Solar Cosmic Ray Measurements at

High Heliocentric Latitudes

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Introduction

Observation of solar cosmic ray fluxes at high heliocentric latitudes would provide several new dimensions in specifying important physical processes in the solar atmosphere and interplanetary space. Valuable new approaches would be available for such problems as the steady state acceleration in the solar atmosphere, propagation of fast charged particles in the solar coronal magnetic fields and in interplanetary space, the true interplanetary particle spectra free of transient solar influence, and acceleration in interplanetary space by shock waves. For this brief review of what might result from a program of solar cosmic ray observations on "out-of-the-ecliptic" spacecraft the following outline will be used:

A. The magnetic fields of the Sun at high latitudes

B. Propagation of fast charged particles in the solar corona and in interplanetary space at high latitudes

C. Origin of interplanetary particle populations

D. Other particle phenomena in interplanetary space(e.g., acceleration of shock waves)

E. Effect of spacecraft mission characteristics on solar cosmic ray studies at high latitudes

A. Solar Coronal Magnetic Fields

It is now well known that the magnetic fields close to the Sun control the intensities of charged particles that appear in interplanetary space. They do so in a variety of ways and to varying degrees. For example, particles from flares near the East limb are detected at central meridian and more westerly longitudes only several hours after the flare (Van Hollenbeke et al., 1975). The measured low cross field diffusivity of the particles in interplanetary space requires that the diffusion occurs in the corona. This is a reasonable requirement since hydromagnetic wave activity should be more intense in the solar corona and the wavelength of such waves can be of the size needed to effectively scatter solar flare particles.

Energetic solar particles stream from the solar corona in high intensities for many days, even weeks, following large solar flares. In general terms, this basic observation means that there is a sequence in which the particles are first accelerated, then stored for some time in the solar corona, then released into interplanetary space. The quantitative behavior of each of these steps is not well known and in fact is at the center of much controversy. For example, the acceleration may be essentially steady state and the storage transient. On the other hand there is the possibility that the acceleration is impulsive and the storage long term. Such a situation requires very low collisional energy losses, something that might be achieved in a "cosmic ray plasma" where all particles are energetic, approaching a Maxwellian distribution (Anderson, 1972). In either case the magnetic fields of the sun play a major role in each step of the three step sequence. All our experience with these processes has been in the magnetic fields of the solar activity zones. It seems unlikely that the full sequence of acceleration, storage and release takes place in the high latitude coronal fields. However, there are two inversely related questions of basic importance:

1. Do solar particles, accelerated in the activity zones, propagate into the high latitude solar regions?
2. Can we use the solar particles, if they do indeed move into the high latitude regions, as probes of the solar magnetic fields there?

With these two questions as the basic motivation for solar cosmic ray studies at high heliographic latitudes, we next summarize some of the information now available on high latitude solar magnetic fields. Figure 1 is a photograph of the solar corona that shows the polar plumes. This old photograph is of interest because it shows an intermediate corona, the kind expected in the 1983 to 1985 period. The polar plumes have generally been considered to outline the magnetic fields over the Sun's polar cap and their appearance suggests that the field lines in these high latitude regions are <u>open</u>. Notice that the polar plumes appear only above latitudes of 50 to 60°. Because these field lines are so different from the activity zone and transition zone field lines, a strong impetus is given to going to the highest possible solar latitudes in order to encounter a qualitatively different phenomenology.

Magnetograph observations suggest that the Sun's polar magnetic fields are not uniform bundles of lines. Figure 2 shows measurements by Stenflo (1971) that lead to the following conclusions about the high altitude fields:

1. They are patchy with large regions (channels) of weak (less than 10 Gauss) fields. These channels extend from the poles down to latitudes less than 50°.
2. The strengths in the strong field patches range from 10 to 20 Gauss.

Polarization methods of magnetic field determination (Charvin, 1971) indicate that the polar fields may not consist entirely of open field lines. Figure 3 shows the polar field topology based on the optical technique. On the other hand the Skylab coronograph shows the polar regions as large coronal holes which are evidently stable at least over the duration of the Skylab mission (Newkirk, 1975). This observation implies that most of the field lines over the poles are open.

B. Solar Cosmic Ray Propagation at High Solar Latitudes

A recent statistical study of solar flare cosmic ray events by Van Hollenbeke et al. (1975) has revealed that:

1. The onset time of 20-80 MeV proton fluxes at Earth systematically decreases with heliolongitude away from a minimum point at 50° ± 30° W of central meridian (Figure 4).

2. The intensity of solar cosmic rays at Earth is strongly dependent on the distance in longitude from the flare site. The preferred connection region is 20° W to 80° W longitude with some of the spread being due to the variable solar wind velocity.

3. Flare sources on the back side can sometimes be identified by very large X-ray and radio emission regions which extend above the limb. Particles from flares located away from the preferred longitude region as much as 150° are sometimes detected at Earth in this way.

4. The energy spectra of the protons from individual flare events located in the preferred connection region (20 to 80° W) are remarkably similar: most of these spectra are fit by power law exponents between -2 and -3.1 (Figure 5).

5. The energy spectra of flare particles measured near Earth changes systematically with distance from the preferred-connection longitude. At 40° E the range of power law exponents is -3.7 to -5.0 (Figure 5).

The authors have eliminated interplanetary diffusion and adiabatic cooling as causes for the above observations. They explain the results in terms of energy dependent diffusion of the flare particles from the flare site through the coronal magnetic fields out to the spiral interplanetary field lines that connect to the observing site. The progressive softening of the flare particle energy spectra is attributed to the more rapid loss of the higher energy particles onto spiral field lines leaving in the vicinity of the flare site. The lower energy particles are preferentially retained so that as the diffusing particle population ages, its average energy and spectral slope decreases.

Such observations will make it possible to specify certain physical conditions in the coronal regions, especially the particle diffusion coefficient. Experiments at lower energy can determine the total amount of matter traversed by the particles and thus a physical model of the diffusion in the high latitude corona can be built up.

The out-of-the ecliptic missions offer the possibility of doing an analogous experiment in which latitude is the variable, thus complementing the longitude studies. In the latitude case the situation is even more complex but also should be more revealing about the spatial structure and characteristics of the solar coronal magnetic fields. To reach high latitudes, the particles will have had to propagate through the transition zone as well as appreciably into the polar fields. There are bound to be great surprises in such observations too far outside our present experience to anticipate. Nonetheless, Figure 6 attempts to qualitatively indicate what might be the outcome of solar cosmic ray observations at high latitudes.

C. Origin of the Interplanetary Particle Populations

Figure 7 shows the so-called quiet time proton energy spectrum in interplanetary space. At the lowest energy end there are the solar wind protons. At high energies (greater than 10 GeV) the protons almost certainly belong to a galactic population of particles, and at the very highest energies, the particles may even be intergalactic in distribution. In the range 30 MeV to about 10 GeV the protons are probably galactic but their intensity is strongly modulated by the Sun's magnetized plasma wind, at least near the ecliptic plane. The range from 2 to 100 MeV has recently been studied extensively by the University of Chicago and Goddard Space Flight Center Groups. A detailed study by J. Kinsey (1970) is based on the hypothesis that the protons in the energy interval come from two distinct populations. Figure 8 shows some spectra in this energy region. Those observations may be represented by

$$\frac{dJ}{dE} = F_s E^{-s} + F_g E^g \tag{1}$$

dJ/dE is the number of protons per square centimeter-steradian-second-MeV. F_s, F_g, s and g are parameters that give best fits to the observations. It is found that F_s and s are highly variable while F_g and g vary much less. The interpretation is that the first term on the right hand side of Equation (1) represents a proton component of solar origin while the other term is presumed to be galactic in origin.

No doubt the proton fluxes in this energy range will prove to be quite different when observed at high heliographic latitudes. There detectors presumably would be far removed from the solar source regions and the reduction of intensity in the galactic component by modulation should be much diminished.

Figure 9 shows the energy spectrum of electrons at times of lowest solar flare activity often referred to as the "interplanetary electron spectrum". As in the case of the protons, the highest energy electrons are presumed to fill the galaxy, while the lowest energy electrons are known to be of solar origin -- they are the solar wind electrons. Between these two components the situation is complicated, perhaps even more so than in the case of protons:

1. The solar wind electrons have a non-Maxwellian tail at energies above about 100 eV. This tail appears to extend to 1 or 2 keV. It can be described by a power law of $E^{-5.1}$.
2. The non-Maxwellian becomes submerged in a new particle population which extends to about 1 MeV. This spectrum approximately follows the power law E^{-3}.

There appears to be no spectral flattening of the 2 keV 1 MeV component as there is in the case of the protons.

The study of the complex electron spectrum would be greatly advanced by observations at high solar latitudes. Much will be learned by investigating how the electron spectrum changes relative to the proton spectrum.

Among the questions we can now pose about the interplanetary fluxes are:

1. Will the medium energy component decrease significantly as the detectors move away from the active sunspot zones?

2. From observing such a change systematically with latitude can we learn more about the sources and the transport of the particles through the coronal magnetic fields at high latitudes?
3. Can we identify a component that is generated by instabilities in the solar wind? Possibly the 100 eV to 1 keV non-Maxwellian tail arises in this way. As the solar wind flow changes as a function of latitude does the character of the non-Maxwellian tail change? Possibly even the 2 to 10 keV region originates, at least in part, from internal energy sources of the solar wind by means of plasma microinstabilities.
4. Is there an electron component, for example the 10 to 100 keV region, which is supplied, at least in part, by strong cosmic X-ray sources?

The high latitude electron and proton measurements will be free of planetary source effects: the Earth's bow shock and magnetosphere and Jupiter's magnetosphere. This is another important motivation for out-of-the ecliptic missions.

D. Shock Waves and Other Interplanetary Phenomena

A variety of complex energetic particle phenomena take place in interplanetary space. Although they must involve basic plasma processes they are not yet well understood. The motivation for further study is strong, however, since these processes must occur throughout our galaxy in systems of similar and larger scale sizes.

One such phenomenon is the acceleration of particles by shock waves of solar origin in interplanetary space. Figure 10 illustrates this effect in a particular case. The important observational features in this event are (R. E. McGuire, Ph.D. thesis, University of California, Berkeley, 1976):

1. The shock velocity was 520 km/µ and the shock normal was close to the Sun-Earth line.
2. Preceding the shock passage the electron and proton flux increased by a factor of 10 due evidently to a flare.
3. Twenty minutes before the shock passage the protons above 200 keV increased by a factor of 20. The flux maximum occurred about one gyroradius in front of the shock. A more gradual increase in the medium and high energy electron flux also occurred.
4. Electrons 0.5 to 14 keV increased 20-fold just behind the shock front. This flux increase may be associated with dissipation of energy by the shock.

Although several detailed models for shock acceleration exist, none seem completely satisfactory. By observing shock effects on particles at high solar longitudes where the characteristic of the interplanetary field are presumably much different it should be possible to arrive at a satisfactory shock acceleration model. This is a problem of first order importance to cosmic ray studies since shock acceleration occurs in many cosmic systems. For example, shock waves probably play an important role in the production of energetic flare particles; shocks may accelerate the entire fast electron component. And it is known that shock waves carry energy into interplanetary space in amounts equal to a large fraction of the total flare energy (Hundhausen and Gentry, 1969). There is still no satisfactory theoretical solution to the problem of magnetic field line merging as an energy source for flare phenomena and it thus becomes vitally important in the study of the flare process to know as much as possible about shock acceleration.

At high solar latitudes the magnetic field will make a smaller angle with respect to the solar wind flow direction, on the average, compared to lower latitudes. Also, one expects that the power spectrum of fluctuations in the interplanetary field to be considerably reduced at high latitudes as compared to the latitude range of the activity zones. These differences can then be used to explain differences in the shock acceleration of particles as a function of heliocentric latitude.

There seem to be several solar-interplanetary phenomena which emerge clearly during part of the solar cycle but then become less apparent or disappear later in the solar cycle. In his presentation at the symposium Dr. Hundhausen (1976) mentioned such an effect in the solar wind. Another example is the abundance of long lived particle streams (recurrence events) early in the solar cycle (McDonald and Desai, 1971). Yet another example is the electron-proton "splitting" effect reported by

Lin and Anderson (1967). This effect occurs in solar co-rotating streams that appear near Earth one or two days following solar flares. The electrons in these streams are displaced to the west of the protons and thus are observed to pass over the detectors before the protons do. This time displacement is a few hours up to 10 hours (a few degrees in longitude). An example of electron-proton splitting is given in Figure 11.

None of the proposed mechanisms has been shown to quantitatively account for this effect, and no explanation has been offered for their apparent disappearance later in the solar cycle. Lin and Anderson (1967) thought that the effect could be due to the larger drift velocities of the protons compared to the electrons (the larger gyroradius of the protons means that the protons sample any gradients in the magnetic field to a greater extent). Jokipii (1969) proposed that the splitting can occur in interplanetary space due to combined gradient and curvature drift in the interplanetary magnetic field.

One expects that these phenomena and perhaps others still unexplained can be effectively studied by an out-of-the ecliptic mission.

E. Jupiter Swing-by Out of the Ecliptic Missions

For a two-spacecraft launch in late 1980 by a Titan-Centaur vehicle as described by the NASA-Ames Research Center group, Figure 12 shows when the spacecraft would reach high solar latitudes with respect to the sunspot cycle. A 1980 launch is probably not ideal for solar cosmic ray studies since the spacecraft arrive at high latitudes near the expected decline of solar cycle 21. However, it is worth noting that several very large flares occurred in this portion of solar cycle 20 including the very great August, 1972 flares. The spacecraft remains above latitude 35° N and 35°S for somewhat more than 2 years.

Figure 13 shows where the spacecraft are positioned in solar latitude on a Maunder's butterfly diagram. This figure shows that there is some advantage in arriving at these high latitudes late in the solar cycle since the activity zones have retreated toward the equator.

Acknowledgments

This work was supported in part by National Aeronautics and Space Administration grant NGR 05-003-017.

References

Anderson, K.A., Lifetime of solar flare particles in coronal storage regions, Solar Phys., **27**, 442, 1972.

Charvin, P., Experimental study of the orientation of magnetic fields in the corona, Solar Magnetic Fields (ed. R. Howard), D. Reidèl, p. 580, 1971.

Hundhausen, A. J., Proceedings of this Symposium, 1976.

Hundhausen, A. J. and G. A. Gentry, Numerical simulation of flare generated disturbances in the solar wind, J. Geophys. Res., **74**, 2908, 1969.

Jokipii, J. R., Proceedings of the Cosmic Ray Conference, Budapest, 1969.

Kinsey, J.H., Ph.D. Thesis, University of Maryland, 1970.

Lin, R. P. and K.A. Anderson, Electrons > 40 keV and protons > 500 keV of solar origin, Solar Phys., **1**, 446, 1967.

McDonald, F. B. and U. D. Desai, Recurrent solar cosmic ray events and solar M regions, J. Geophys. Res., **76**, 808, 1971.

McGuire, R. E., Ph. D. Thesis, University of California, Berkeley, 1976.

Newkirk, G., Proceedings of this Symposium, 1976.

Stenflo, J. O., Observations of the polar magnetic fields, Solar Magnetic Fields (ed. R. Howard), D. Reidel, p. 714, 1971.

Van Hollenbeke, M.A.I., L.S. MaSung and F. B. McDonald, The variation of solar proton energy spectra and size distribution with heliolongitude, Solar Phys., **41**, 189, 1975.

Figure Captions

Figure 1. The intermediate solar corona. This photograph was taken following solar maximum and before solar minimum. At this time the polar plumes are clearly visible. Their appearance suggests that the polar zone magnetic field lines do not close in the vicinity of the Sun. (Yerkes Observatory photograph.)

Figure 2. Synoptic charts of the polar magnetic fields $H_{\parallel}/\cos\theta$. Solid lines represent N polarity, dashed lines S polarity. The isogauss levels are 10 and 20 G. The areas covered by the observations are enclosed by curves with shadings on the outside. (a) North pole. Observations from August 1-23 1968. (b) South pole. Observations from July 31-August 23, 68. (From J. O. Stenflo, Observations of the polar magnetic fields, in Solar Magnetic Fields (ed. R. Howard), D. Reidel Publ. IAU Symposium No. 43).

Figure 3. Schematic map of the polar coronal magnetic fields (July 26, 1970). The prominences and filaments observed on spectroheliograms are shown on the map. (From P. Charvin, Experimental study of the orientation of magnetic fields in the corona, in Solar Magnetic Fields (ed. R. Howard), D. Reidel, I. A. U. Symp. No. 43).

Figure 4. The difference ΔT_m of the time between onset of 20-80 MeV proton and maximum particle intensity is plotted as a function of the heliolongitude. The solid line is a least square fit through the data. It shows a minimum at $\sim 50^{\circ} \pm 30^{\circ}$ W of the central meridian.

Figure 5. Variation of the spectral index γ_p in the 20-80 MeV range as a function of the heliolongitude $\lambda_\odot$. The open circles are 'long rise time events' with a rise time longer than 24 hours. For these events, effects of interplanetary propagation may be significant. The dashed countour lines enclose 92 % of all the other events. The solid line is a least square fit obtained for them. $\gamma_p(\lambda_\odot)$ can be represented approximately by $\gamma_p(\lambda_\odot) = 2.7 [1 + \Delta\lambda/2]$.

Figure 6. This figure idealizes how solar flare particle fluxes might depend on latitude for various coronal magnetic field configurations which vary with heliographic latitude.

Figure 7. The interplanetary quiet time proton spectrum is made up of several components: at the lowest energy the solar wind protons and at the highest energies, the galactic cosmic rays. In between is a spectrum which probably has solar origin.

Figure 8. This figure shows the region of presumed overlap between interplanetary protons of galactic and of solar origin.

Figure 9. The interplanetary quiet time electron spectrum is also made up of several components: the solar wind electrons at the lowest energies and the galactic component at the highest. Several components appear to exist at intermediate energy. Little is known about their origin.

Figure 10. An interplanetary shock (speed 540 km/sec at 1 AU) that produced large effects on particles. Protons in the 0.3 to 0.5 MeV range are swept up or accelerated by the shock. A blanket of hot electrons appears just behind the shock possibly the result of energy dissipation by the shock.

Figure 11. This figure shows an example of electron-proton splitting early in solar cycle 20. The particles arrive at Earth in a co-rotating stream but the electrons are displaced toward the West by a few degrees. The origin of this effect is not known and it appears to become less frequent later in the solar cycle.

Figure 12. This figure shows that for certain Jupiter swing-by out-of-the-ecliptic missions launched in late 1980, the spacecraft will arrive at high ($> 35°$) latitudes in late 1983 and remain there for somewhat over two years.

Figure 13. For the same missions the spacecraft is seen to rapidly rise past the sunspot zones which, late in the solar cycle, have moved close to the equator.

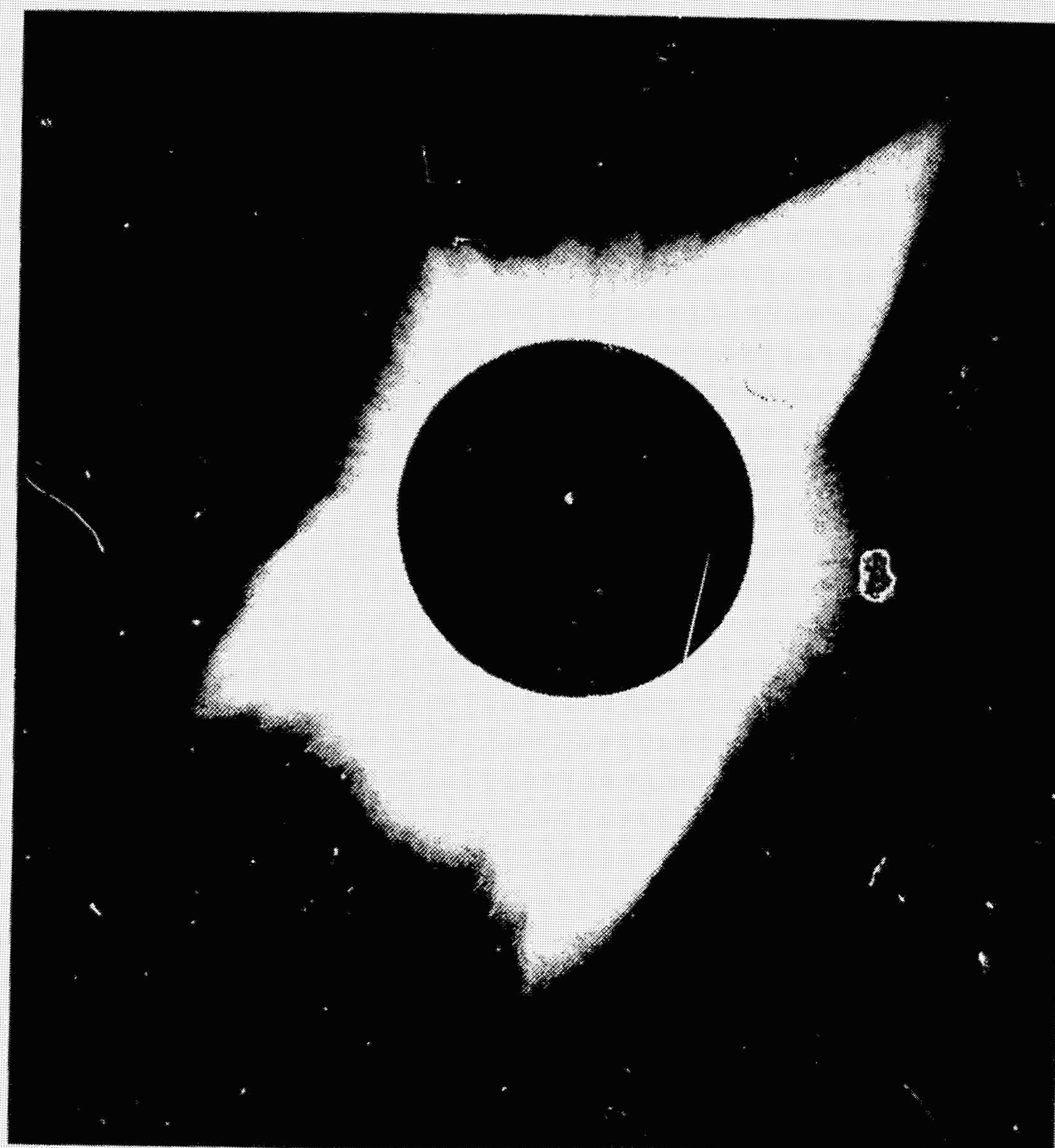


Figure 1

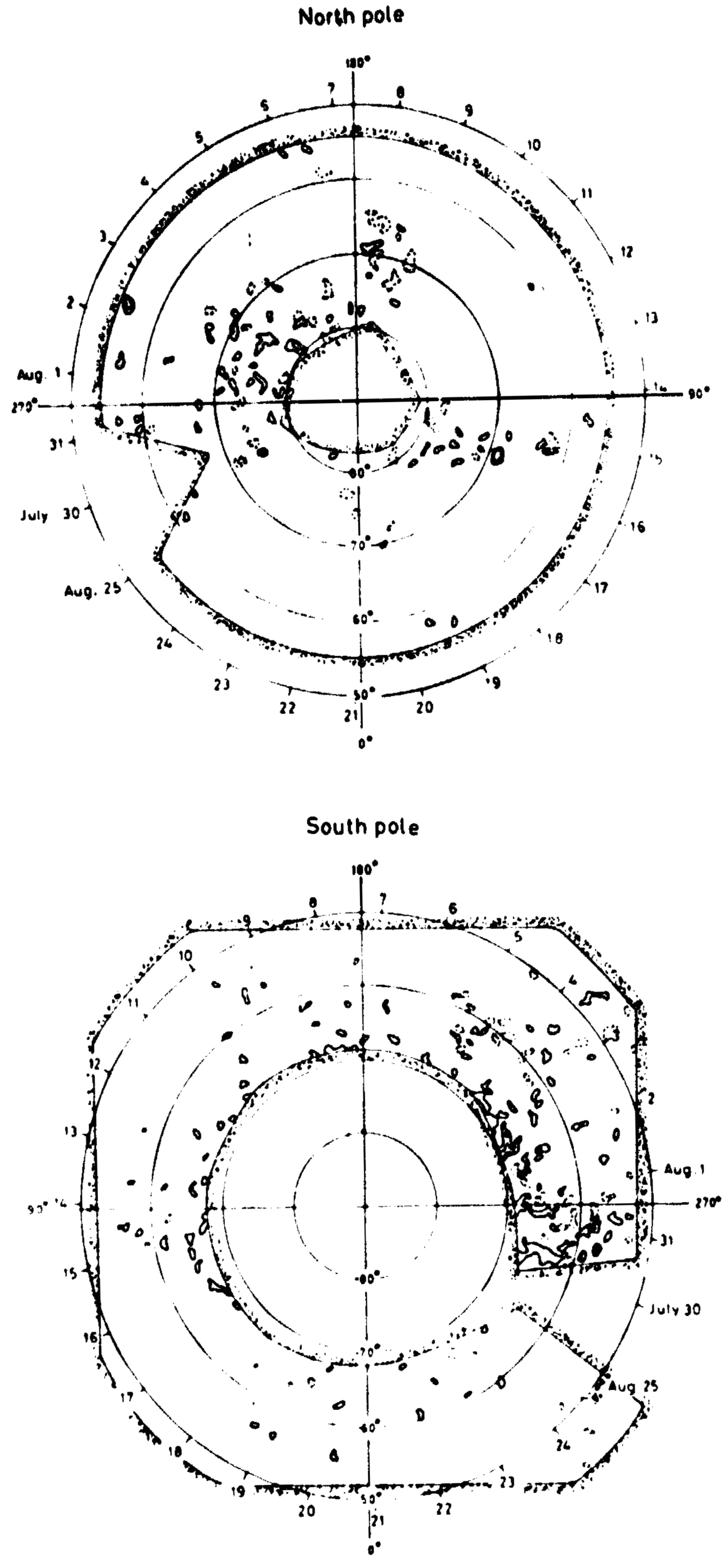

North pole
180°
7
8
9
10
11
12
13
14
90°
15
16
17
18
19
20
21
22
23
24
Aug. 25
July 30
31
270°
Aug. 1
2
3
4
5
6
80°
70°
60°
50°
0°
South pole
180°
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
Aug 25
July 30
31
270°
Aug. 1
2
3
5
6
80°
70°
60°
50°
0°

Figure 2

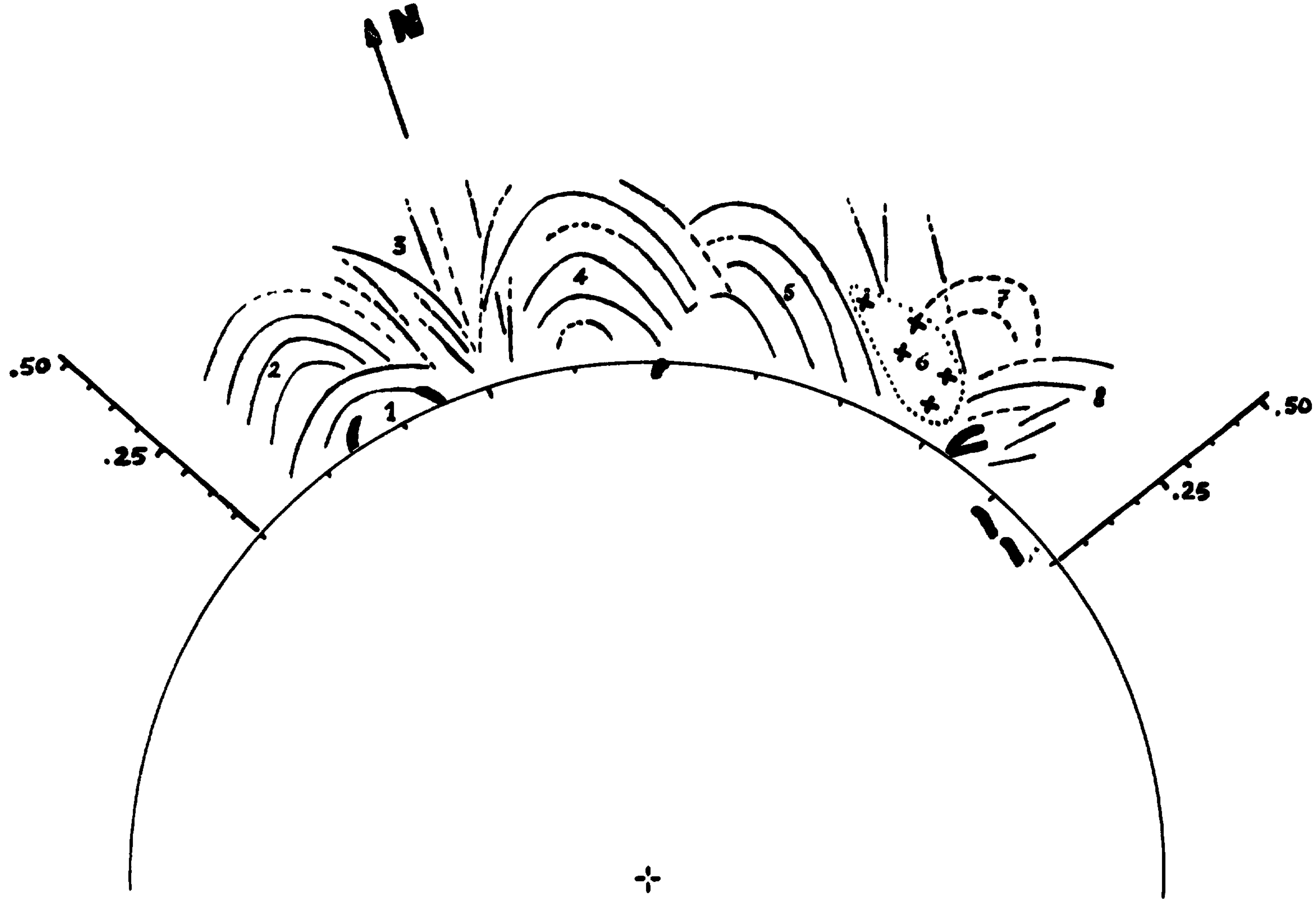
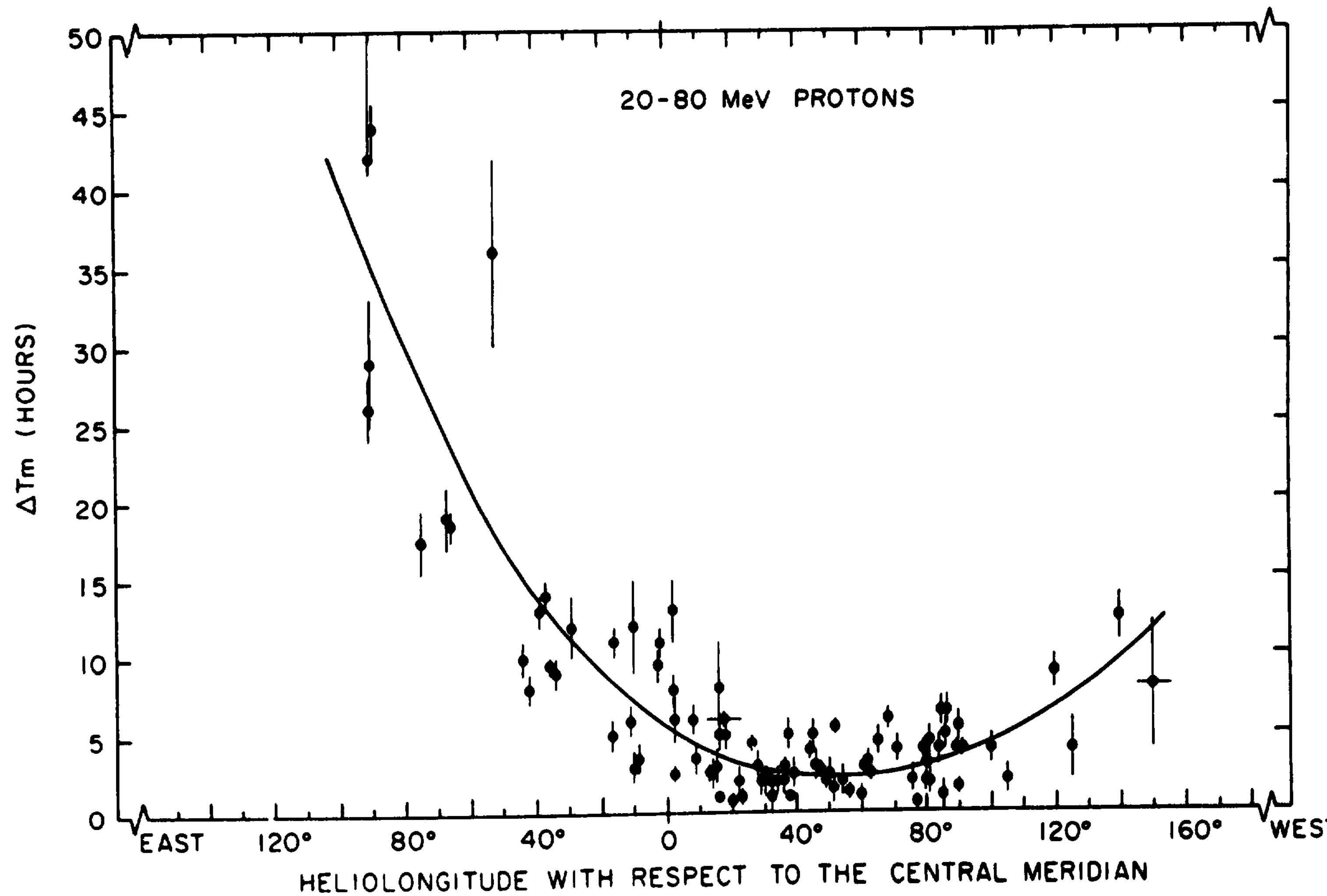


Figure 3



20-80 MeV PROTONS
ΔTm (HOURS)
0
5
10
15
20
25
30
35
40
45
50
EAST
120°
80°
40°
0
40°
80°
120°
160°
WEST
HELIOLONGITUDE WITH RESPECT TO THE CENTRAL MERIDIAN

Figure 4

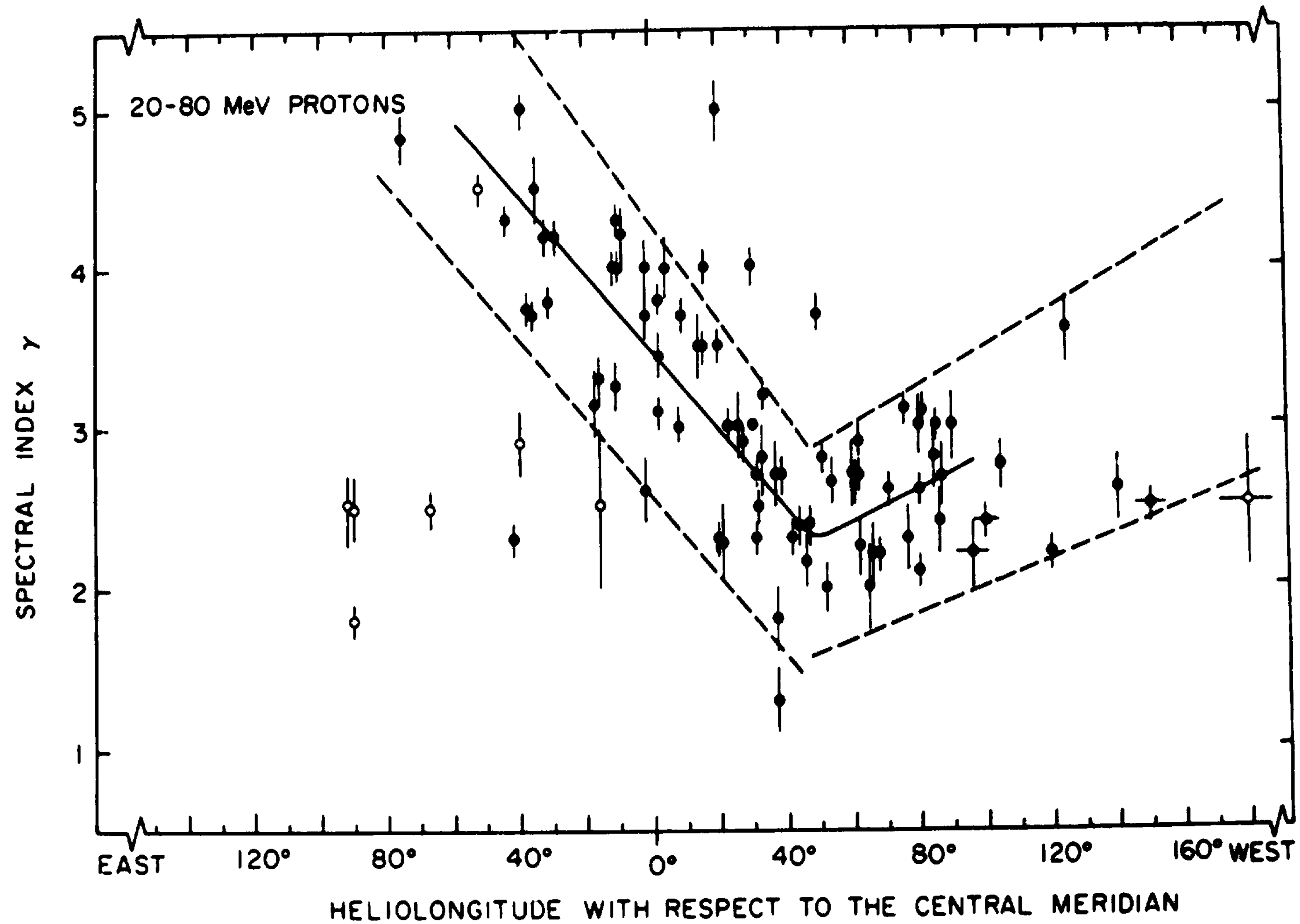

20-80 MeV PROTONS
SPECTRAL INDEX γ
5
4
3
2
1
EAST
120°
80°
40°
0°
40°
80°
120°
160° WEST
HELIOLONGITUDE WITH RESPECT TO THE CENTRAL MERIDIAN

Figure 5

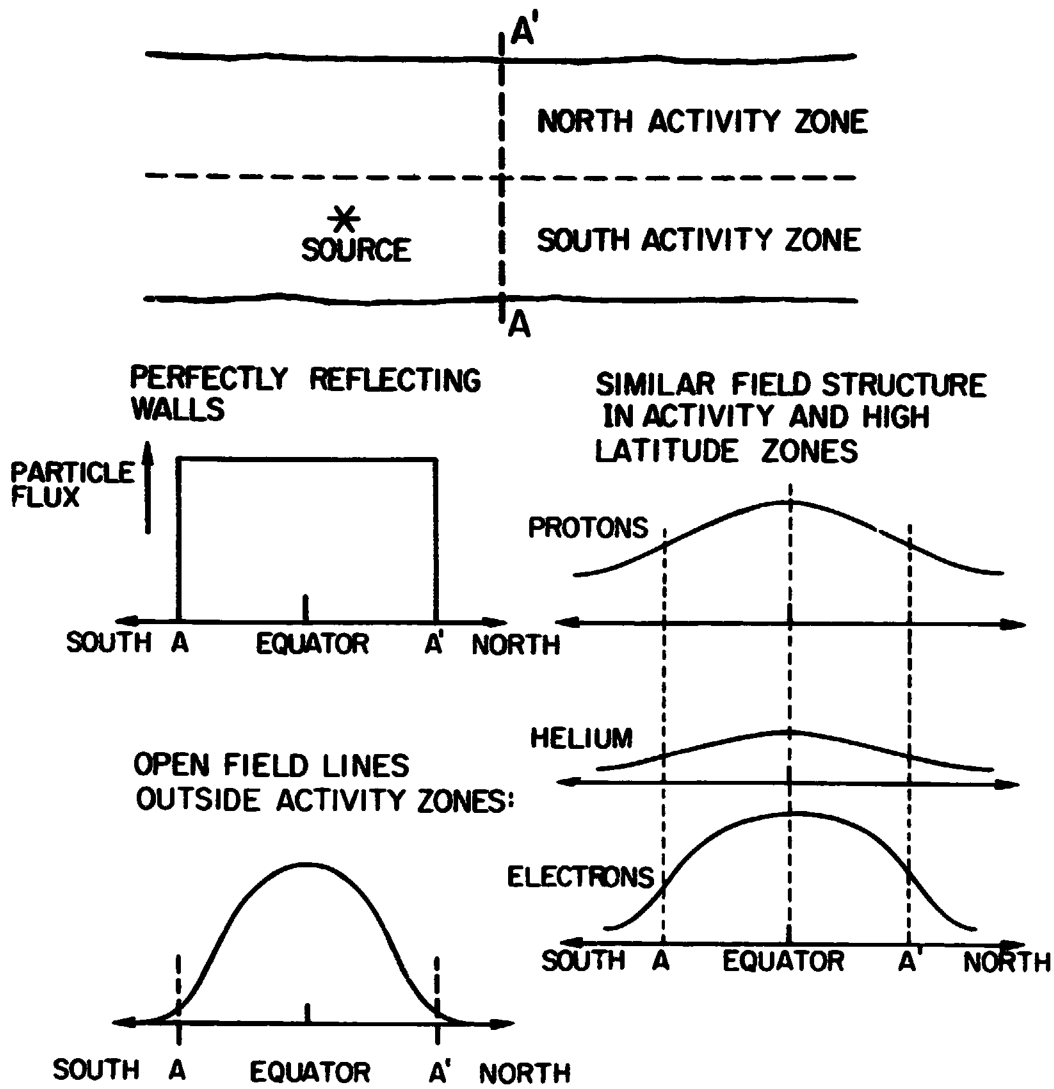

A'
NORTH ACTIVITY ZONE
SOURCE
SOUTH ACTIVITY ZONE
A
PERFECTLY REFLECTING WALLS
PARTICLE FLUX
SOUTH A EQUATOR A' NORTH
OPEN FIELD LINES OUTSIDE ACTIVITY ZONES:
SOUTH A EQUATOR A' NORTH
SIMILAR FIELD STRUCTURE IN ACTIVITY AND HIGH LATITUDE ZONES
PROTONS
HELIUM
ELECTRONS
SOUTH A EQUATOR A' NORTH

Figure 6

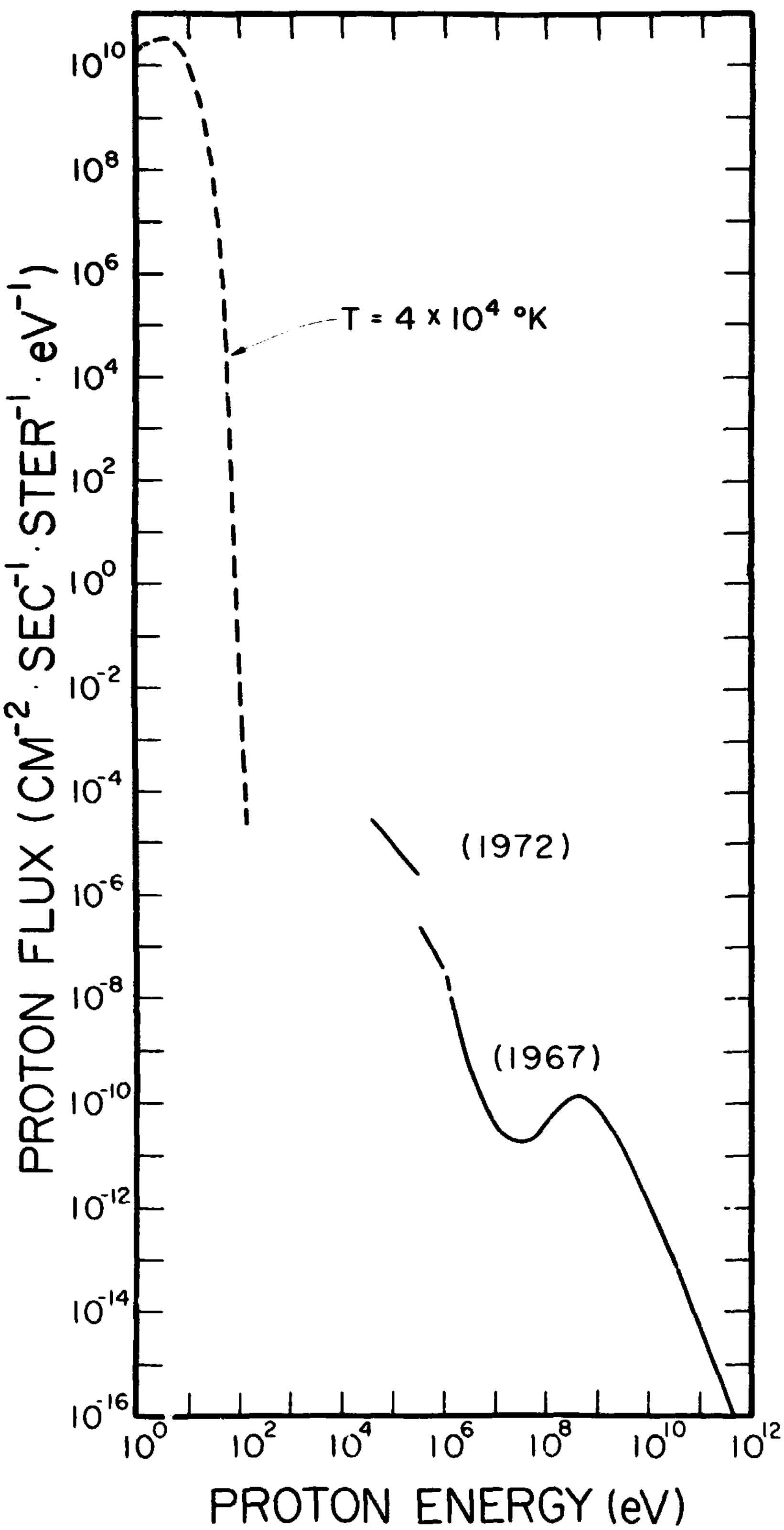

PROTON FLUX (CM^{-2} · SEC^{-1} · STER^{-1} · eV^{-1})
10^{10}
10^{8}
10^{6}
10^{4}
10^{2}
10^{0}
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
T = 4 x 10^4 °K
(1972)
(1967)
10^{0}
10^{2}
10^{4}
10^{6}
10^{8}
10^{10}
10^{12}
PROTON ENERGY (eV)

Figure 7

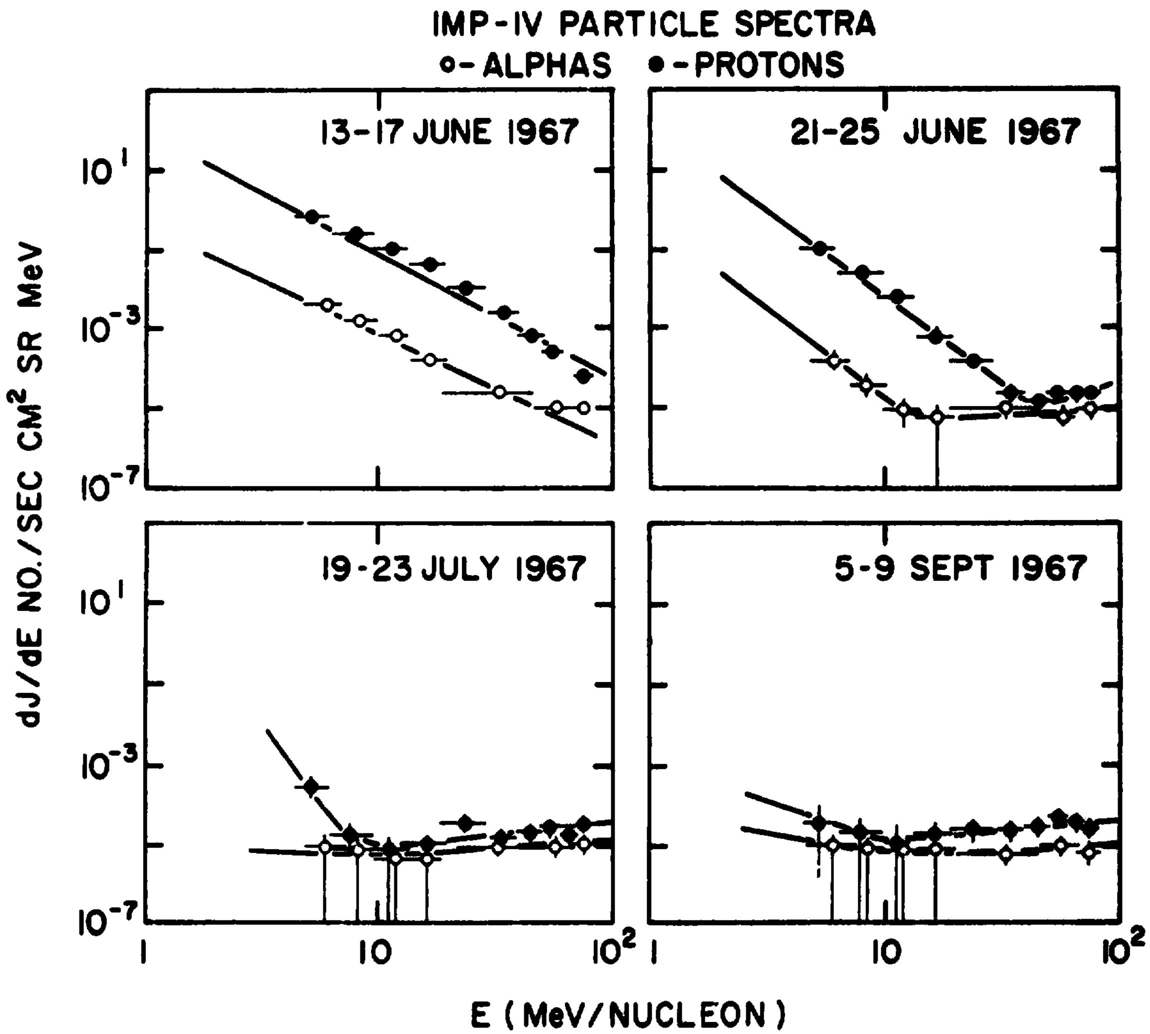

IMP-IV PARTICLE SPECTRA
o- ALPHAS • - PROTONS
13-17 JUNE 1967
21-25 JUNE 1967
19-23 JULY 1967
5-9 SEPT 1967
dJ/dE NO./SEC CM² SR MeV
10¹
10⁻³
10⁻⁷
1
10
10²
E (MeV/NUCLEON)

Figure 8

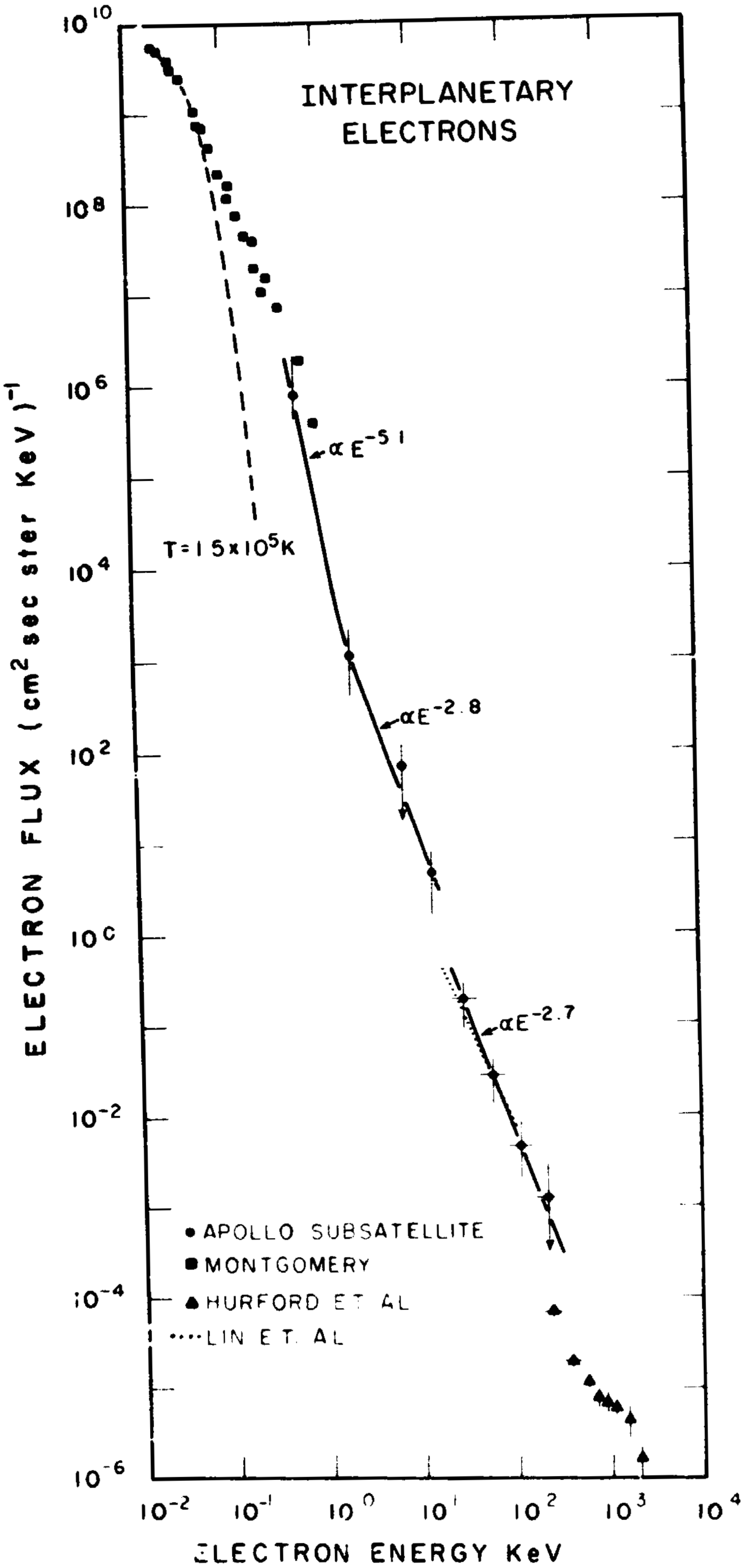

INTERPLANETARY
ELECTRONS
ELECTRON FLUX (cm² sec ster KeV)⁻¹
ELECTRON ENERGY KeV
T=1.5x10⁵K
αE⁻⁵·¹
αE⁻²·⁸
αE⁻²·⁷
APOLLO SUBSATELLITE
MONTGOMERY
HURFORD ET AL
LIN ET. AL

Figure 9

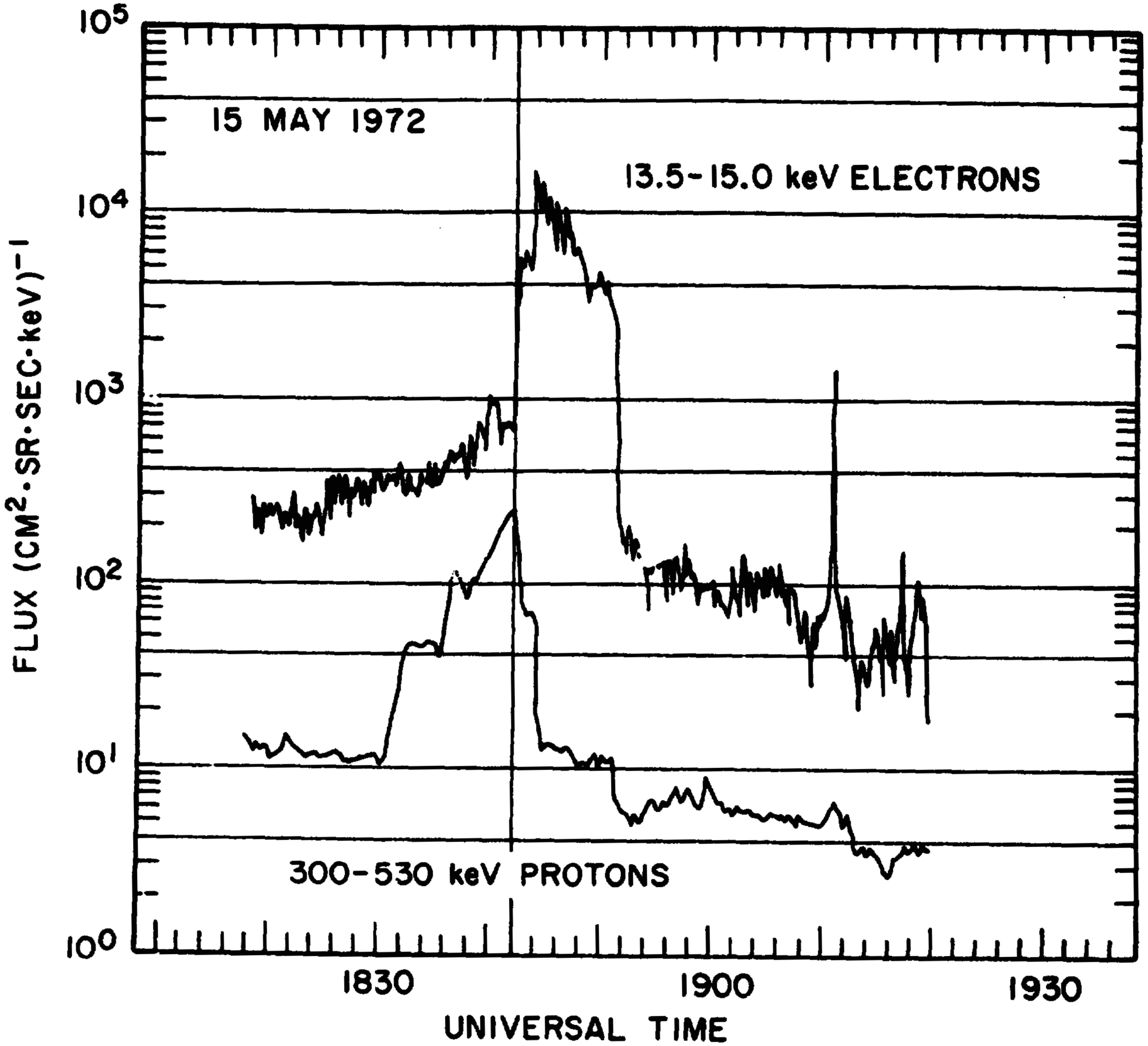

15 MAY 1972
13.5-15.0 keV ELECTRONS
300-530 keV PROTONS
FLUX (CM²·SR·SEC·keV)⁻¹
10⁵
10⁴
10³
10²
10¹
10⁰
1830
1900
1930
UNIVERSAL TIME

Figure 10

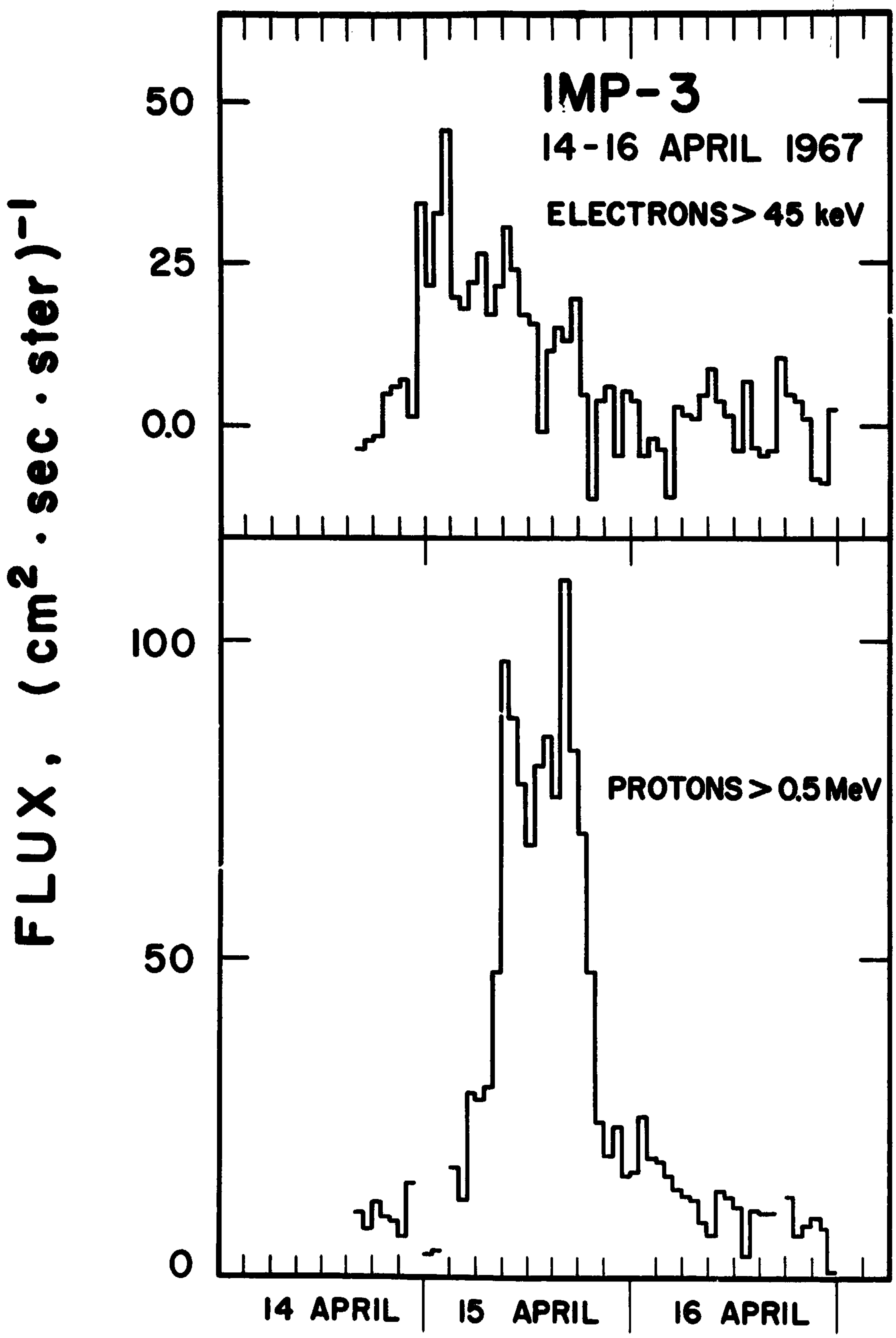
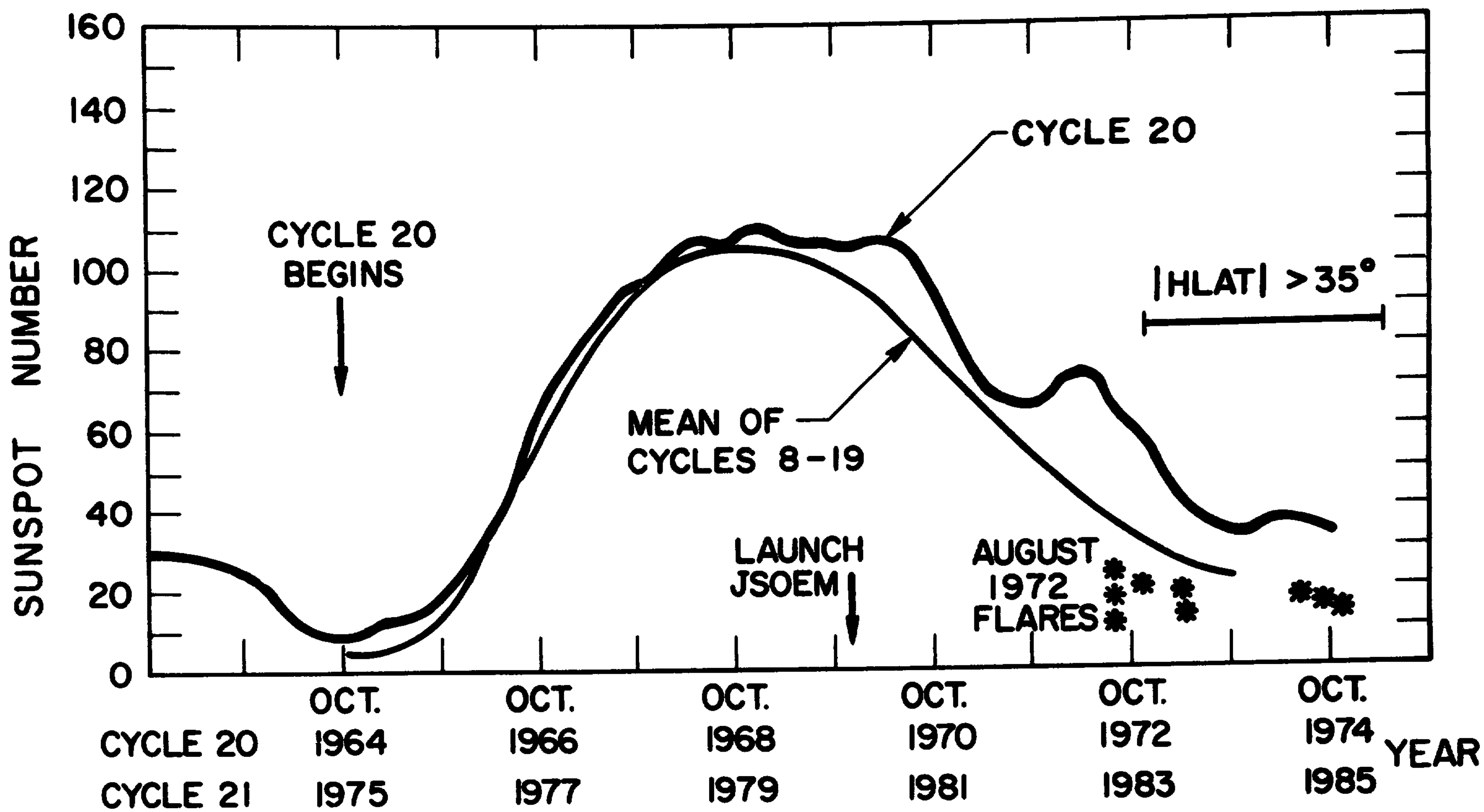

IMP-3
14-16 APRIL 1967
ELECTRONS > 45 keV
PROTONS > 0.5 MeV
FLUX, (cm2 · sec · ster)-1
50
25
0.0
100
50
0
14 APRIL
15 APRIL
16 APRIL

Figure 11



160
140
120
100
80
60
40
20
0
SUNSPOT NUMBER
CYCLE 20 BEGINS
CYCLE 20
MEAN OF CYCLES 8-19
LAUNCH JSOEM
AUGUST 1972 FLARES
|HLAT| >35°
OCT.
CYCLE 20 1964 1966 1968 1970 1972 1974
CYCLE 21 1975 1977 1979 1981 1983 1985
YEAR

Figure 12

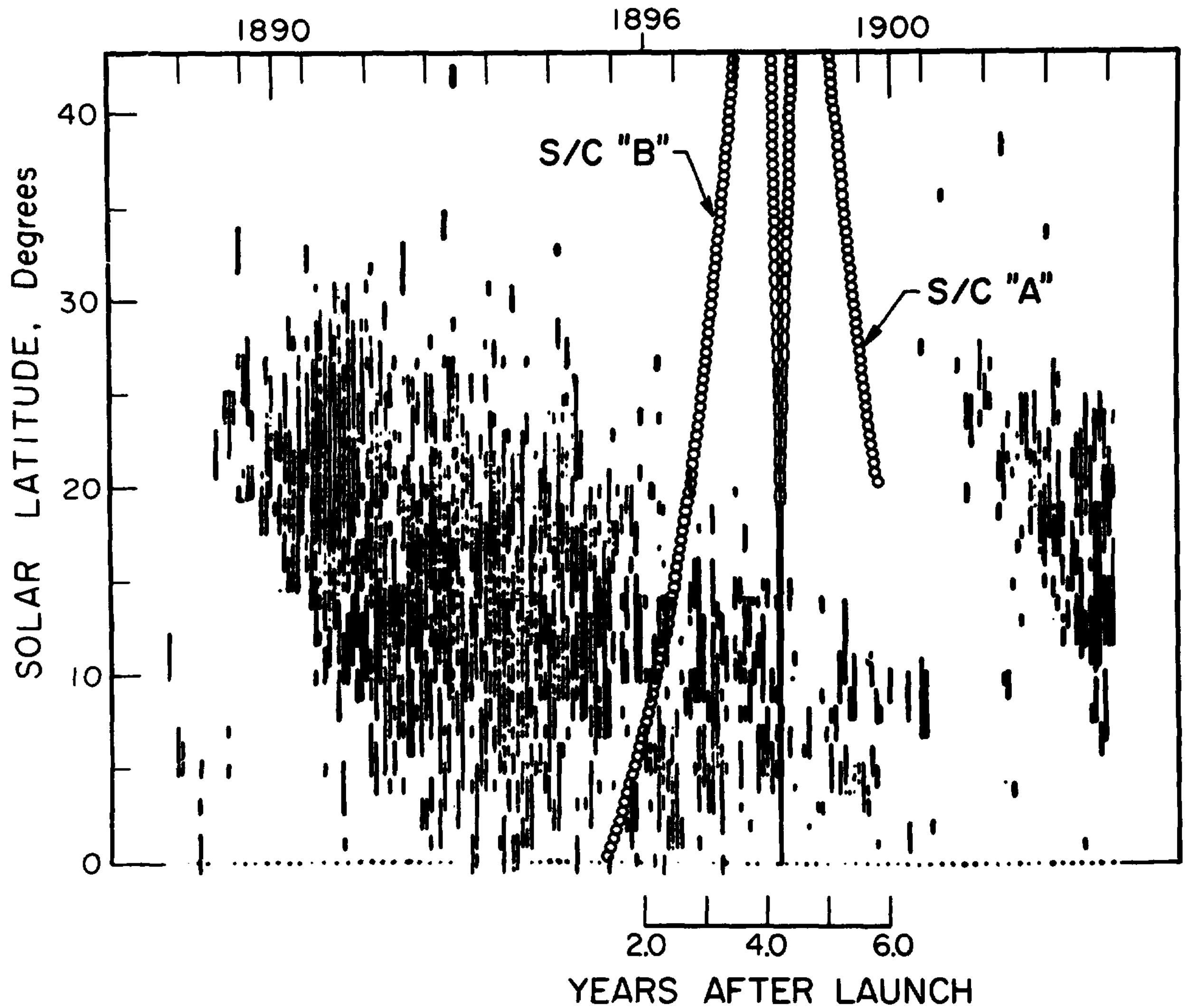

1890
1896
1900
40
30
20
10
0
SOLAR LATITUDE, Degrees
S/C "B"
S/C "A"
2.0
4.0
6.0
YEARS AFTER LAUNCH

Figure 13