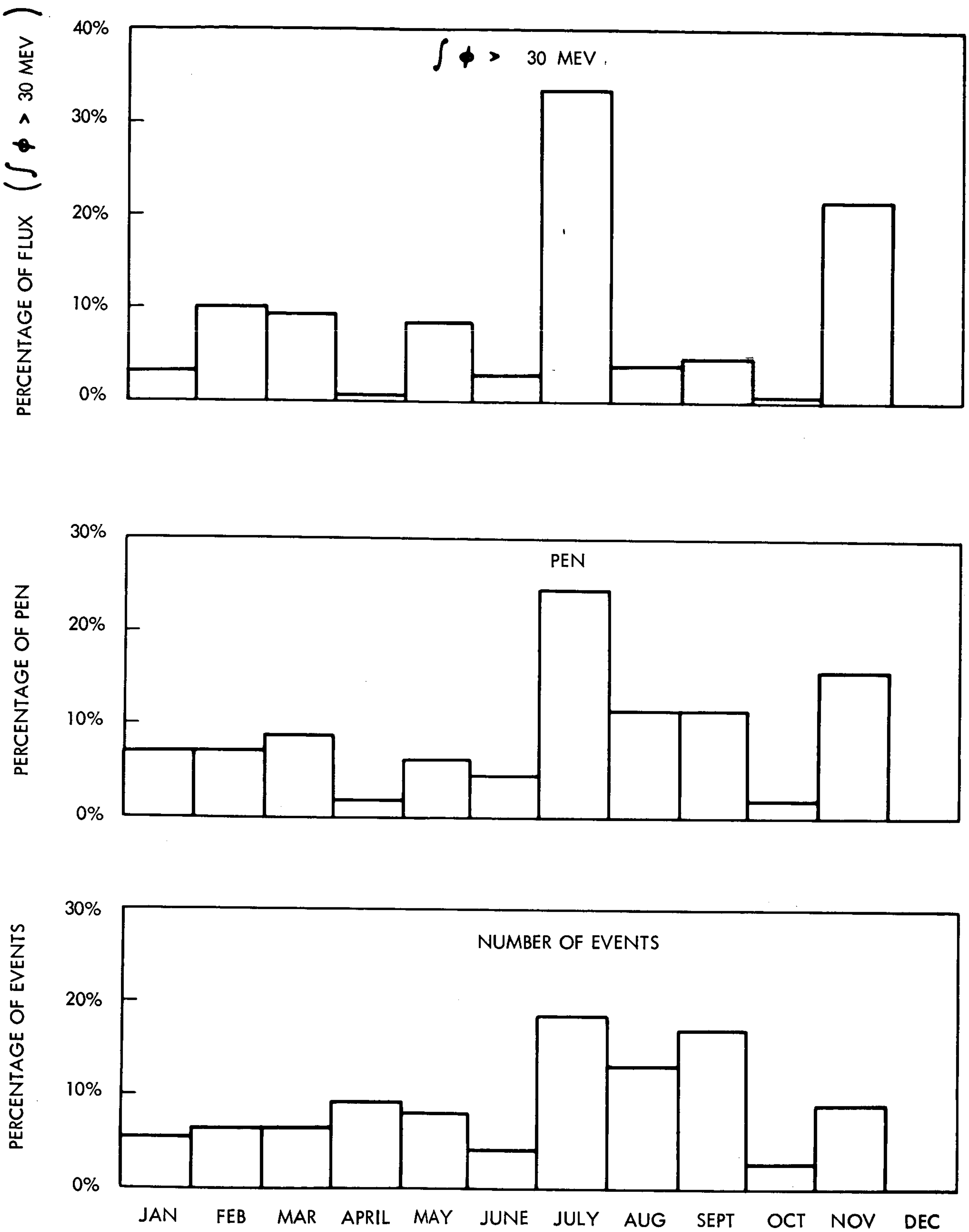

Figure 25. Monthly Distribution of Events, Event Number, and Integral Flux

Table 11. Distribution of Events by Month, 1942-1963

Month	Number of Observed Events	Proton Event Number	$\int \phi > E$ (p/cm^2) 10 Mev	30 Mev	100 Mev
January	4	8	5.5×10^9	3.6×10^8	1.6×10^7
February	5	8	2.8×10^9	1.2×10^9	3.7×10^8
March	5	10	7.5×10^9	1.1×10^9	1.0×10^8
April	7	2	5.6×10^8	7.3×10^7	6.7×10^6
May	6	7	6.2×10^9	1.0×10^9	9.4×10^7
June	3	5	2.0×10^9	2.4×10^8	2.2×10^7
July	14	28	2.0×10^{10}	4.0×10^9	4.1×10^8
August	10	13	3.7×10^9	4.5×10^8	2.3×10^7
September	13	13	3.7×10^9	5.5×10^8	6.5×10^7
October	2	2	2×10^8	5×10^7	1×10^7
November	7	18	1.1×10^{10}	2.6×10^9	4.4×10^8
December	0	0	0	0	0
Totals	76	114	6.5×10^{10}	1.2×10^{10}	1.5×10^9

some suspicion. While the earth is 7 degrees above the solar equator in July, and most of the events in solar cycle 19 took place at northern solar latitudes, these two facts may very well be unrelated. An alternate (and probably equally plausible) explanation is that balloon measurements of solar proton events require high geomagnetic latitudes, which are far less attractive in December than in July in the Arctic.

One can conclude that the probability of a proton event varies inversely with some function (approximately the logarithm) of event size, and that both the number and size of the probable events increase when the sun is active. The monthly event probabilities (Figure 24) should be corrected for the appropriate portions of the solar cycle and perhaps for the actual months involved (Figure 25) before applying them to mission analysis studies.

DEPENDENCE ON SOLAR DISTANCE

It is sufficient for purposes of establishing radiation protection requirements to determine the dependence on solar distance of the total flux of flare-associated protons in each solar proton event, as a function of proton energy. The motion of a spacecraft during a proton radiation event has negligible effect on the radiation environment. It is obvious from the requirement of conservation of particles that the total flux at any energy should vary as the inverse square of the solar distance, unless the protons are confined to some channel or tube by interplanetary magnetic fields. A proof is presented later that this inverse-square dependence holds if the interplanetary magnetic field is that due to the solar field in the steadily expanding corona.

The adequate design of spacecraft instrumentation to measure the particulate radiation environment requires knowledge of the expected effect of solar distance on the temporal and angular dependence of the flare-associated proton flux as a function of proton energy. Consideration of angular dependence is beyond the scope of this program, although the evaluation of temporal dependence included analysis of the angular distribution of the proton flux versus energy and solar distance.

Theoretical Basis of Model

In order to express the dependence of the proton flux on energy, time, and solar distance, a model must be used which quantitatively describes the processes by which a solar flare transfers energy to protons in the solar atmosphere and by which the protons are transported through the interplanetary medium. The model selected in this work is based on:

1. Acceleration of protons by Lorentz forces in a hydromagnetic shock wave induced in the solar corona by absorption of electromagnetic radiation emitted by a flare

2. In the absence of local irregularities in the interplanetary medium, circular motion of energetic protons about guiding centers that move parallel to the interplanetary magnetic field vector

3. Random walk of energetic protons which enter local plasma concentrations containing disordered magnetic fields.

The results of these assumptions agree in many respects with the temporal and angular distribution of flare-associated proton energy spectra observed in the vicinity of the earth, as will be demonstrated.

Reasonable confidence, therefore, may be placed in the solar distance relationships based on this model.

Proton Acceleration by Hydromagnetic Shocks

It has been shown by Parker (Reference 52) that the sudden expansion of the solar corona, as a result of the absorption of electromagnetic radiation emitted by a flare, creates a hydromagnetic shock wave in the corona. This shock carries with it a disturbance of the interplanetary magnetic field, which does work on the solar wind protons overtaken by the shock. The accelerated protons are scattered forward of the shock by an approximately thermal process and are transported through the generally steady interplanetary magnetic field. The emergent protons remove energy from the shock wave, which gradually weakens and disappears. Superposition of the proton energy distributions emerging from shocks in all regions of the corona heated by the flare permits calculation of the time-dependent angular distribution versus energy of the protons arriving at a point at a given distance from the sun (Reference 54).

The magnetic field in the steadily expanding solar corona ahead of the shock is swept back azimuthally from the radial direction due to solar rotation relative to the coronal plasma. The components of the field in the solar equatorial plane are given by Parker (Reference 55) as

$$B_r(r, \theta, \phi) = B_r(r_1, \theta, \phi - r\Omega/u_o^x)\,(r_1/r)^2 \tag{40}$$

$$B_\theta(r, \theta, \phi) = 0 \tag{41}$$

$$B_\phi(r, \theta, \phi) = B_r(r_1, \theta, \phi - r\Omega/u_o^x)\left(\frac{r_1\Omega}{u_o^x}\right)\left(\frac{r_1}{r}\right)\sin\theta \tag{42}$$

where r, θ, and φ are the radial, polar, and azimuthal heliocentric coordinates; Ω is the sidereal angular velocity of the sun; and u_o^x is the solar wind transport velocity; i.e., the velocity of steady coronal expansion. When the leading edge of the shock wave is at $r = R_1$ and its trailing edge is at $r = R_2$, the magnetic field just inside the shock at $r > R_2$ is

$$B_{x_2} = B_{x_1} \tag{43}$$

$$B_{y_2} = B_{y_1} \left(\frac{f^2}{1 - g}\right)\left(\frac{R_2}{R_1}\right)^4 \left(\frac{r}{R_2} - 1\right)^{1-g} \tag{44}$$

$$B_{z_2} = B_{z_1} = 0 \tag{45}$$

In Equation 44, f and g are functions of the dimensionless shock parameter λ (Reference 52). A convenient form of the field inside the shock, reasonably accurate except when r is very slightly larger than R_2, is the plane wave

$$B_i(x, y, z, t) = B_{i_1} + \left(\frac{x - vt}{x_2}\right)(B_{i_2} - B_{i_1}), \tag{46}$$

$$0 < t < t_2$$

$$x_2 = vt_2 \tag{47}$$

where i = 1, 2, 3 denotes the x-, y-, z-components, respectively, v is the velocity of the leading edge of the shock which passes the observer at t = 0, and the trailing edge passes him at $t = t_2$ (Reference 53).

If the magnetic field given by Equation 46, and a weak radial electrostatic field corresponding to a potential of 10^4 volt (the upper limit of solar wind proton energies is near 10^4 ev) between the sun and a point at 1 AU, are used in solution of the relativistic ponderomotive equations (References 53 and 54) of protons encountering the shock, the protons are found to reach energies from 1 Mev to about 400 Mev. Acceleration of a given proton terminates when it is scattered into the region in front of the shock. Coulomb and Rutherford scattering in the hot (5×10^5 to 2×10^6 degrees K) and nearly collisionless plasma are essentially random processes (Reference 54), so that the protons emerging from the shock have an isotropic angular distribution about the normal to the shock. The flux per unit time duration of the solar flare and the mean energy of the emerging protons are plotted in Figure 26 as functions of the heliocentric distance of the point of emergence. These results are for $\lambda = 4/3$ and are very similar to results for other values of λ in the allowed range $1 < \lambda < 3/2$.

Proton Transport in Regular Interplanetary Medium

A proton can reach a receiver point if the guiding center of its trajectory passes the receiver at a distance equal to the gyroradius measured at the receiver. The proton must emerge from the shock at a distance from the guiding center equal to the gyroradius at the point of emergence.

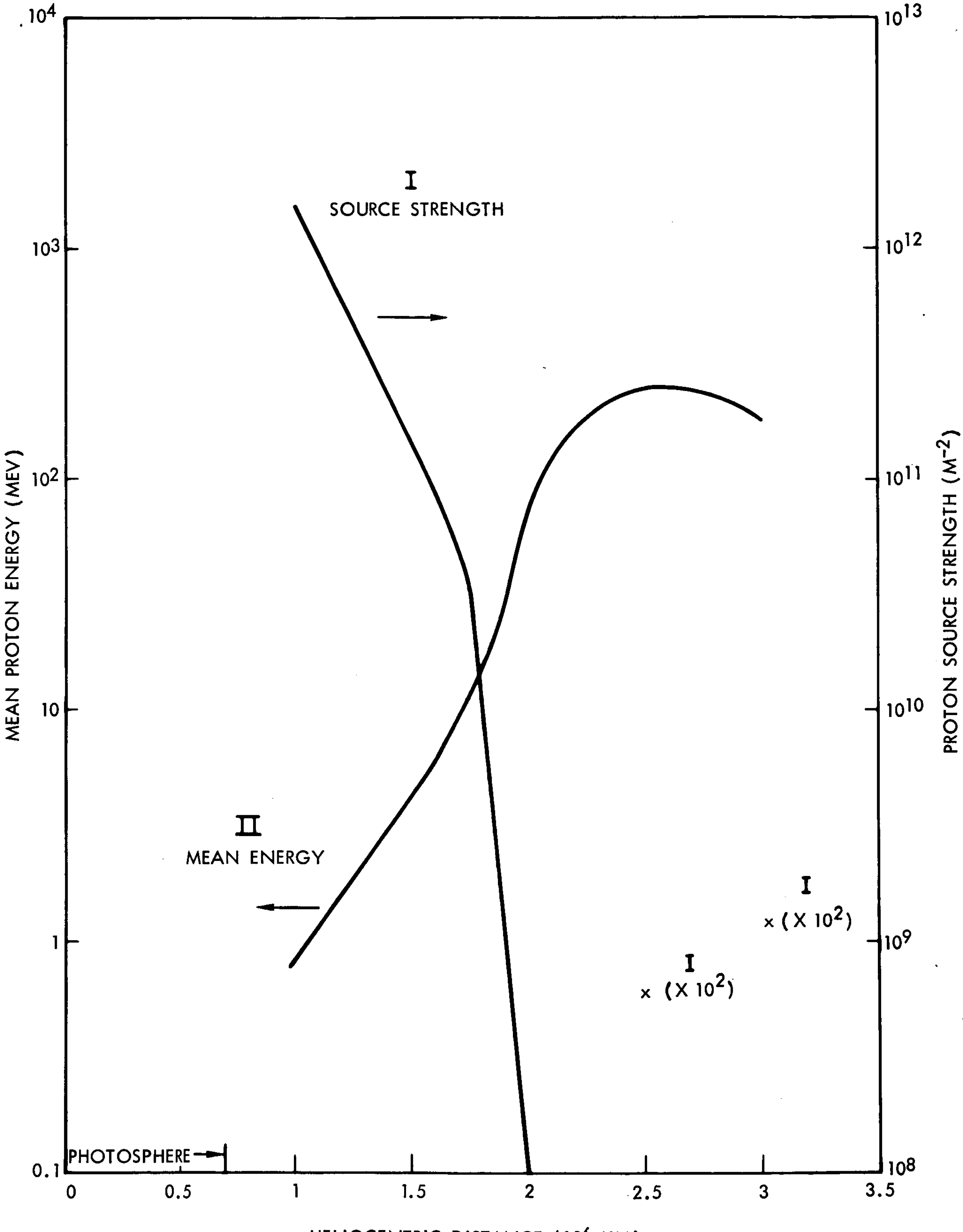

Figure 26. Proton Source Distribution Due to Hydromagnetic Shock

A typical trajectory is illustrated in Figure 27. It is a helical curve wrapped on a horn-shaped solid with a curving axis and an expanding cross-sectional radius.

In the unshocked corona, a magnetic line of force makes an angle with a heliocentric radial line given by (Reference 55)

$$\xi = \tan^{-1} (B_\phi / B_r) \tag{48}$$

$$\xi = \tan^{-1} \left(\frac{\Omega r \cos \theta}{u_o^x} \right) \tag{49}$$

From Equations 40, 41, 42, 48, and 49, the field intensity at a point on the solar equatorial plane ($\theta = 0$) is

$$B(r) = B(r_1) \left[(r_1/r)^4 + (r_1 \Omega / r u_o^x)^2 \right]^{1/2} \tag{50}$$

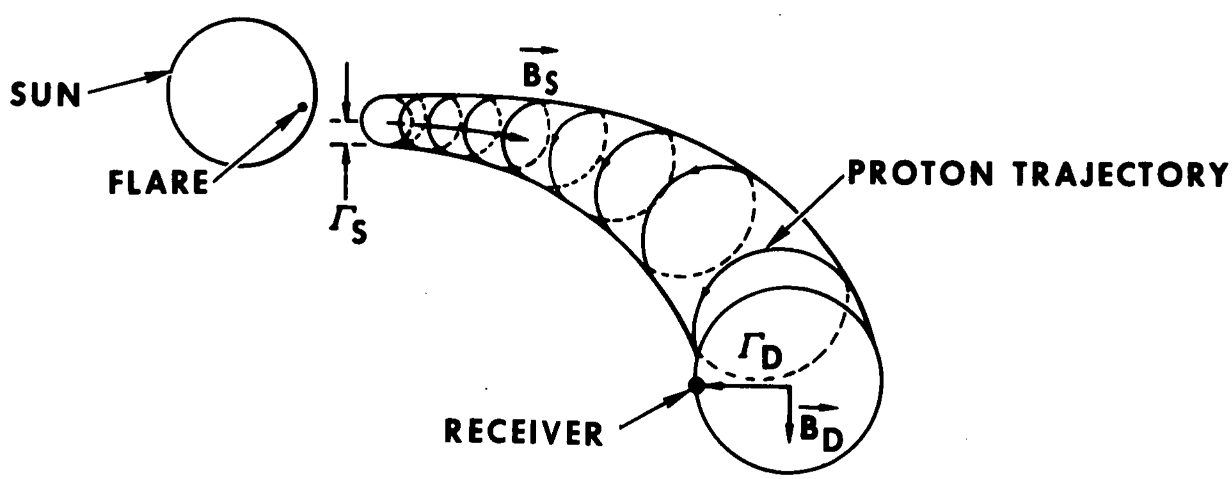

Figure 27. Proton Trajectory in Undisturbed Interplanetary Magnetic Field

The distance of an allowed emergence point from the line of force along which the guiding center of the proton moves is

$$\Gamma_s = \frac{m_o}{qB_s}\left(1 - \frac{u_s^2}{c^2}\right)^{-1/2} u_s \sin\beta \tag{51}$$

where B_s is the undisturbed field at the emergence point ($r = r_s$), u_s is the velocity of the scattered proton, β is the pitch angle of the trajectory, m_o is the proton rest mass, c is the velocity of light, and q is the proton charge. The field varies so slowly along the trajectory ($\lesssim 6 \times 10^{-3}$ gauss sec^{-1}) that β and u_s are very nearly adiabatic invariants of the motion. The proton arrives at the receiver from a direction at an angle β to the local field direction; the flux is axially symmetric about the field direction except for a brief initial period comparable to one gyration period. The distance (Γ_D) of the proton from its guiding center when it reaches the receiver is given by an equation similar to 51 with B_s replaced by B_R, the field at the receiver, which is found from Equations 40, 41, and 42 with $r = r_R$. The proton flux emerging from the shock at r_s with a given pitch angle $\beta<90$ degrees is, therefore, attenuated by a factor $(r_s/r_R)^2$ at the receiver ($r = r_R$).

The time of flight of a proton from its point of emergence from the shock to the receiver is the integral of the gyration period along the trajectory,

$$t_R = \frac{\dfrac{2\pi}{u_s}\displaystyle\int_{(r_s,\phi_s)}^{(r_R,\phi_R)} \Gamma(r) \sec\beta \, d\ell}{\displaystyle\int_{(r_s,\phi_s)}^{(r_R,\phi_R)} d\ell} \tag{52}$$

where $d\ell$ is an element of the path (i.e., the line of force) followed by the guiding center. The line integrals in Equation 52 can be transformed to integrals over the radial coordinate r by

$$d\ell = \sec\xi \, dr = \left[\left(\frac{\Omega u_o x}{r}\right)^2 + 1\right]^{1/2} dr \tag{53}$$

The structure of the field is such that the gyroradius at any solar distance $r > r_s$ is

$$\Gamma(r) = \Gamma_s (r_s/r)^2 \left[\left(\frac{\Omega u_o^x}{r} \right)^2 + 1 \right]^{1/2} \tag{54}$$

so for $r_R > r_s$

$$t_R = \frac{2m_o}{3qB_s} \left(1 - \frac{u_s^2}{c^2} \right)^{-1/2} (r_s^2 \tan \beta) \cdot \frac{\Omega^2 (u_o^x)^2 \left(\frac{1}{r_s^3} - \frac{1}{r_R^3} \right) + 3 \left(\frac{1}{r_s} - \frac{1}{r_R} \right)}{(r_R^2 - r_s^2)^{1/2} - \Omega u_o^x \, \ell n \left\{ \frac{r_s [1 + (1 + r_R^2/\Omega^2 u_o^{x2})^{1/2}]}{r_R [1 + (1 + r_s^2/\Omega^2 u_o^{x2})^{1/2}]} \right\}} \tag{55}$$

The time of flight can be measured with reasonable accuracy from the beginning of the flash phase of the flare, when coronal heating is maximum. The results must be corrected for the time required for light emitted by the flare to reach the receiver. The time of flight t_R is much longer than the time required for light from the flare to reach the region in which acceleration occurs.

Results of this analysis are presented later in this section.

Proton Interaction with Irregularities in Medium

Magnetometers carried on interplanetary spacecraft such as Mariner 2 (Reference 56) reveal a highly disordered structure of the magnetic field in regions where the concentration of protons at energies from 10^2 to 10^4 ev is significantly greater than their concentration in the steady solar wind. These regions, referred to below as "plasma clouds," apparently result from solar activity and may be injected into space in association with the flare which produces a given energetic proton radiation event, or in association with a previous flare or eruptive prominence. The region moves outward from the sun at a velocity comparable to that of a hydromagnetic shock wave in the outer corona, i.e., about 1.0×10^6 to 1.5×10^6 m sec^{-1}, reaching 1 AU in 1.0×10^5 to 1.5×10^5 sec. If a given energetic solar proton radiation event has been preceded within one to three or four days by another such event which produced a plasma cloud, this cloud affects the energetic proton radiation environment associated with the later event. A proton event not preceded by formation of a plasma cloud is affected by the cloud (if any) accompanying this event. The magnetic field in the plasma cloud has the effect of greatly prolonging the time required for a proton to traverse the cloud. Protons magnetically trapped in the cloud generally remain in the cloud for several hours and are transported in the cloud away from the sun.

Magnetic field measurements inside plasma clouds support the assumption that each component of the field (induction) vector $\vec{B}$ has a Gaussian distribution about zero. The rms average scalar field intensity $\overline{B}$, therefore, has a χ-distribution (Reference 57) with rms average value

$$\overline{B} = \sigma_B \sqrt{3} \tag{56}$$

where σ_B is the standard deviation of a component of $\vec{B}$ from the mean value of zero. The magnetic energy density $E_B = |\vec{B}|^2/8\pi$ has the corresponding χ^2-distribution. A reasonable value of $\overline{B}$ is 10 B_e, where B_e is the scalar field intensity outside the plasma cloud; the components of B_e are given by Equations 40, 41, and 42. Plasma cloud diameters apparently range from about 0.1 R_o (Reference 58) to about R_o (References 59 and 60), where R_o is the heliocentric distance of the geometric centroid of the cloud.

In order to evaluate the energetic proton concentration inside a plasma cloud, the probability of reflection of an externally incident proton at the plasma boundary was calculated. The proton will be reflected if its pitch angle β about the external magnetic field (B_e) satisfies

$$\sin^2 \beta > B_e/B_i \tag{57}$$

where B_i is the field intensity in the cloud at the point of incidence, selected from the χ-distribution with rms average value $\overline{B}$. It can be shown (Reference 61) that the probability that (B_i/B_e) will correspond to the condition of Equation 57 is

$$P\,(B_i > B_e \sin^2 \beta) = 1 - \frac{B_e/\overline{B}}{2\sqrt{6\pi}\,\sin^2\beta} \sum_{n=0}^{\infty} \frac{(-3B_e^{\,2}/2\overline{B}^2 \sin^4 \beta)^n}{\left(n + \frac{3}{2}\right) \cdot n\,!} \tag{58}$$

The probability of absorption of the proton by the plasma,

$$P_a = 1 - P(B_i > B_e \sin^2 \beta) \tag{59}$$

is plotted in Figure 28 as a function of β for various values of $(\overline{B}/B_e)$ in a spherical plasma cloud surrounded by a uniform field B_e.

If a proton enters the plasma, it is assumed to perform random walk on the vector space $\{\vec{r}\}$, $r < R$, where $\vec{r}$ is the displacement of the proton in one step of the walk from its position at the beginning of the step (the position $\vec{r}$ is measured from the center of the cloud), and R is the plasma cloud radius (Reference 62). The step length $(\delta\vec{r})$ of the random walk is variable and is selected from a χ-distribution in which the rms average scalar displacement equals the gyroradius of the proton in the magnetic field at the beginning of the step,

$$\overline{\delta r} = \frac{m_o cu}{q(c^2 - u^2)^{1/2} \left|\vec{u} \times \vec{B}\right|} . \tag{60}$$

where u is the proton velocity. The field intensity B is selected from a χ-distribution as previously described; values of the angle between $\vec{u}$ and $\vec{B}$ are isotropically distributed. If $r > R$, the proton reaches the plasma boundary and emerges.

The distribution r(t) was calculated for particles with $r < R$ after $n = 250$, 500 and 1000 steps, at proton energies of 1, 10, and 100 Mev. The distribution of the time t_R when particles first reach $r = R$ was also calculated in order to establish the median time $\overline{t}_R$ at which one-half of the particles initially in the plasma have escaped. A practical upper bound of the effect of the plasma was sought by using $R = (2/3)\, R_o$, with $R_o = 1$, 1.41, and 2 AU. Figure 29 presents a typical position distribution r(t); here $E = 100$ Mev, $R_o = 1$ AU, $B_e = 3\gamma$ $(3 \times 10^{-5}$ gauss), $\overline{B} = 30\gamma$, $n = 500$ steps, and 50 protons are assumed initially present. The sample size corresponds to a probable error of 14 percent in the concentration, which is smaller than the uncertainties in B_e and $\overline{B}$. The distribution of escape times t_R in this case is shown in Figure 30.

Results

The time-dependent energy distributions of protons reaching points at 1, 1.41, and 2 AU following isotropic emergence from a hydromagnetic shock were calculated from the source function given graphically in Figure 26, using Equations 51 and 55. These results, presented as the solid curves in Figures 31, 32, and 33, are based on a hydromagnetic shock parameter

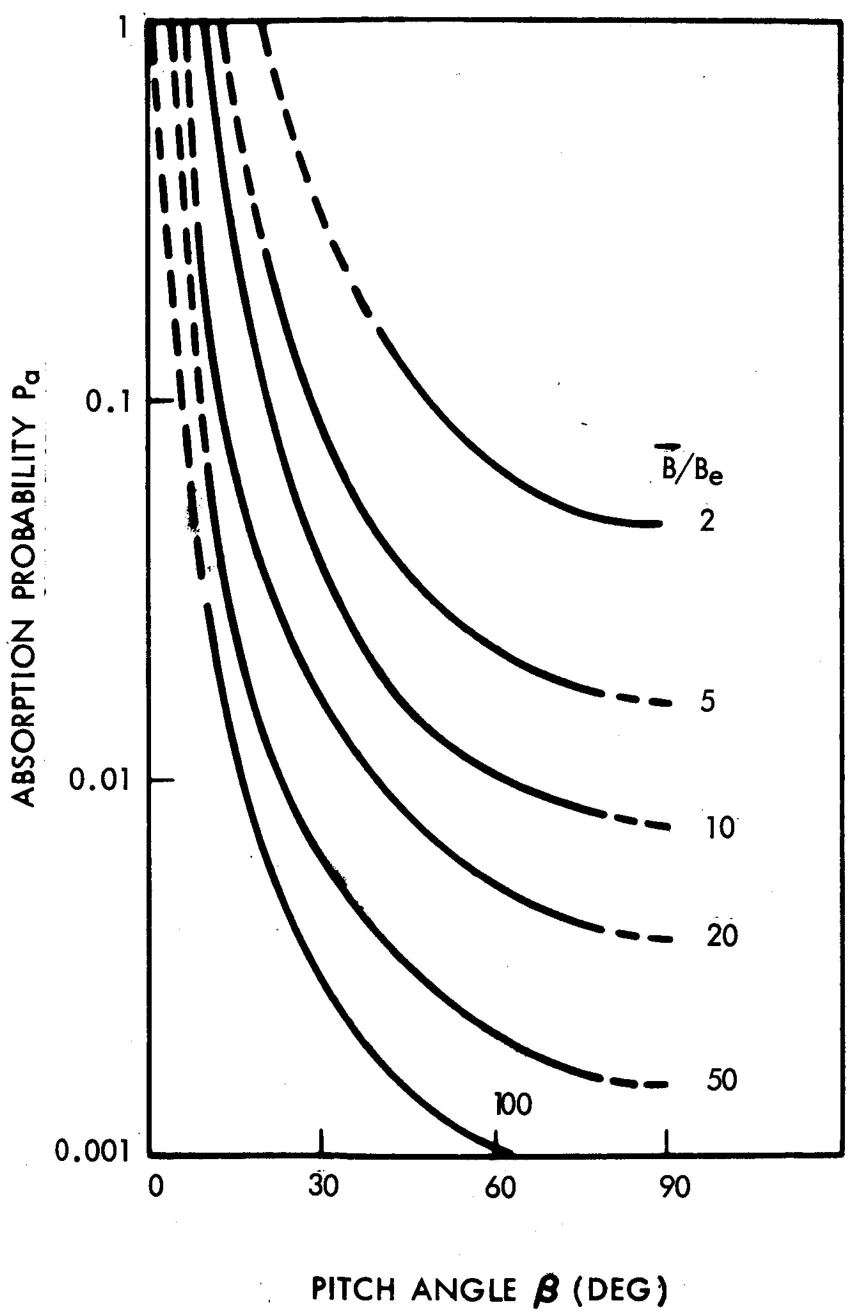

Figure 28. Probability of Absorption of Proton in Plasma

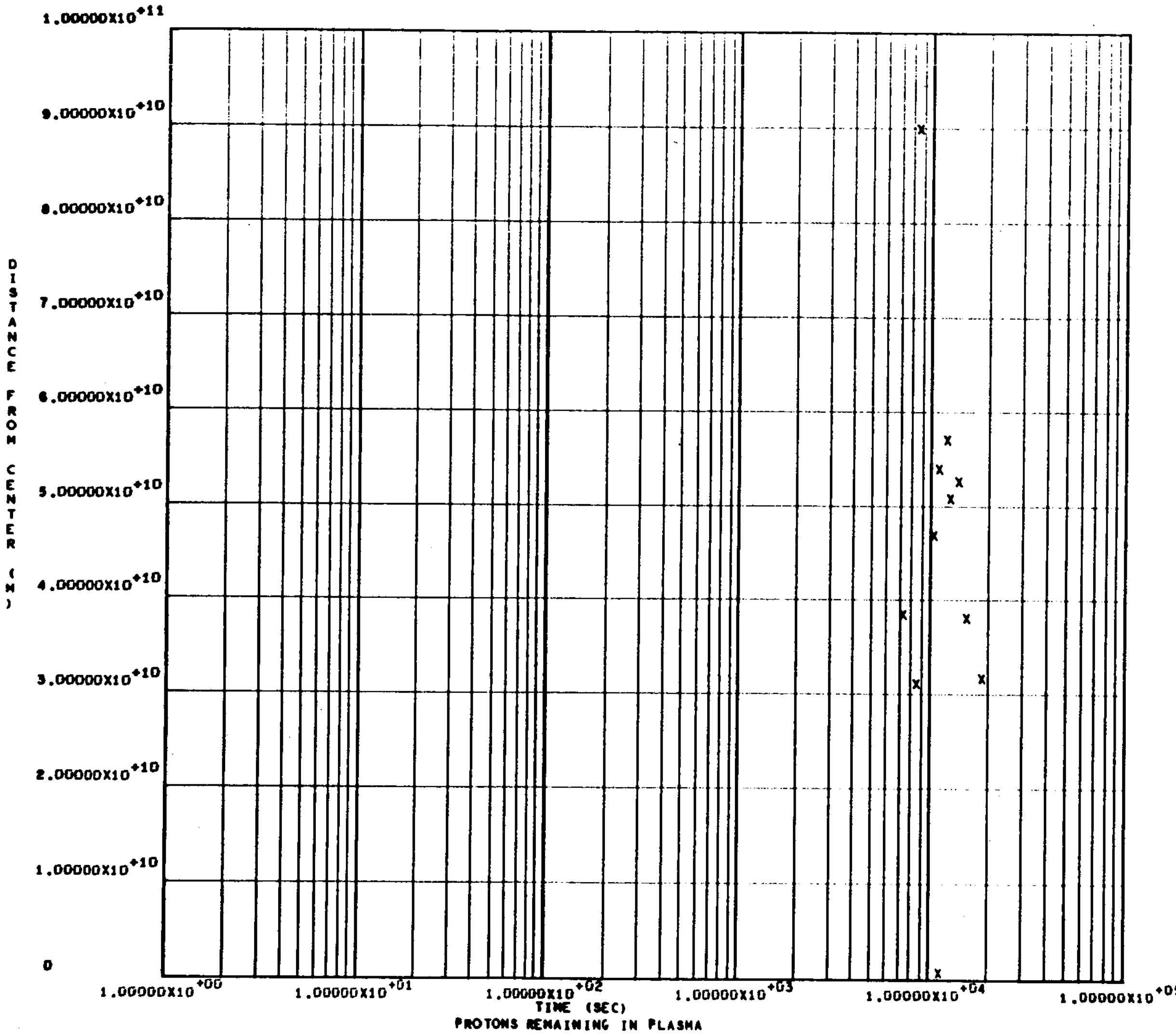

Figure 29. Space-Time Distribution of Protons in Plasma

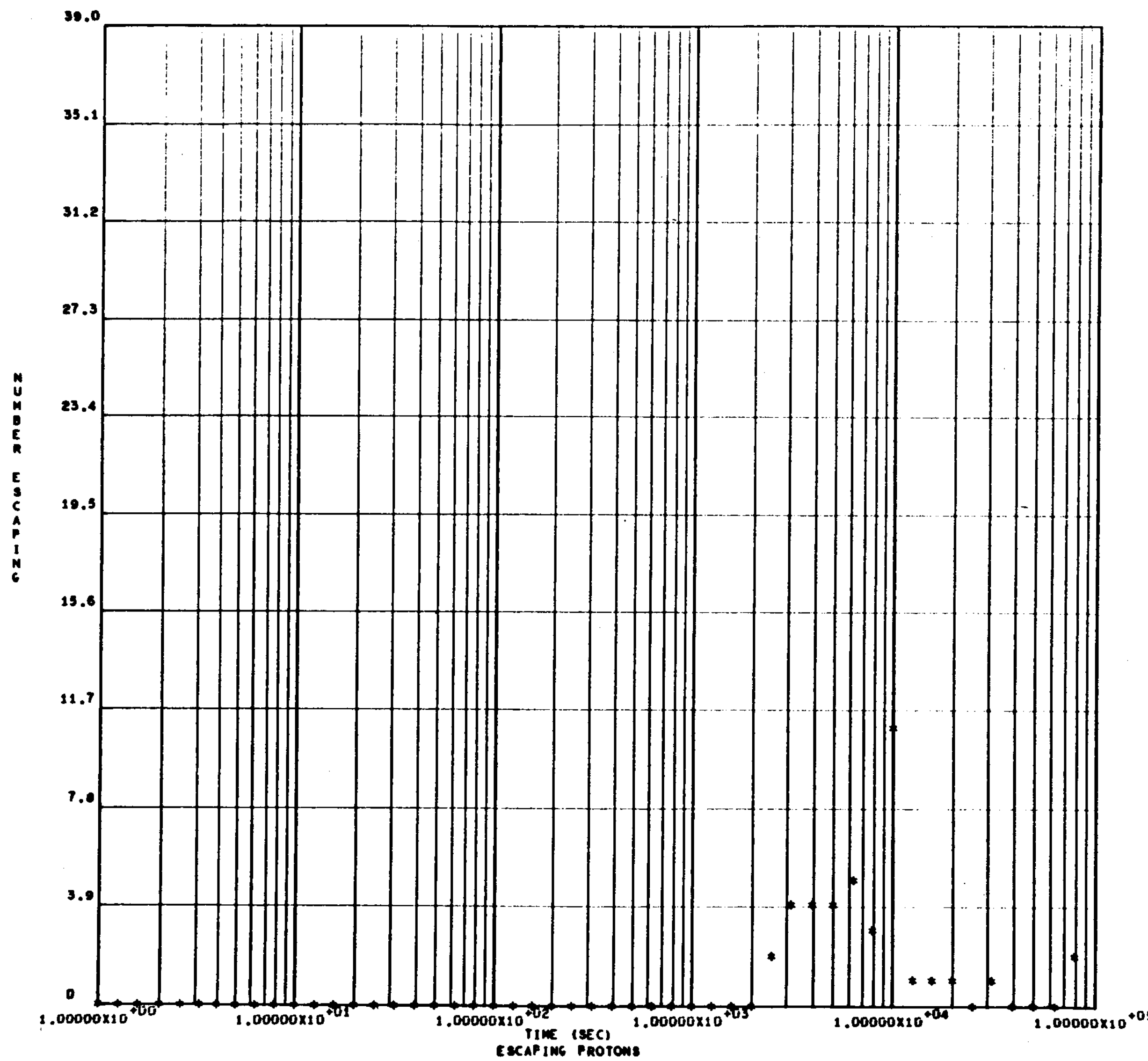

Figure 30. Distribution of Proton Escape Times from Plasma

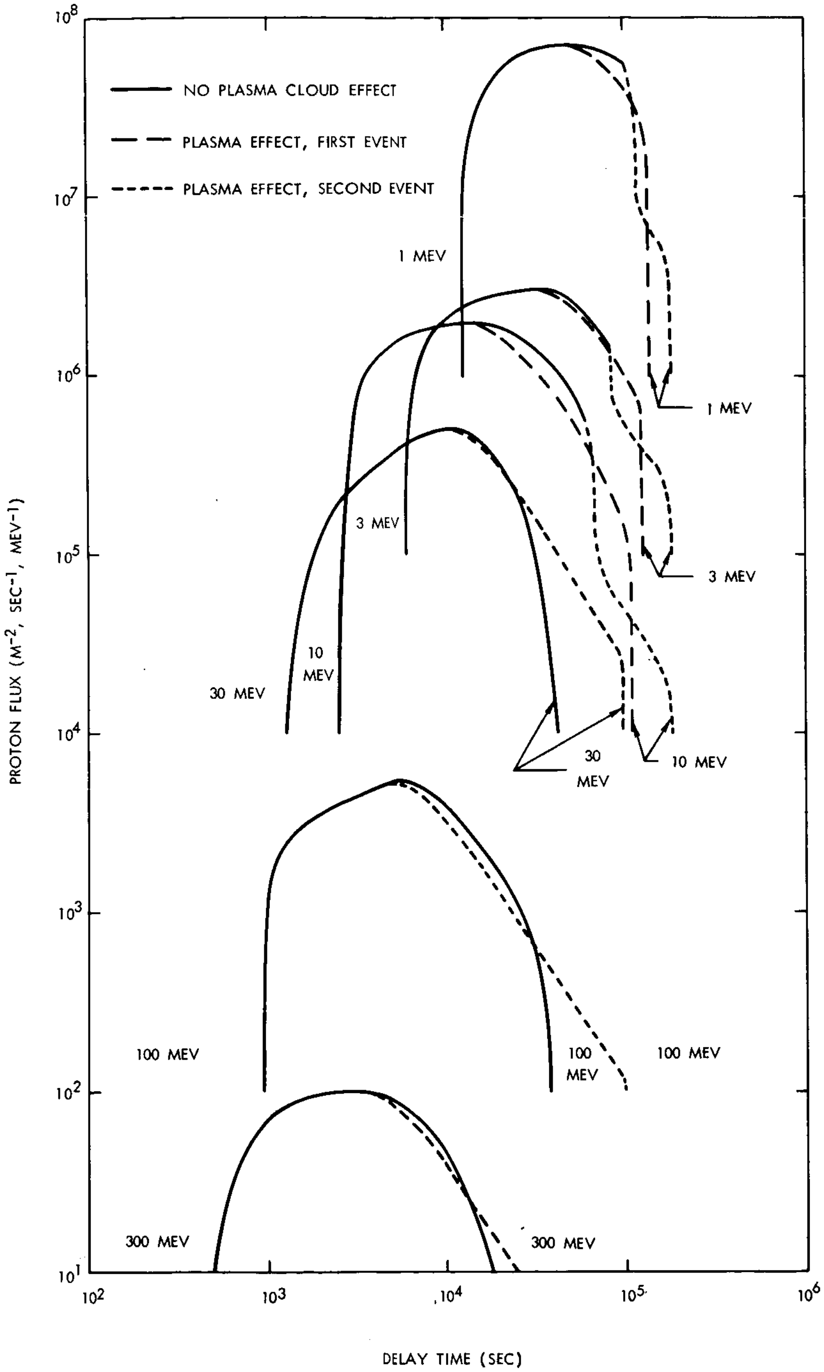

Figure 31. Proton Flux Rate Versus Energy at 1 AU

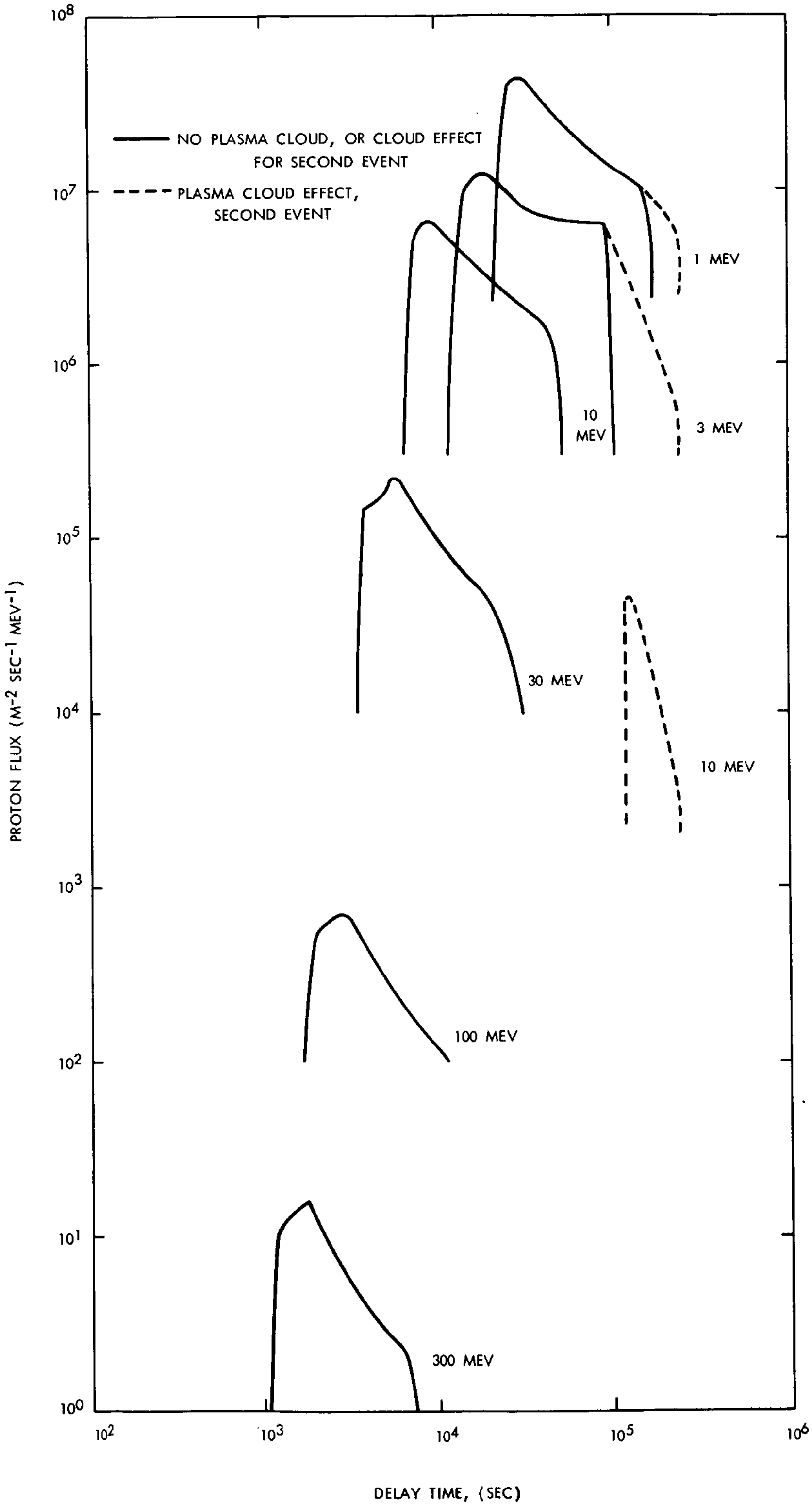

Figure 32. Proton Flux Rate Versus Energy at 1.41 AU

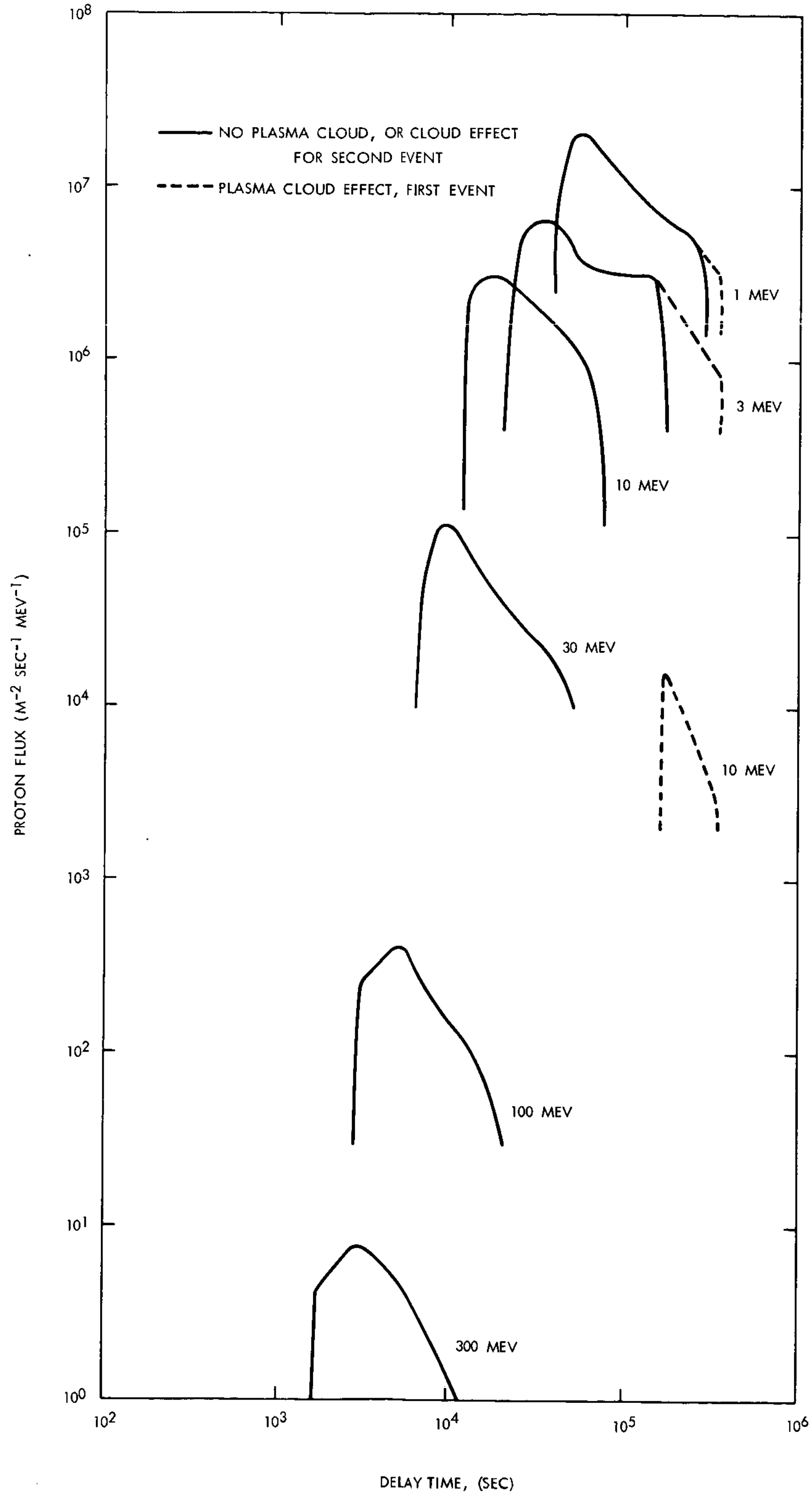

Figure 33. Proton Flux Rate Versus Energy at 2 AU

$\lambda = 4/3$ and a flare with duration 10^3 sec at the point at which the interplanetary magnetic line of force through the receiver intersects the solar chromosphere (see Figure 34). The "delay time" is the time interval following arrival of the first light from the flare at a solar distance equal to that of the receiver.

The value of λ has little effect on the proton environment (Reference 32). If the flare longitude differs by more than a few degrees from the assumed position, light from the flare cannot induce a shock in the part of the lower corona from which accelerated protons can reach the receiver. Figure 26 shows that the consequence is absence of lower-energy protons from the received spectrum. The minimum proton energy at the receiver is plotted versus solar distance in Figure 35 for various flare longitudes (at the solar equator) as observed from the receiver. The environment at energies above the cut-off is negligibly affected by the flare longitude and latitude.

The results shown in Figure 31 were integrated over time to obtain the total proton flux versus energy distribution at 1 AU, shown as the solid curve in Figure 36. The corresponding results at other solar distances may be found by dividing the result of Figure 36 by the square of the solar distance, as shown previously.

In order to include the effects of plasma clouds on the proton radiation environment, two alternative situations were considered:

1. The proton radiation event is the first to occur in at least four days. Approximately simultaneously with the flare that produces this event, a plasma cloud moves radially from the sun toward the receiver with velocity v_c = 1160 km/sec, the velocity of a hydromagnetic shock front with $\lambda = 4/3$ (Reference 52). The front of the cloud, with radius $R = (2/3)\, R_o$, reaches 1 AU in 8.5×10^4 sec, and the trailing surface passes 1 AU 1.7×10^5 sec after the flare. Protons associated with the flare are reflected or captured by the plasma near the sun; the number of protons inside the cloud decreases exponentially with median escape time $\overline{t}_R$, measured from the time of the flare.

2. The proton radiation event has been preceded by one that has produced a plasma cloud which, at the time of the flare causing the later event, has just reached the receiver. The protons that enter the cloud now do so at solar distances from $R_o/3$ to R_o. The median emergence time $\overline{t}_R$ is still measured from the time of the later flare, but now few protons emerge from the plasma before it reaches the receiver.

Results based on situations 1 and 2 are shown by dashed and dotted curves in Figure 31, 32, 33, and 36. The effect of the plasma on the total (time-integrated) radiation environment at 1 AU is not great, and is even

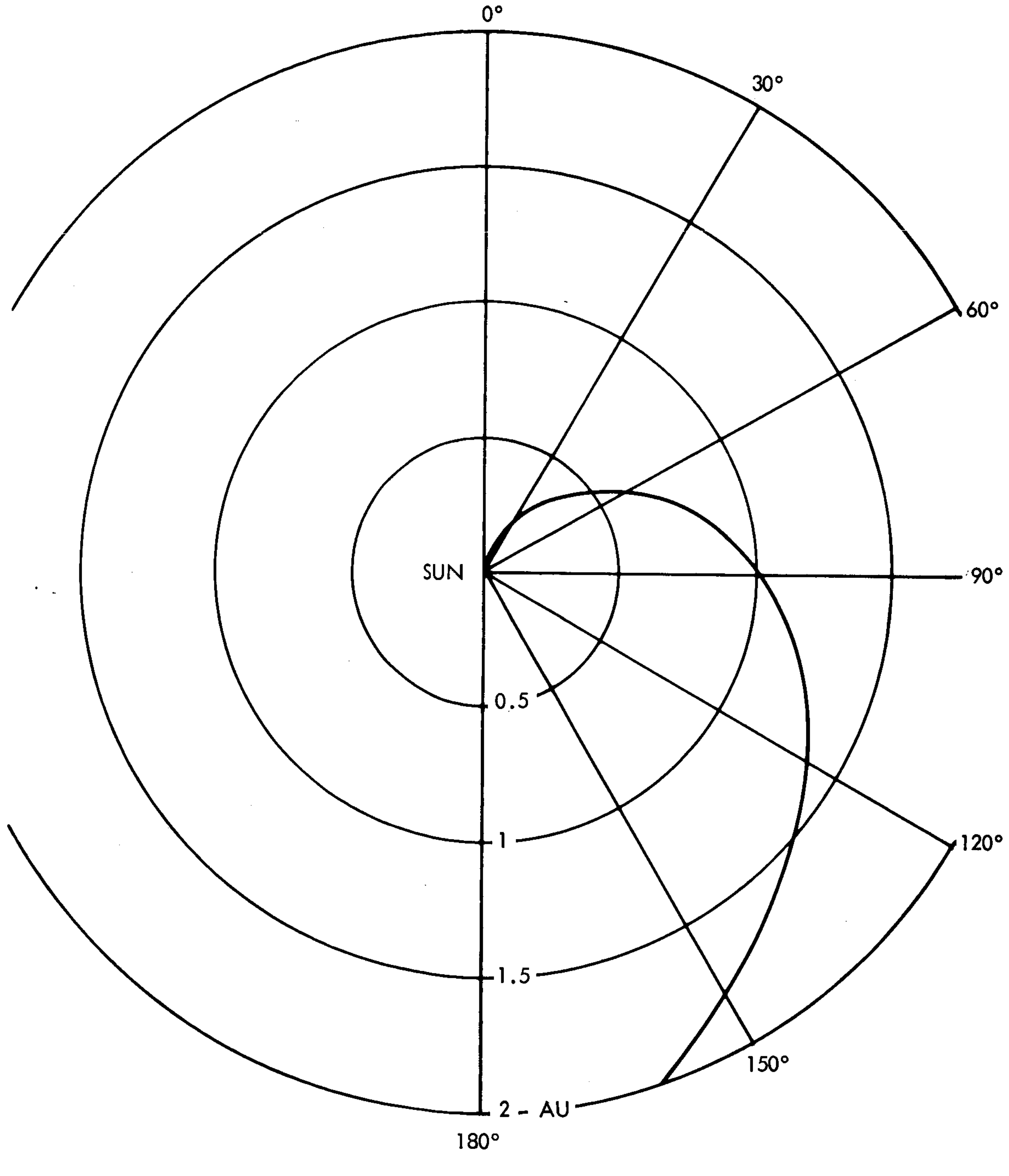

Figure 34. Line of Force in Quiescent Interplanetary Magnetic Field

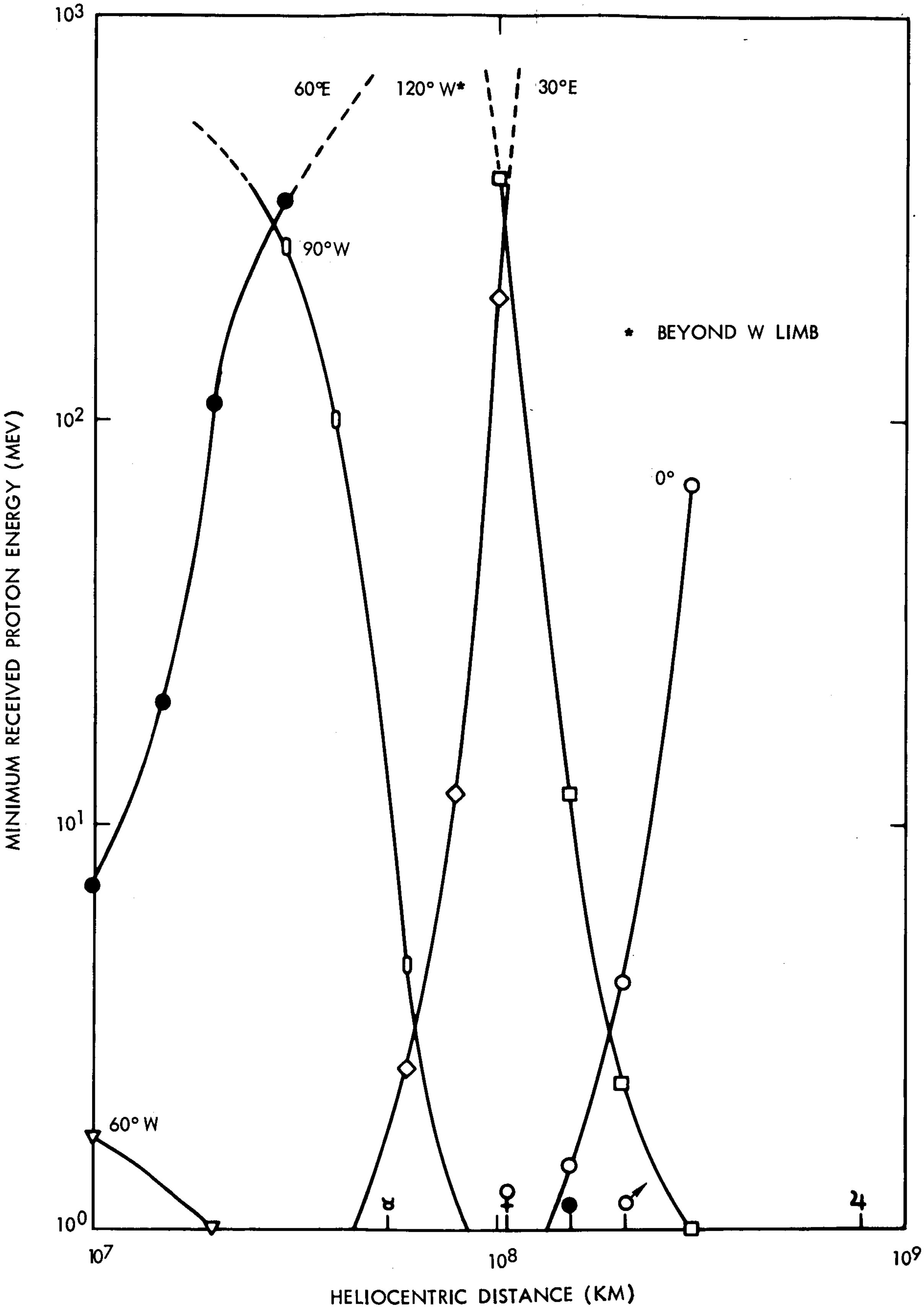

Figure 35. Minimum Proton Energy at Receiver Versus Flare Longitude

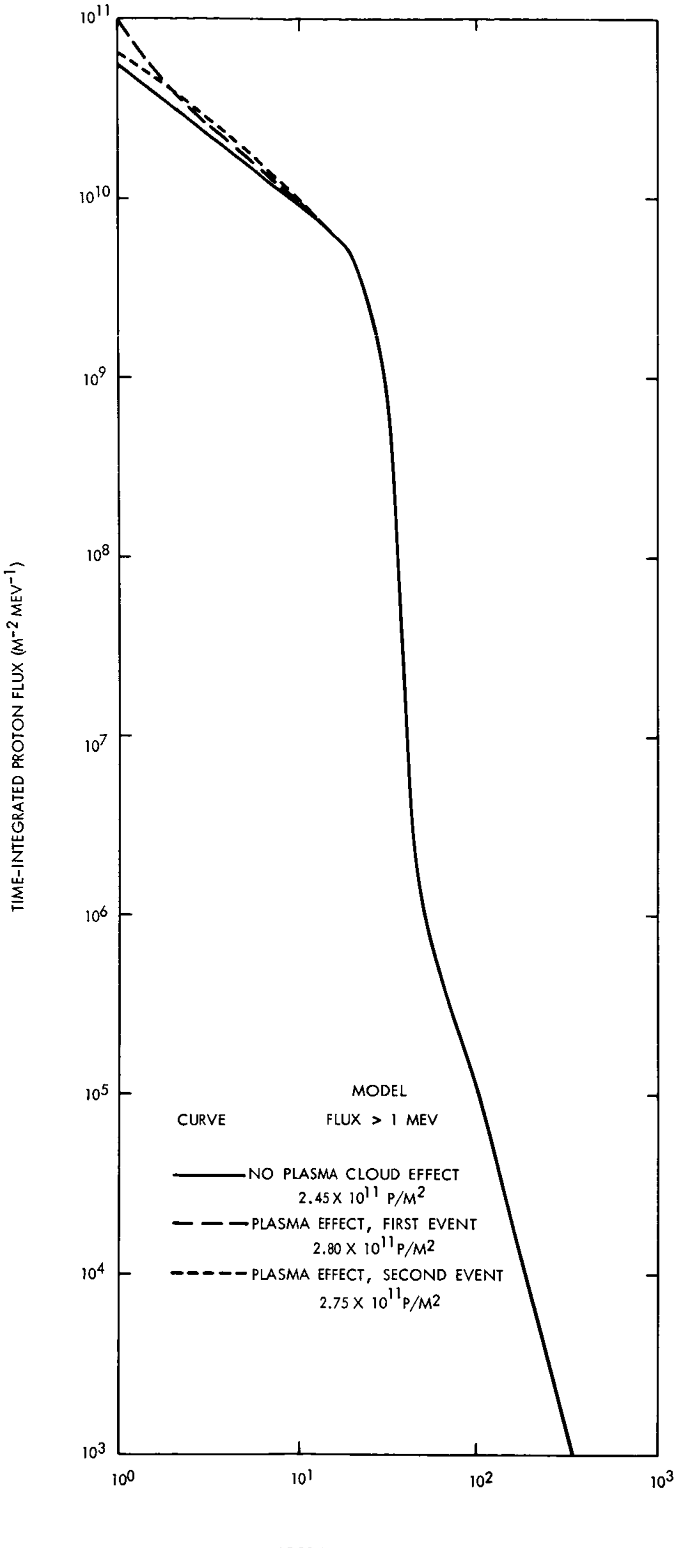

Figure 36. Proton Flux Versus Energy at 1 AU

less at greater solar distances. The plasma does, however, considerably prolong a proton radiation event, especially at energies below 100 Mev.

Discussion of Results

The proton event model developed here exhibits several of the characteristics of observed events tabulated in Section II, including

1. The slope of the differential energy spectrum with its "knee" between 20 and 40 Mev

2. The increasing softness of the spectrum with time

3. The appearance of protons with given energy at increasing arrival angles (Reference 63)

4. The ability of flares on the western half of the visible solar hemisphere, or just east of the central meridian, or just beyond the western limb, to lead to observable proton events.

The size or total proton flux of the model event can be adjusted by altering the assumed duration of the flare.

This model is based upon the propagation of a single shock wave in the previously unshocked solar corona. After passage of the initial shock wave, the corona remains at a temperature higher than that of the unshocked corona. Secondary shocks may, therefore, produce a larger yield of energetic protons than does the initial shock, since the average proton energy before arrival of the secondary shocks is greater than in the unshocked corona. Consideration of multiple shocks may result in a greater proton flux from a flare of given duration.

This model predicts neither flares nor solar proton radiation occurrence probabilities. It is limited to a description of the proton radiation environment associated with flares bright enough and large enough to induce hydromagnetic shock waves in the corona.

V. RADIATION ENVIRONMENT EVALUATION

APPLICATION TO MARS MISSION

To illustrate the techniques discussed in previous sections, a specific mission is considered. This mission is a 1971, unmanned, one-way trip to Mars. Some of the parameters for such a mission (chosen to minimize the ΔV required) are listed in Table 12.

The solar proton event environment for this mission is chosen from the following two relationships derived earlier

$$\log_{10}\left[\int\phi_Y > 30\ \text{Mev}\right](1971) = 8.3 + 0.0023\ R_Y\ (1970) \quad (61)$$

$$\text{PEN}\ (1971) = 0.1\ R_Y\ (1970) \quad (62)$$

where $\int\phi_Y > 30$ Mev is the integral particle flux (protons/cm^2-year) above 30 Mev, R_Y is the annual smoothed Wolf sunspot number, and PEN is the

Table 12. Trajectory Parameters for a 1971 Mission to Mars

Date		Time After Launch (days)	Solar Distance (AU)	Longitude (degrees)
Calendar	Julian			
24 May 1971	244, 1095.5	0	1.00	242
23 June 1971	1125.5	30	1.05	273
23 July 1971	1155.5	60	1.11	301
22 August 1971	1185.5	90	1.18	326
21 September 1971	1215.5	120	1.27	346
21 October 1971	1245.5	150	1.35	6
20 November 1971	1275.5	180	1.40	22
20 December 1971	1305.5	210	1.45	38

proton event number. Equation 61 represents the major axis of the 30-Mev, 95-percent confidence ellipse (see Equation 7 and Figure 4) and, thus, corresponds to the most probable (mean) value of $\log_{10}(\int\phi_Y > 30 \text{ Mev})$.* Equation 62 is the same as Equation 9; the PEN concept was illustrated in Figure 5 and Table 5.

Since R_Y has been predicted as 135±54 for 1970 (Figure 2), the use of Equations 61 and 62 leads to the following values for 1971 at 1 AU:**

$$\int\phi_Y > 30 \text{ Mev} = 4.1 \times 10^8 \text{ p/cm}^2 \text{ above 30 Mev}$$

$$\text{PEN} = 14$$

Based upon the observed event size distribution (Figure 23), the following combination of events (at 1 AU) appears probable:

1 event 2×10^8 p/cm^2 >30 Mev PEN = 3

2 events 5×10^7 p/cm^2 >30 Mev PEN = 2 x 2 = 4

4 events 2×10^7 p/cm^2 >30 Mev PEN = 4 x 1 = 4

3 events 1×10^7 p/cm^2 >30 Mev PEN = 3 x 1 = 3

It will be noted that this combination totals to 4.1×10^9 p/cm^2 >30 Mev and a PEN of 14, as desired.

To correct for the spacecraft-sun distance, it is necessary to select probable months in which these events occur. As shown in Figure 25, July has been the most active month, with November the second most active, etc. Based upon the probability distributions of Figure 25, the following somewhat arbitrary month assignments are made for the 10 events expected in 1971:

$$\left.\begin{array}{llll}
1 \text{ event} & 1 \times 10^7 & \text{p/cm}^2 & \text{January} \\
1 \text{ event} & 5 \times 10^7 & \text{p/cm}^2 & \text{February} \\
1 \text{ event} & 1 \times 10^7 & \text{p/cm}^2 & \text{March} \\
1 \text{ event} & 2 \times 10^7 & \text{p/cm}^2 & \text{May} \\
1 \text{ event} & 2 \times 10^7 & \text{p/cm}^2 & \text{July} \\
1 \text{ event} & 2 \times 10^8 & \text{p/cm}^2 & \text{July} \\
1 \text{ event} & 1 \times 10^7 & \text{p/cm}^2 & \text{August}
\end{array}\right\} \text{ at 1 AU}$$

$$\left.\begin{array}{lll} \text{1 event} & 2 \times 10^7 \text{ p/cm}^2 & \text{September} \\ \text{1 event} & 5 \times 10^7 \text{ p/cm}^2 & \text{November} \\ \text{1 event} & 2 \times 10^7 \text{ p/cm}^2 & \text{November} \end{array}\right\} \text{ at 1 AU}$$

For the hypothetical mission to Mars (Table 12) the first four events take place prior to launch and are, therefore, ignored. The expected proton fluxes for the remaining events are decreased by a factor of r_R^2 over those expected at 1 AU, where r_R is the sun-spacecraft distance in AU.

$$\left.\begin{array}{lll} \text{July 1971} & \text{1 event} & \int\phi = 1.6 \times 10^7 \\ \text{July 1971} & \text{1 event} & \int\phi = 1.6 \times 10^8 \\ \text{August 1971} & \text{1 event} & \int\phi = 7.2 \times 10^6 \\ \text{September 1971} & \text{1 event} & \int\phi = 1.2 \times 10^7 \\ \text{November 1971} & \text{1 event} & \int\phi = 2.5 \times 10^7 \\ \text{November 1971} & \text{1 event} & \int\phi = 1.0 \times 10^7 \end{array}\right\} \begin{array}{l} \text{at spacecraft} \\ (\text{p/cm}^2 > 30 \text{ Mev}) \end{array}$$

The total expected proton flux due to solar events expected during the hypothetical mission is 2.3×10^8 p/cm^2 >30 Mev, as contrasted to 3.2×10^8 p/cm^2 >30 Mev if the entire corresponding mission had been carried out at 1 AU.

It should be pointed out that the peak flux rates are reduced by more than the factor of r_R^2 by which the integral fluxes are reduced (Figures 31 through 33). This reduction is due to an increase in the rise and decay times as r_R (the sun-spacecraft distance) increases, due to the greater path lengths from the sun and the increased dimensions of the plasma cloud. To a first approximation, the peak flux rates vary as $r_R^{-2.5}$, and so the peak flux rates expected at the spacecraft are:

$$\left.\begin{array}{lll} \text{July 1971} & \text{1 event} & \hat{\phi} = 200/1.28 \cong 160 \\ \text{July 1971} & \text{1 event} & \hat{\phi} = 1600/1.28 \cong 1250 \\ \text{August 1971} & \text{1 event} & \hat{\phi} = 100/1.51 \cong 70 \\ \text{September 1971} & \text{1 event} & \hat{\phi} = 200/1.82 \cong 110 \\ \text{November 1971} & \text{1 event} & \hat{\phi} = 450/2.30 \cong 200 \\ \text{November 1971} & \text{1 event} & \hat{\phi} = 200/2.30 \cong 90 \end{array}\right\} \begin{array}{l} \text{at spacecraft} \\ (\text{p/cm}^2 \text{ sec} > 30 \text{ Mev}) \end{array}$$

These predicted peak fluxes, when multiplied by the effective areas of the proton detectors (cm^2 - sterad), provide a basis for designing electronic circuitry to handle the expected proton detector outputs.

It will be recognized that this sort of analysis is based upon several assumptions. Among these are:

1. The proton event environment near the ecliptic plane is expected to be independent of solar longitude and latitude.

2. The monthly distribution of solar proton events is assumed to be real.

3. The integral fluxes are assumed to vary as $1/r_R^2$, where r_R is the distance from the sun.

Of these assumptions, the last is probably reasonably valid, but one of the first two is probably not. If the event environment is independent of solar latitude and longitude, there is no reason to believe that the monthly distribution is real. If, however, there is a non-uniform monthly distribution of solar proton events (at 1 AU) the solar longitude and latitude almost certainly are important. The data are not adequate to decide which, if either, of the first two assumptions is valid.

It is possible to select the numbers and sizes of solar proton events for the years 1969 through 1975 based upon the yearly smoothed Wolf sunspot number. These predictions are listed in Table 13. As before, the expected events are those that add up to the expected integral flux ($\int\phi$) above 30 Mev and the proton event number (PEN). (The events listed in Table 13 are not a unique set of events and, considering the statistical distributions about the most probable values of R_Y, PEN, and $\int\phi$, at least several hundred combinations are possible.)

The extension of this technique to a computer is straightforward. The computer would select the events from the event size distribution and the year(s) of the mission. Once the sizes of the events expected each year had been generated by a random table look-up technique, the month in which each event is expected to take place would be assigned on the basis of the monthly event distributions. This environment would then be used to calculate the mission flux expected for any preassigned spacecraft mission. By repeating this procedure several hundred times, mission flux probabilities would be generated for any desired mission. By applying this procedure to several different missions, it would be possible to calculate mission flux probabilities as a function of mission parameters.

Table 13. Solar Proton Events Expected at 1 AU for 1969-1975

Year	Ry for Previous Year	PEN	$\int\phi$>30 Mev (p/cm^2)	Events Expected p/cm^2 >30 Mev
1969	128	13	3.9×10^8	1 event ~ 2×10^8 2 events ~ 5×10^7 3 events ~ 2×10^7 3 events ~ 1×10^7
1970	132	13	4.0×10^8	1 event ~ 2×10^8 2 events ~ 5×10^7 4 events ~ 2×10^7 2 events ~ 1×10^7
1971	135	14	4.1×10^8	1 event ~ 2×10^8 2 events ~ 5×10^7 4 events ~ 2×10^7 3 events ~ 1×10^7
1972	126	13	3.9×10^8	1 event ~ 2×10^8 2 events ~ 5×10^7 3 events ~ 2×10^7 3 events ~ 1×10^7
1973	108	11	3.5×10^8	1 event ~ 2×10^8 1 event ~ 5×10^7 4 events ~ 2×10^7 2 events ~ 1×10^7
1974	92	9	3.2×10^8	1 event ~ 2×10^8 1 event ~ 5×10^7 3 events ~ 2×10^7 1 event ~ 1×10^7
1975	77	8	3.0×10^8	1 event ~ 2×10^8 1 event ~ 5×10^7 2 event ~ 2×10^7 1 event ~ 1×10^7

VI. CONCLUSIONS

The novel results of the work reported are the establishment of a solar proton radiation environmental model which includes (1) dependences on the cyclic level of solar activity and on solar distance, (2) the analytic representation of the proton flux versus energy distribution so as to include the dependence of this distribution on the total flux, and (3) the quantitative expression of the standard deviations and, hence, the probability distributions of the calculated quantities. In addition, a critical review of original research reports led to a definitive tabulation of proton radiation event and solar flare parameters. The correlation of proton radiation event and solar flare occurrence probabilities with predictable solar phenomena was established for the 1969 to 1975 period. Methods that permit calculation of not only the most probable proton radiation environment in interplanetary space flight, but also the probability of occurrence of other environmental levels have been established.

The results leave something to be desired, however. The analytical representation of the temporal dependence of the proton flux versus energy is based on data which include early and primitive measurements and which may exclude significant radiation events in years before about 1956. The association of the proton radiation environment with predictable solar phenomena is well defined but suffers from randomness of the association and of the supposedly predictable phenomena. For example, future sunspot numbers can be predicted only with some uncertainty, and the proton flux-sunspot number correlation, while significant, is not excellent.

RECOMMENDATIONS

The results are incomplete in that they portray only a portion, although perhaps the most important portion, of the complete particulate radiation environment associated with solar flares. Additional work is recommended to provide a fuller description of this environment. The recommended work primarily concerns inclusion of particle types other than protons, evaluation of directional distributions of the radiation flux, extension of the solar distance range, and improvement of the method of evaluating environmental levels on interplanetary missions.

The charged particulate radiation emitted in association with solar flares may contain, in addition to protons, electrons, alpha particles, and heavy nuclei (References 64, 65, and 66). It has been shown (References 64 and 67) that alpha particle radiation may produce greater material and biological damage than protons produce. Electrons may also be a significant part of the radiation environment of exposed or thinly protected spacecraft components. Radiation instrumentation intended to accomplish comprehensive studies of space radiation and solar activity should be designed in light of the most probable levels of all types of particles composing the radiation environment; therefore, the electron and alpha particle fluxes versus energy, time after a flare, solar activity level, and solar distance should be evaluated. If feasible, similar results should be obtained for the flux of heavy nuclei (lithium to iron). Results of experimental measurements of electrons and alpha particles in space should be supplemented by analyses based on particle acceleration by hydromagnetic shocks, synchrotron radiation energy loss of electrons in the solar magnetic field, and diffusion of energetic particles in local clouds of disordered plasma in the interplanetary medium.

The analyses of hydromagnetic shock acceleration and proton transport presented in Section IV can be used to provide values of the distribution of solar proton arrival angles versus time, proton energy, and solar direction (Reference 54). These results agree well with observed angular distributions in the vicinity of the earth (Reference 68) and also with earlier models of the anisotropy of solar proton radiation (Reference 69). The directional distribution of the radiation is significant in spacecraft shielding analysis and in the design of particle spectrometer arrays which measure the angular distribution of the charged particle flux. Therefore, the solar radiation directional distribution should be evaluated for protons, alpha particles, and electrons as a function of time after a flare, stage of the sunspot number cycle, particle energy, and solar distance. This work will reveal the dependence of the degree of anisotropy on solar distance.

The solar distance interval from 1 to 2 AU contains most unmanned vehicle trajectories to Mars. Manned missions to Mars reach aphelion distances beyond 2 AU before returning to earth; any flights to the major asteroids or Jupiter extend to as much as 5 AU. Approaching the sun, Venus missions which have immediate interest reach perihelion distances near 0.7 AU, while future solar probes and Mercury missions may reach solar distances as small as 0.3 AU. It is, therefore, worthwhile to extend the proton radiation models developed here, as well as the recommended studies of electron and alpha particle environments and of anisotropy, to the solar distance range from 0.3 to 5 AU. The analyses below 1 AU will be very straightforward because of the diminishing importance of irregularities in the interplanetary medium, while results beyond 2 AU will admittedly suffer in reliability because of the poorly known extent of solar magnetic fields and the solar wind into the interstellar medium. The importance of the galactic particle radiation environment also increases with increasing solar distance, both absolutely and with respect to the solar radiation.

The application of the present and recommended analyses to the evaluation of the radiation environment on space missions can be improved by automation. It is recommended that a computer program be prepared which uses Monte Carlo techniques to select randomly from probability distribution tables the dates and particle fluxes of the solar particulate radiation events encountered on a specified trajectory. If the same mission is "flown" repeatedly, the probability distribution of radiation environment profiles can be established.

The work presented here provides a valuable technique for estimating the expected solar proton radiation environment in interplanetary space. If this work is supplemented by the recommended effort, the planning of space missions and the design of space vehicles will benefit from a quantitative statistical description of present knowledge of all significant aspects of the radiation environment associated with solar activity.

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APPENDIX A. BIBLIOGRAPHY

This bibliography cites all significant documents located in the literature survey described in Section II of this report. The first part of the bibliography lists references to specific solar flares and flare-associated proton radiation events and magnetic disturbances; this list is in chronological order of the natural events described. Each of the following parts is topical, in chronological order of publication. The topics are prediction of solar flares, origin of solar flares, solar radio bursts, source of solar flare particles, propagation of solar flare particles, cosmic ray (i.e., galactic particle) effects, energy spectra of solar flare particles, polar cap absorptions, geomagnetic disturbances related to solar flares, ionization and reactions in the earth's atmosphere, and miscellaneous references.

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APPENDIX B. FLARE-PLAGE CORRELATION TABLES

Tables B1 through B14 give values of w_{ijk}, the probability of occurrence of at least one flare (with corrected area 100 millionths of the solar hemisphere or greater) at a calcium plage region with given area, age, and luminosity. Odd-numbered tables refer to flares on the same disk passage as that on which the plage is observed; even-numbered tables refer to flares on the next disk passage of the position of the plage. A pair of tables is presented for each year from 1958 through 1964; these years correspond to 1969 through 1975, in sunspot number cycle 20.

When $P_{ijk} = 0$ in Equation 10, w_{ijk} is indeterminate; i. e., no plages with the given characteristics were observed. These values of w_{ijk} may be interpolated or extrapolated from adjacent values or adjacent years.

Table B1. Probability of Flare Occurrence on Same Rotation, 1958 (1969)

Plage Area	Plage Age	Plage Luminosity			
		1-1.5	2-2.5	3-3.5	4-5
<1000	1	0.148	0.404	0.800	1
	2	0.136	0.478	0.500	*
	3	0.133	0.556	*	*
	4	0.300	0.500	1	*
	5	0.125	0.667	*	*
	6	0.200	0.667	*	*
	7	*	*	*	*
	≥8	*	*	*	*
1000-2000	1	0.500	0.533	0.706	1
	2	0.556	0.563	0.714	1
	3	0.125	0.692	0.667	*
	4	0.333	0.667	1	*
	5	0.333	0.625	*	*
	6	0.500	0.833	1	*
	7	*	*	*	*
	≥8	*	*	*	*
2000-4000	1	*	0.800	0.944	*
	2	*	0.875	0.909	*
	3	*	0.800	0.875	*
	4	1	0.750	1	*
	5	*	0.800	1	*
	6	*	0.500	1	*
	7	*	1	1	*
	≥8	*	*	*	*
≥4000	1	*	1	0.971	1
	2	*	1	1	1
	3	*	1	1	*
	4	*	1	1	1
	5	*	1	1	*
	6	*	*	1	*
	7	*	*	*	*
	≥8	*	*	*	*

* = indeterminate

Table B2. Probability of Flare Occurrence on Next Rotation, 1958 (1969)

Plage Area	Plage Age	Plage Luminosity			
		1-1.5	2-2.5	3-3.5	4-5
<1000	1	0.041	0.128	0.522	0
	2	0.100	0.111	0	*
	3	0.071	0	*	*
	4	0.154	0.375	0	*
	5	0.083	0.250	*	*
	6	0	0	*	*
	7	*	*	*	*
	≥8	0	*	*	*
1000-2000	1	0.250	0.162	0.120	1
	2	0.200	0.043	0.111	1
	3	0	0.428	0.286	*
	4	0	0.273	0.667	*
	5	0	0.357	0	*
	6	0.333	0.222	1	*
	7	0	0	1	*
	≥8	*	*	*	*
2000-4000	1	*	0.412	0.333	*
	2	*	0.304	0.236	*
	3	0	0.236	0.267	*
	4	0	0	0.250	*
	5	1	0	0.500	*
	6	0	0	0	1
	7	*	0	0	*
	≥8	0	*	*	*
≥4000	1	*	0.200	0.293	0.667
	2	0.500	0.750	0.500	0.500
	3	*	0.444	0.640	*
	4	0	1	0.400	1
	5	*	0	0.400	0
	6	*	1	0	*
	7	*	*	*	*
	≥8	*	*	*	*

* = indeterminate

Table B3. Probability of Flare Occurrence on Same Rotation, 1959 (1970)

Plage Area	Plage Age	Plage Luminosity 1-1.5	2-2.5	3-3.5	4-5
< 1000	1	0.222	0.431	0.818	*
	2	0.125	0.545	0.500	*
	3	0.250	0.400	*	*
	4	*	1	1	*
	5	0.200	0.500	*	*
	6	*	0.750	*	*
	7	*	*	*	*
	≥ 8	*	*	*	*
1000-2000	1	0.500	0.538	0.833	*
	2	*	0.455	0.667	*
	3	1	0.444	1	*
	4	*	0.571	*	*
	5	1	0.600	1	*
	6	1	0.333	*	*
	7	0.500	1	*	*
	≥ 8	*	*	1	*
2000-4000	1	*	0.571	0.952	*
	2	*	0.706	0.700	*
	3	*	0.667	0.700	*
	4	*	0.750	1	*
	5	*	0.750	1	*
	6	*	1	0.750	*
	7	1	0.500	1	*
	≥ 8	*	*	1	*
≥ 4000	1	*	*	1	*
	2	*	1	1	*
	3	*	0.750	0.923	*
	4	*	1	1	1
	5	*	0.500	1	*
	6	*	1	1	*
	7	*	*	*	*
	≥ 8	*	1	*	1

* = indeterminate

Table B4. Probability of Flare Occurrence on Next Rotation, 1959 (1970)

Plage Area	Plage Age	Plage Luminosity 1-1.5	2-2.5	3-3.5	4-5
< 1000	1	0.172	0.159	0.333	*
	2	0.625	*	*	*
	3	0.833	0.267	*	*
	4	*	0.500	1	*
	5	0.143	0.250	*	*
	6	*	0.250	*	*
	7	*	*	*	*
	≥ 8	*	*	*	*
1000-2000	1	*	0.154	0.368	*
	2	*	0.280	0.666	*
	3	*	0.250	0.500	*
	4	1	0.400	*	*
	5	*	0.091	*	*
	6	*	0.666	*	*
	7	*	1	*	*
	≥ 8	*	1	*	*
2000-4000	1	*	0.125	0.524	*
	2	*	0.500	0.333	*
	3	*	0.400	0.429	*
	4	*	0.714	0.800	*
	5	*	0.571	1	*
	6	*	*	0.250	*
	7	1	0.333	*	*
	≥ 8	*	*	0.666	*
≥ 4000	1	*	*	0.625	*
	2	*	0.250	0.750	*
	3	*	0.750	0.785	*
	4	*	1	0.889	*
	5	*	0.500	0.750	*
	6	*	0.500	0.666	*
	7	*	0.500	1	*
	≥ 8	*	*	*	*

* = indeterminate

Table B5. Probability of Flare Occurrence on Same Rotation, 1960 (1971)

Plage Area	Plage Age	Plage Luminosity 1-1.5	2-2.5	3-3.5	4-5
<1000	1	0.235	0.286	0.750	*
	2	*	0.235	*	*
	3	0.250	0.250	*	*
	4	0.143	0.250	*	*
	5	0.200	0.111	*	*
	6	*	*	*	*
	7	*	*	1	*
	≥ 8	*	*	*	*
1000-2000	1	0.500	0.529	0.900	*
	2	0.333	0.308	0.333	*
	3	*	0.333	1	*
	4	0.167	0.214	*	*
	5	*	0.727	1	*
	6	*	0.500	*	*
	7	*	*	*	*
	≥ 8	*	0.333	*	*
2000-4000	1	*	1	0.733	*
	2	*	0.846	0.688	*
	3	*	0.667	0.933	*
	4	*	0.556	0.833	*
	5	*	0.800	1	*
	6	*	1	1	*
	7	*	0.667	1	*
	≥8	*	0.500	*	*
≥4000	1	*	*	1	*
	2	*	1	1	*
	3	*	1	1	*
	4	*	0.500	0.750	*
	5	*	*	1	*
	6	*	*	0.667	*
	7	*	*	1	*
	≥8	*	*	1	*

* = indeterminate

Table B6. Probability of Flare Occurrence on Next Rotation, 1961 (1972)

Plage Area	Plage Age	Plage Luminosity			
		1-1.5	2-2.5	3-3.5	4-5
<1000	1	0.100	0.053	0.411	*
	2	0	0.154	*	*
	3	0	0.222	0.667	*
	4	0	0	*	*
	5	0.667	0.250	*	*
	6	0	0	*	*
	7	*	*	*	*
	≥8	0	0	*	*
1000-2000	1	*	0.167	0.200	*
	2	*	0.222	0.111	*
	3	0	0.357	0.750	*
	4	0.500	0.167	0.333	*
	5	1	0	*	*
	6	0	0.333	*	*
	7	*	0	0	*
	≥8	*	0	*	*
2000-4000	1	*	0	0.400	*
	2	*	0.500	0.143	*
	3	*	0.667	0.500	*
	4	*	*	0.250	*
	5	*	0.500	0	*
	6	*	*	0	*
	7	*	*	1	*
	≥8	*	0	*	*
≥4000	1	*	*	1	*
	2	*	0.500	0.750	*
	3	*	*	0.667	*
	4	*	*	0.500	*
	5	*	*	*	*
	6	*	*	*	*
	7	*	*	0	*
	≥8	*	*	*	*

* = indeterminate

Table B7. Probability of Flare Occurrence on Same Rotation, 1961 (1972)

Plage Area	Plage Age	Plage Luminosity			
		1-1.5	2-2.5	3-3.5	4-5
<1000	1	0.111	*	0.529	*
	2	0.200	*	*	*
	3	*	*	0.666	*
	4	0.333	0.333	*	*
	5	*	*	*	*
	6	0.250	0.500	*	*
	7	*	*	*	*
	≥8	*	0.500	*	*
1000-2000	1	*	0.833	0.720	*
	2	*	0.400	0.250	*
	3	*	0.133	0.500	*
	4	*	0.333	1	*
	5	1	0.666	*	*
	6	*	0.666	*	*
	7	*	*	1	*
	≥8	*	*	*	*
2000-4000	1	*	1	0.789	*
	2	*	0.400	0.833	*
	3	*	0.333	0.750	*
	4	*	*	1	*
	5	*	*	0.500	*
	6	*	*	1	*
	7	*	*	*	*
	≥8	*	*	*	*
≥4000	1	*	*	1	*
	2	*	1	1	*
	3	*	*	1	*
	4	*	*	0.500	*
	5	*	*	*	*
	6	*	*	*	*
	7	*	*	*	*
	≥8	*	*	*	*

* = indeterminate

Table B8. Probability of Flare Occurrence on Next Rotation, 1961 (1972)

Plage Area	Plage Age	Plage Luminosity 1-1.5	2-2.5	3-3.5	4-5
< 1000	1	0.100	0.056	0.412	*
	2	*	0.154	*	*
	3	*	0.182	0.666	*
	4	*	*	*	*
	5	0.666	0.250	*	*
	6	*	*	*	*
	7	*	*	*	*
	≥8	*	*	*	*
1000-2000	1	*	0.167	0.200	*
	2	*	0.182	0.111	*
	3	*	0.357	0.750	*
	4	0.500	0.167	0.111	*
	5	1	*	*	*
	6	*	0.333	*	*
	7	*	*	*	*
	≥8	*	*	*	*
2000-4000	1	*	*	0.400	*
	2	*	0.500	0.143	*
	3	*	0.666	0.500	*
	4	*	*	0.250	*
	5	*	0.500	*	*
	6	*	*	*	*
	7	*	*	1	*
	≥8	*	*	*	*
≥4000	1	*	*	1	*
	2	*	0.500	0.750	*
	3	*	*	0.666	*
	4	*	*	0.500	*
	5	*	*	*	*
	6	*	*	*	*
	7	*	*	*	*
	≥8	*	*	*	*

* = indeterminate

Table B9. Probability of Flare Occurrence on Same Rotation, 1962 (1973)

Plage Area	Plage Age	Plage Luminosity 1-1.5	2-2.5	3-3.5	4-5
< 1000	1	*	*	*	*
	2	*	*	*	*
	3	*	*	*	*
	4	*	*	*	*
	5	*	*	*	*
	6	*	*	*	*
	7	*	*	*	*
	≥ 8	*	*	*	*
1000-2000	1	*	0.300	0.650	*
	2	*	0.333	0.636	*
	3	*	*	0.600	*
	4	*	0.167	*	*
	5	*	0.500	*	*
	6	*	0.333	*	*
	7	*	*	*	*
	≥ 8	*	*	*	*
2000-4000	1	0.105	0.036	0.444	*
	2	*	*	0.900	*
	3	1	0.333	1	*
	4	*	*	0.333	*
	5	*	*	0.666	*
	6	*	*	1	*
	7	*	*	*	*
	≥ 8	*	*	*	*
≥4000	1	0.250	0.239	0.400	1
	2	0.111	0.300	0.400	*
	3	*	0.111	1	*
	4	*	*	1	*
	5	*	0.500	1	*
	6	*	*	*	*
	7	*	*	*	*
	≥8	*	*	*	*

* = indeterminate

Table B10. Probability of Flare Occurrence on Next Rotation, 1962 (1973)

Plage Area	Plage Age	Plage Luminosity 1-1.5	2-2.5	3-3.5	4-5
< 1000	1	*	*	*	*
	2	*	*	*	*
	3	*	*	*	*
	4	*	*	*	*
	5	*	*	*	*
	6	*	*	*	*
	7	*	*	*	*
	≥ 8	*	*	*	*
1000-2000	1	*	*	0.087	*
	2	*	*	*	*
	3	*	*	*	*
	4	*	*	1	*
	5	*	*	*	*
	6	*	*	*	*
	7	*	*	*	*
	≥ 8	*	*	*	*
2000-4000	1	*	*	0.111	*
	2	*	*	*	*
	3	*	*	0.125	*
	4	*	*	0.250	*
	5	*	*	*	*
	6	*	*	*	*
	7	*	*	*	*
	≥ 8	*	*	*	*
≥ 4000	1	*	*	*	*
	2	*	*	*	*
	3	*	*	*	*
	4	*	*	*	*
	5	*	*	*	*
	6	*	*	*	*
	7	*	*	*	*
	≥ 8	0.500	1	*	*

* = indeterminate

Table B11. Probability of Flare Occurrence on Same Rotation, 1963 (1974)

Plage Area	Plage Age	Plage Luminosity			
		1-1.5	2-2.5	3-3.5	4-5
< 1000	1	0.017	0.039	0.200	*
	2	*	*	*	*
	3	*	*	*	*
	4	*	0.143	*	*
	5	*	*	*	*
	6	*	*	*	*
	7	*	*	*	*
	⩾ 8	*	*	*	*
1000-2000	1	*	0.250	0.929	1
	2	*	0.166	0.400	*
	3	*	*	0.400	*
	4	*	*	*	*
	5	*	*	*	*
	6	*	*	1	*
	7	*	*	*	*
	⩾ 8	*	*	*	*
2000-4000	1	*	0.043	0.857	*
	2	*	*	0.714	*
	3	*	*	0.800	*
	4	*	*	0.666	*
	5	*	1	*	*
	6	*	*	*	*
	7	*	*	*	*
	⩾ 8	*	*	*	*
⩾ 4000	1	0.083	0.100	0.500	*
	2	*	0.250	1	1
	3	*	*	*	*
	4	*	*	1	*
	5	*	*	*	*
	6	*	*	*	*
	7	*	*	*	*
	⩾ 8	*	*	*	*

* = indeterminate

Table B12. Probability of Flare Occurrence on Next Rotation, 1963 (1974)

Plage Area	Plage Age	Plage Luminosity			
		1-1.5	2-2.5	3-3.5	4-5
<1000	1	0.013	0.055	*	*
	2	*	*	*	*
	3	*	*	*	*
	4	*	0.143	*	*
	5	*	*	*	*
	6	*	*	*	*
	7	*	*	*	*
	≥ 8	*	*	*	*
1000-2000	1	*	0.125	0.176	1
	2	*	*	0.167	*
	3	*	0.200	*	*
	4	*	*	*	*
	5	*	*	*	*
	6	*	*	*	*
	7	*	*	*	*
	≥ 8	*	*	*	*
2000-4000	1	*	*	*	*
	2	*	0.500	0.222	*
	3	*	*	0.600	*
	4	*	*	*	*
	5	*	1	0.500	*
	6	*	*	*	*
	7	*	*	*	*
	≥ 8	*	*	*	*
≥ 4000	1	*	0.048	0.111	*
	2	*	*	0.500	1
	3	*	*	*	*
	4	*	*	1	*
	5	*	*	*	*
	6	*	*	*	*
	7	*	*	*	*
	≥ 8	*	*	*	*

* = indeterminate

Table B13. Probability of Flare Occurrence on Same Rotation, 1964 (1975)

Plage Area	Plage Age	Plage Luminosity 1-1.5	2-2.5	3-3.5	4-5
< 1000	1	0.016	0.069	0.419	*
	2	0.111	0.333	*	*
	3	*	*	*	*
	4	*	*	*	*
	5	*	*	*	*
	6	*	*	*	*
	7	*	*	*	*
	≥ 8	*	*	*	*
1000-2000	1	*	0.500	0.714	*
	2	*	0.333	0.500	*
	3	*	0.666	1	*
	4	*	*	1	*
	5	*	*	1	*
	6	*	*	*	*
	7	*	*	*	*
	≥ 8	*	*	*	*
2000-4000	1	*	1	1	*
	2	*	*	1	*
	3	*	*	*	*
	4	*	*	*	*
	5	*	*	*	*
	6	*	*	*	*
	7	*	*	*	*
	≥ 8	*	*	*	*
≥ 4000	1	*	*	*	*
	2	*	*	*	*
	3	*	*	*	*
	4	*	*	*	*
	5	*	*	*	*
	6	*	*	*	*
	7	*	*	*	*
	≥ 8	*	*	*	*

* = indeterminate

Table B14. Probability of Flare Occurrence on Next Rotation, 1964 (1975)

Plage Area	Plage Age	Plage Luminosity 1-1.5	2-2.5	3-3.5	4-5
< 1000	1	0.003	0.028	0.094	*
	2	*	*	*	*
	3	*	*	*	*
	4	*	*	*	*
	5	*	*	*	*
	6	*	*	*	*
	7	*	*	*	*
	≥ 8	*	*	*	*
1000-2000	1	*	*	0.250	*
	2	*	*	0.333	*
	3	*	0.333	*	*
	4	*	*	1	*
	5	*	*	*	*
	6	*	*	*	*
	7	*	*	*	*
	≥ 8	*	*	*	*
2000-4000	1	*	*	*	*
	2	*	*	0.500	*
	3	*	*	*	*
	4	*	*	1	*
	5	*	*	*	*
	6	*	*	*	*
	7	*	*	*	*
	≥ 8	*	*	*	*
≥ 4000	1	*	*	*	*
	2	*	*	*	*
	3	*	*	*	*
	4	*	*	*	*
	5	*	*	*	*
	6	*	*	*	*
	7	*	*	*	*
	≥ 8	*	*	*	*

* = indeterminate

APPENDIX C. COMPUTER PROGRAMS

One computer program listed and described below was prepared in this study. Other programs used in the study were completed, under the sole support of North American Aviation, Inc., prior to the inception of this contract.

DESCRIPTION OF PROGRAM

Name: SPOTNO

Purpose: This program calculates the monthly smoothed Wolf sunspot number R_M at each month from a given date to a date 250 years later.

Method: The program evaluates the sum of the contributions to R_M of each of 1 to 50 terms which are a discrete representation of a power frequency spectrum P(f) of the R_M from July 1749 to June 1964. P(f) is defined by Equation 3 in this report, and the summation process replaces the integral in Equation 4 by

$$R_M(t'') = \sum_{n=1}^{N} P(f_n)\,(f_{n+1}-f_n)\,\sin 2\pi f_n\,(t''=t_o) \qquad \text{(C-1)}$$

where t_o is a time at which $R_M(t_o) = 0$.

Language: FORTRAN 4, for the IBM 7094 computer; compiler - FAP; operating system - IBSYS.

Instructions for Use: Compilation time - 7 seconds; loading time - 17 seconds; execution time - 10 seconds; printing - 3000 lines. Program requires subroutine DECRD, which is on NAA library tapes.

Program Decks: Source, BCD, 29 cards; object - relocatable column binary, 16 cards. These decks are transmitted separately. Program is on file at NAA as Deck 3M906.

Input-Output Variables: FORTRAN variables appearing in input and output statements of SPOTNO are defined in Table C1, in the order of their appearance in the program.

Table C1. Definition of Variables in SPOTNO

FORTRAN Name	Algebraic Symbol	Definition
TO	t_o	Time at which sunspot number = 0 (year AD)
T1	$t''(min)$	Earliest date at which sunspot number is to be found (year AD)
NF	N	Number of terms in power frequency spectrum, Equation C1
F(I)	f_n	Frequency of nth term ($year^{-1}$)
P(I)	$P(f_n)$	Amplitude of nth term
TC	t''	Any date at which sunspot number is found (year AD)
SN	R_M	Sunspot number

LISTING

The listing of SPOTNO follows (Figure C1).

DATA

Values of data variables used in this study are given in Table C2.

```
SPOTNO
    SPOTPS      -  EFN   SOURCE STATEMENT  -  IFN(S)  -                  03/11/86

C     COMPUTES EXPECTED SUNSPOT WOLF NUMBER AT TIME TP FROM POWER        SSPS0015
C     SPECTRUM OF FREQUENCIES BASED ON ANNUAL SMOOTHED WOLF NUMBER       SSPS0020
C     (1749-1961). F = CYCLES PER YEAR, FO = MAXIMUM F, P = POWER AT F,  SSPS0025
C     TP = TIME (YR) AFTER 1 JULY 1749 AT WHICH SN = SUNSPOT WOLF        SSPS0030
C     NUMBER IS TO BE FOUND. TC = CALENDAR DATE OF TP, TO = DATE AT      SSPS0035
C     WHICH SN = 0. (1810), NF = NUMBER OF VALUES OF F, P.               SSPS0040
C     THIS VERSION DOES EACH MONTH JUL 1749 - JUN 1999. T1 = 1ST DATE.   SSPS0041
      DIMENSION F(50), P(50), DA(2)                                      SSPS0045
      EQUIVALENCE (DA(1), TO), (DA(2), T1)                               SSPS0047
   10 READ (5,710) NF, (F(I), P(I), I = 1, NF)                           SSPS0050     1
  710 FORMAT (1I12/(2E12.5))                                             SSPS0055
   20 CALL DECRD(DA)                                                     SSPS0058    11
      TO = TO - 1749.0                                                   SSPS0060
      FO = F(NF)                                                         SSPS0062
  810 WRITE (6,910)                                                      SSPS0065    14
  910 FORMAT (17H1  DATE      SPOTS)                                     SSPS0070
   22 DO 200 IT = 1, 3000                                                SSPS0076
   24 TC = T1 + FLOAT(IT - 1)/12.0                                       SSPS0078
   30 TP = TC - 1749.0                                                   SSPS0080
  100 XSUM = 0.0                                                         SSPS0085
      NF1 = NF - 1                                                       SSPS0090
  110 DO 150 I = 1, NF1                                                  SSPS0095
  120 XSUM = XSUM + P(I) * (F(I+1) - F(I)) * SIN (6.2832 * F(I) * (TP    SSPS0100
     1 - TO))                                                            SSPS0101    29
  150 CONTINUE                                                           SSPS0105
  160 SN = SQRT(ABS(XSUM)/FO)                                            SSPS0110    34
  820 WRITE (6,920) TC, SN                                               SSPS0115    35
  920 FORMAT (1HO,F8.2,2X,F6.1)                                          SSPS0120
  200 CONTINUE                                                           SSPS0122
      GO TO 20                                                           SSPS0125
      END                                                                SSPS0130
```

Figure C1. SPOTNO Listing

Table C2. SPOTNO Data.

$t_o = 1810.5$

t'' (min) = 1749.5

n = 25

n	f_n (year^{-1})	$P(f_n)$ (spots^2/yr^2)
1	0.0045	4,600
2	0.0112	21,500
3	0.0176	12,300
4	0.0233	6,100
5	0.0281	700
6	0.0345	2,200
7	0.0406	1,200
8	0.0475	3,400
9	0.0522	600
10	0.0567	2,100
11	0.0650	2,200
12	0.0705	4,800
13	0.0765	5,200
14	0.0828	5,200
15	0.0903	41,700
16	0.0945	10,500
17	0.1011	30,200
18	0.1063	15,300
19	0.1122	5,600
20	0.1178	7,800
21	0.1236	5,200
22	0.1290	1,300
23	0.1340	2,100
24	0.1410	1,500
25	0.1450	0