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THE MC DONNELL DOUGLAS GEOPHYSICAL OBSERVATORY PROGRAM PROGRESS REPORT XIII (CONJUGATE POINT RIOMETER PROGRAM)

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This report, the thirteenth and final progress report on the McDonnell Douglas Geophysical Observatory Program, is made up of two parts: the first (comprising Sections 2 through 7) is a comprehensive report on the history of the program from 1962 through 1973; the second part (the subsequent Sections) is a report on the results of the research carried out in 1974.

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MDAC is indebted to the United States Navy for its operational support of the Antarctic Observatory and to the Government of Canada and the United States Air Force for allowing operation of the Arctic Observatory.

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Section 1

INTRODUCTION

This report, the thirteenth and final progress report on the McDonnell Douglas Geophysical Observatory Program, is made up of two parts: the first (comprising Sections 2 through 7) is a comprehensive report on the history of the program from 1962 through 1973; the second part (the subsequent Sections) is a report on the results of the research carried on in 1974.

Section 2
STATION OPERATION

The MDAC Antarctic Geophysical Observatory (77°57'S, 166°43'E) at McMurdo Sound began operation in February 1962. The magnetically conjugate Arctic Observatory (68°29'N, 93°26'W) at Shepherd Bay, Canada (See Figure 1) began operation in August 1963. These stations, at a magnetic latitude of 80° (L = 32), were established to study the characteristics of solar cosmic ray events continuously, at a fixed location, and at a reasonable cost. The locations were chosen inside the polar cap regions, removed poleward from the auroral zones to minimize auroral interference and geomagnetic cutoff effects.

Radio techniques were used which monitor effects taking place at altitudes from 30 to 90 kilometers with ground-based equipment. Riometers were operated that measure the signal strength of galactic radio noise at 30 and 50 MHz. The ionization produced by the interaction of the charged particles with the atmosphere increases the electron density so that radio waves passing through the ionosphere are significantly absorbed. The absorption of the radio wave at a given frequency is proportional to the square root of the intensity of charged particles for a fixed energy spectrum. This technique is sensitive to protons from about 5 to 100 MeV.

Two photometers were also operated at 5577 Å, to measure the line emission of OI, and at 3914 Å measuring band emission of N_2^+ First Negative. Each was equipped with a 30Å bandpass interference filter with the center line of transmission at the respective wavelengths given above. The full viewing cone of each was about 60° at the apex and the axis of the viewing cone pointed to the zenith of the observatory. The signal output was analog mode and was recorded on the same strip chart and magnetic tape as the other experiments. Magnetometers were also operated at the stations, triaxial at Shepherd Bay and single axis at McMurdo Sound.

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Figure 1. Station Map

The objectives of the program included:

A. Investigation and Monitoring of Solar Particle Activity--We observed and monitored each solar particle event which occurred, in a continuous and intercomparable manner for 13 years. This required standardized, well maintained equipment, located at high latitudes poleward of the auroral zone to minimize interference and in both polar regions to get daytime coverage throughout the year.

D. F. Smart and M. A. Shea proposed a polar proton classification system (Smart and Shea, 1970). This system was approved by the Inter-Union Commission on Solar Terrestrial Physics and COSPAR. The system uses three digits: the first is E > 10 MeV proton flux; the second, 30-MHz riometer absorption by a daylight polar riometer; and the third, a high-latitude sea-level neutron monitor. Because of the high quality and consistency of our riometer data and the importance of our two locations, Shea and Smart have selected the results of our stations as an international standard to be used in the classification system and, with Virginia Lincoln, have requested that in the future we make the data available to World Data Center A so that they can be included in Solar Geophysical Data on a regular basis. The solar proton event observations will then be available to all U. S. and foreign scientists.

B. Joint ATS-Polar Station Particle Access and Propagation Study--The polar ground-based observations play a key role in conjunction with observations made by the MDAC experiment on ATS-6 launched in July 1974. The Polar Station-ATS-6 combined experiments were planned to study the complex problem of solar cosmic ray access propagation using simultaneous observations at synchronous orbit (L = 6.6) and in the North and South Polar regions (Figure 2). Solar cosmic rays and trapped particles have been measured directly parallel and perpendicular to the magnetic line of force on ATS. The polar stations provided the only observation of the important group of particles reaching the polar region. The 30 MHz riometer data can be directly and accurately converted to the > 10 MeV proton flux as has been shown by Kane and Masley (1973).

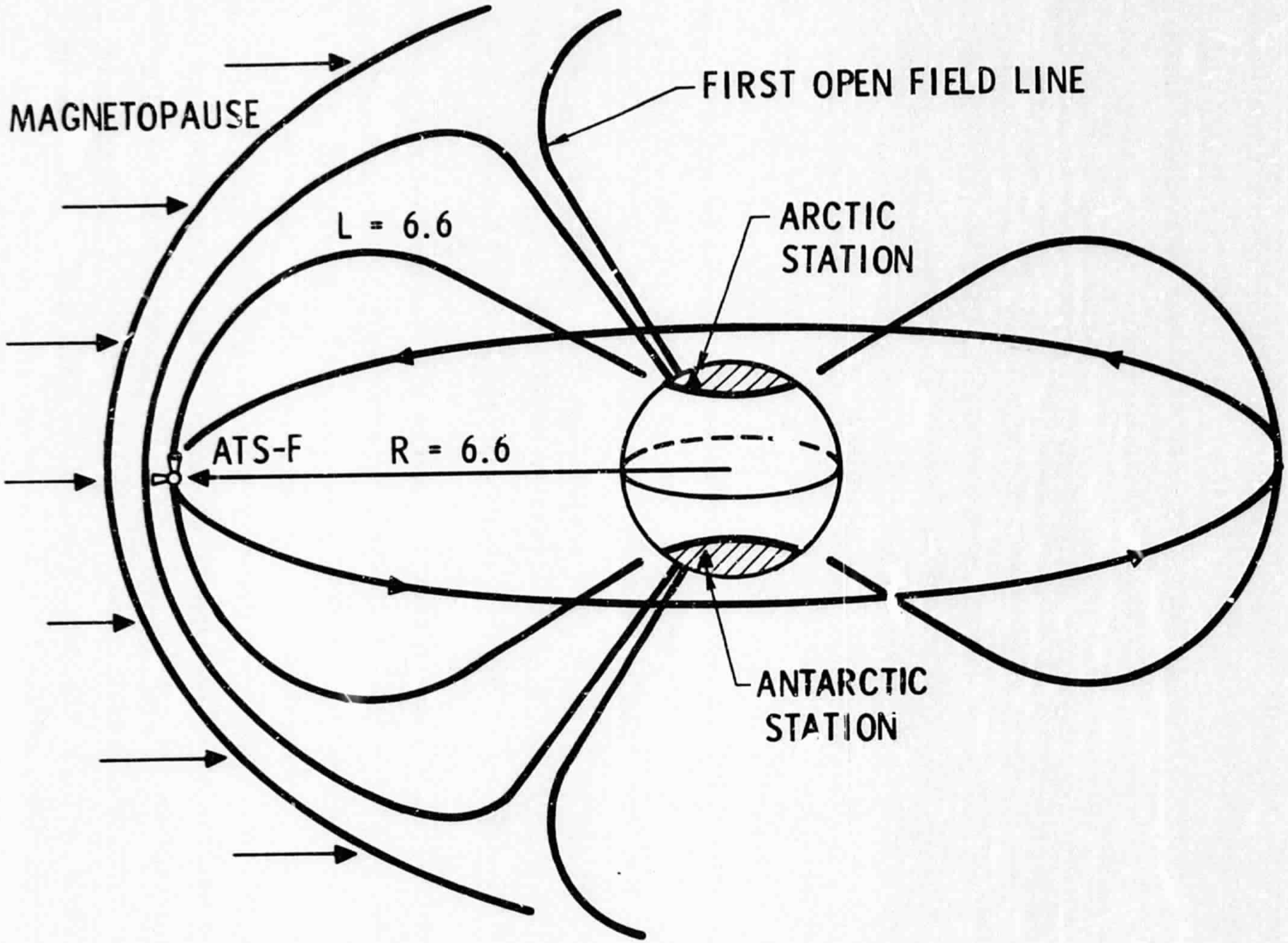

Figure 2. Polar Stations – ATS Orbit Geometry

C. Magnetospheric Studies--The stations were located near the cusp latitude or region (~80 deg geomagnetic) where the geomagnetic field lines part on the sunside and sweep in the antisolar direction along the boundary of the magnetospheric tail. The access of solar particles to the magnetosphere has been investigated using the riometer data in conjunction with the OGO-6 measurements. Local time and geomagnetic activity effects were considered. Also a theoretical study of particle trajectories using Olson's magnetospheric model was made. The sources of particles reaching particular locations in the polar cap can therefore be identified.

D. Ionospheric Physics--Auroral precipitation in high polar regions was investigated and the ionospheric electron density determined utilizing measurements of the 3914Å emission. Seasonal and diurnal variations of the electron density are not well known at high latitude since most previous investigations concentrated on the auroral zone. The high-latitude phenomena are of basic interest and are important with respect to radio communications. The photometer data allow the high-latitude study of precipitating particle type (electrons and protons), their energy fluxes, and the relation between their precipitation and the local K-index. Our studies have indicated that the probability of electron precipitation increases with local K-index < 4 whereas the probability of proton precipitation increases with local K-index > 4. Further studies are required to determine the configuration of the high-altitude polar precipitation, and comparisons between the north and south polar caps and with the auroral zone regions.

Section 3
IONOSPHERIC WORK

In the early stages of this program (1964-1965) our original work contributed to solving the proton-ionosphere interaction problem for the first time. This was done quantitatively and in great detail (Adams and Masley 1965b, 1966a, 1966b). The results of this work have been used and quoted regularly nationally and internationally up to the present time including two major review articles which appeared in 1970. The work has been verified experimentally during the past few years. Some of the results concerning the response of riometers to different intensities and energies of particles (see Figure 3) can be summarized as follows:

A. The proton energy which is most efficient for causing absorption goes from 35 MeV at 10 MHz to 90 MeV at 100 MHz.

B. The minimum intensity (i.e., the intensity of protons at the most efficient energy) required to give 0.1 db is 0.15 protons/cm^2-sec-ster at 10 MHz, 0.9 protons/cm^2-sec-ster at 30 MHz, and 2.0 protons/cm^2-sec-ster at 50 MHz. For typical solar proton spectra, such as an exponential rigidity, where p_o = 75 MV, rather than monoenergetic beams, the required intensities are 0.3, 4.0, and 20 protons/cm^2-sec-ster at 10, 30, and 50 MHz.

C. The absorption varies as the square root of the intensity when the shape of the spectrum is constant and when the absorption is much greater than the absorption resulting from the normal ionosphere. For absorption values close to the ambient absorption, the absorption varies directly as the intensity.

D. In general, the riometer is sensitive to protons with energies between 5 and 80 MeV, although this range depends on the frequency of the riometer and the shape of the energy spectrum.

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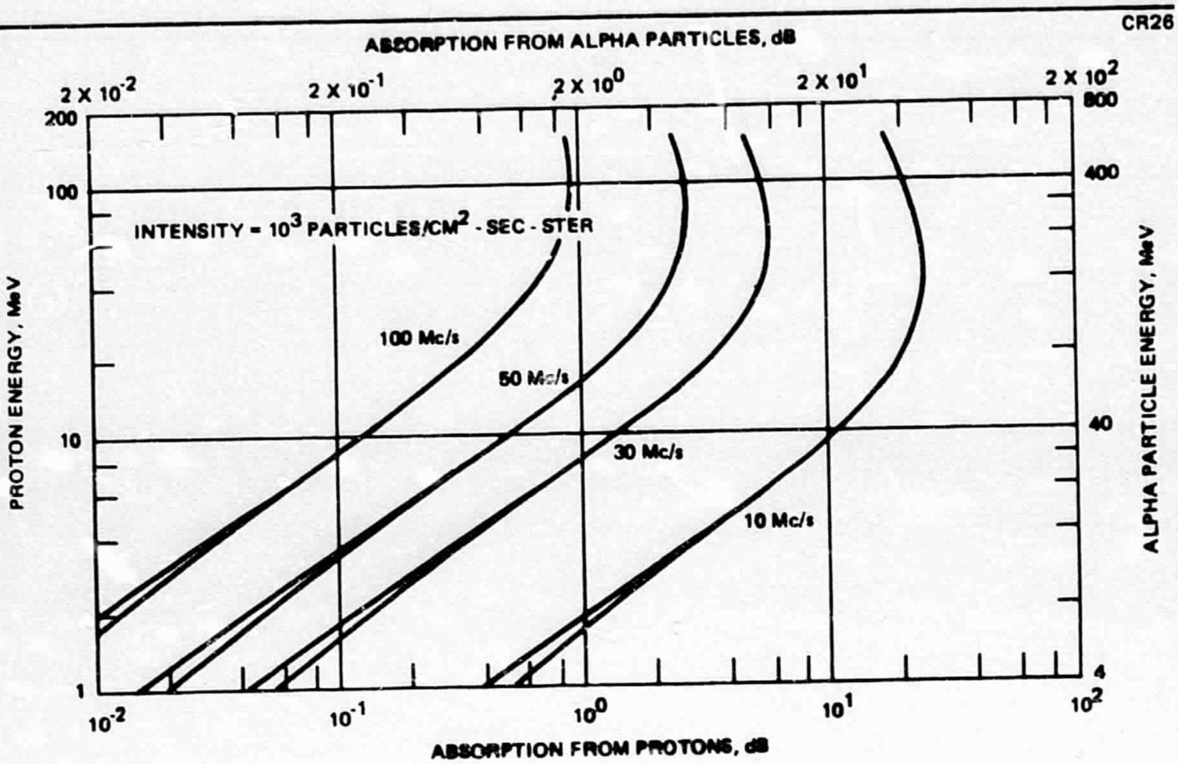

Figure 3. Response of Riometers to Protons and Alpha Particles

E. As measured by the riometer, one alpha particle is the equivalent of four protons with the same energy per nucleon.

F. The absorption profiles (absorption vs frequency) are a function of the shape of the spectrum and are measurably different for different spectra.

One specific problem clarified by our work related to the relative contribution of α-particles to Polar Cap absorption. Calculations by Weir and Brown (1964) indicated that riometers were often responding primarily to alpha particles rather than protons. This was investigated in detail (Adams and Masley, 1966b, d). It was found that the alpha particle contribution to riometer measurements is a strong function of the alpha-proton ratio and the geomagnetic cutoff. The cutoff preferentially eliminates the proton contribution; this is a consequence of the fact that a cutoff is a rigidity selector, while the riometer is sensitive to the energy/nucleon of the particles.

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Weir and Brown used a cutoff of 112 MeV in their calculations - a cutoff appropriate to somewhere on the equatorial side of the auroral zones. For cutoffs appropriate to the auroral zones and the polar caps, Adams and Masley found that the riometer absorption is almost always dominated by protons, rather than by alpha particles.

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Section 4
SOLAR STUDIES

A complete, continuous, and accurate monitoring of particle production by the sun has been carried out by the McDonnell Douglas conjugate polar observatories. This was done through the past solar minimum (1962) up to the present, which encompasses one complete solar cycle (see Figure 4). This was the first time high quality observations had been made on the increasing side of the solar cycle. This has contributed much to understanding solar particle acceleration, propagation and interaction with the earth's magnetosphere. Although sunspot numbers have been recorded over 100 years, low energy solar cosmic rays were just discovered in 1957-1958. Therefore reasonable quality data was collected only for the decreasing side of cycle 19 and cycle 20. Figure 5 shows the number of events per year as a function of size and sunspot number for the years 1962 through 1974. This, of course, is only a beginning in the pioneering effort to understand the sun. Through 1974, we have taken data on over 100 significant PCA events, essentially all of which have been analyzed and the results published.

Some years ago, based on our analysis, we proposed that solar particle production does not follow the sunspot cycle but in fact lags by 2 to 3 years and has a very broad maximum (see Figure 4). We also presented the concept that solar particles are present in a non-uniform distribution over the polar cap. At that time it was popularly believed that the particles were uniformly distributed above some geomagnetic latitude or L value. This has important implications for access into and propagation within the magnetosphere. We also showed that the major production of particles by the sun is due to one or two active regions per year although events do occur throughout the year. For example on Figure 4 the about 3×10^8 protons per year is due to an integral over many medium events, but the 10^9 to 10^{10} integrated intensities are due primarily to one series of events during that year. We also presented for the first time the unique situation during 1967 and 1968 when most of the events observed originated in the NE and SE quadrants of the solar disk. For all preceding years and since this period the NW quadrant has originated most events observed at earth. This unique observation has important implications on propagation and the solar acceleration mechanism.

Cycle 20 has generated 5×10^8 to 4×10^9 protons/cm^2-yr (see Figure 4). The production plateau is broad with no evidence for decrease until 1973. The large integrated intensity in 1972 is almost entirely due to the August events, consistent with the effect in 1959 (July) and 1960 (November).

The results of the work have been used by numerous groups to assist them in interpreting their data or to carry out related studies. This includes the key university groups, government laboratories and industrial laboratories. It has been used for basic studies and also contributed to both the NASA and DOD space programs. The results of this program have been referenced in the leading space and geophysical journals.

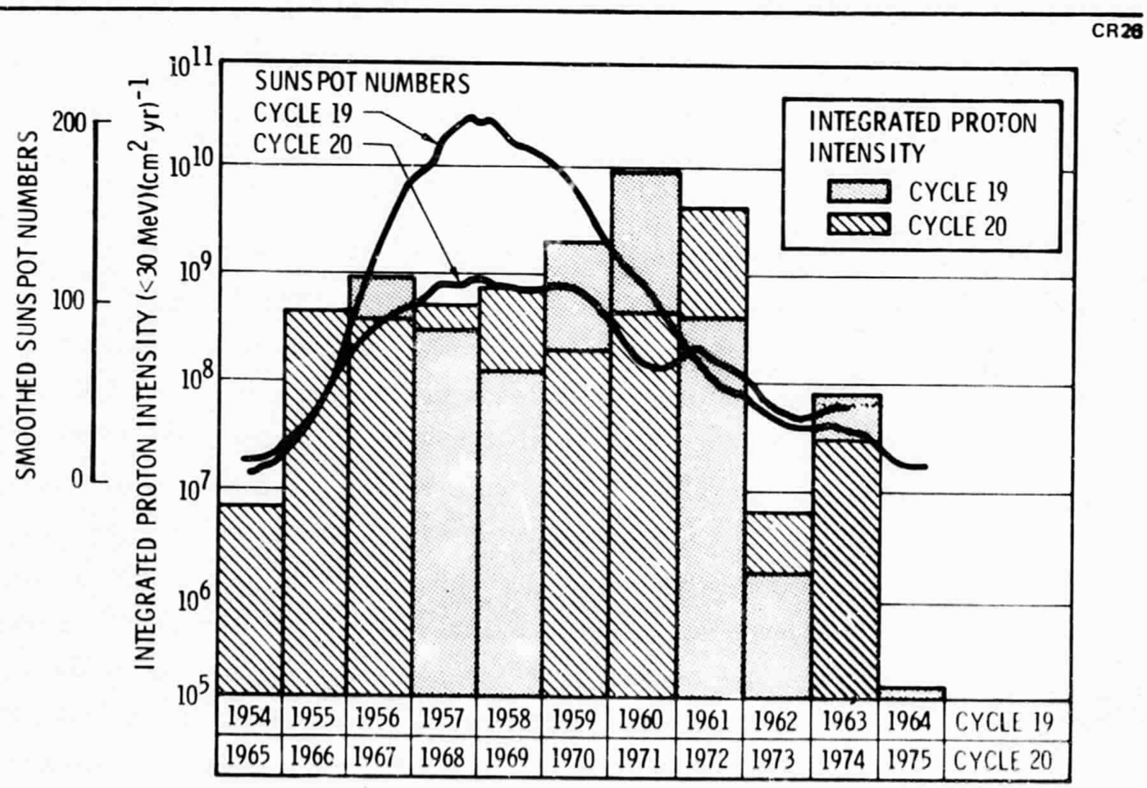

Figure 4. Integrated Solar Proton Intensity Distribution (Sunspot Cycles 19 and 20)

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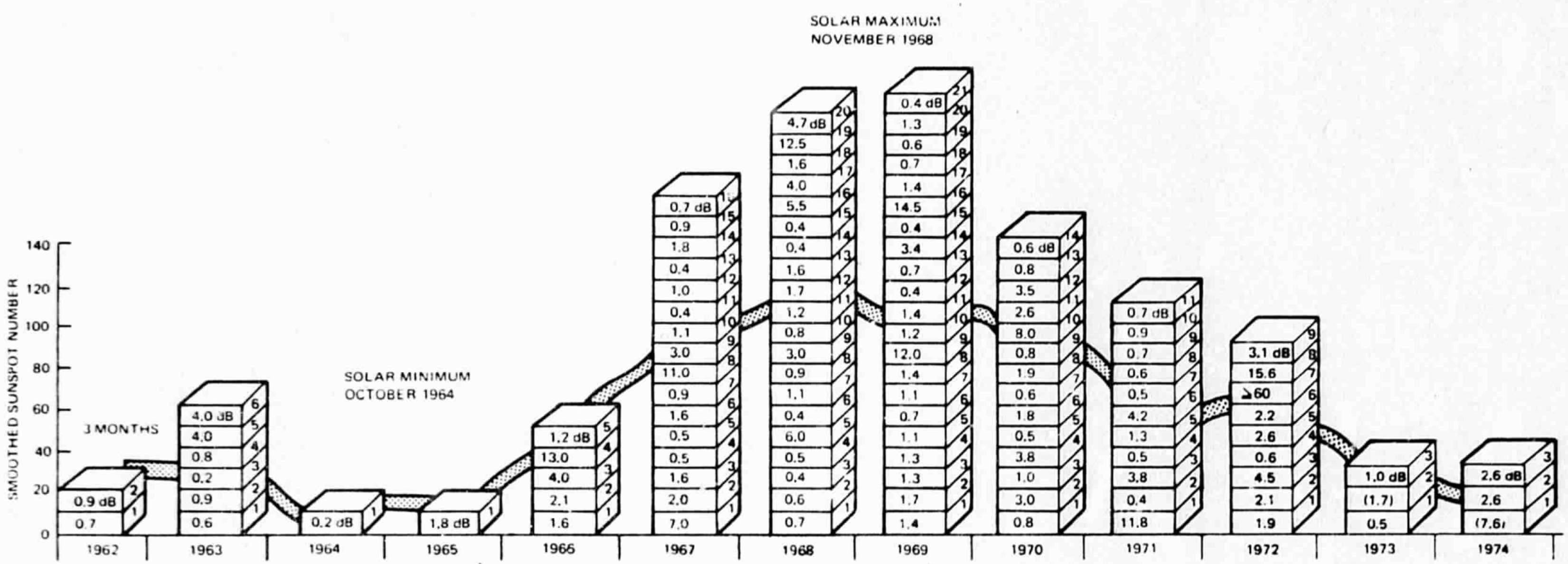

Figure 5. Solar Particle Event Distribution

Section 5
MAGNETOSPHERIC STUDIES

5.1 HIGH-LATITUDE STUDY

A high-latitude magnetospheric study was undertaken based on the MDAC-WD conjugate stations located at 80° geomagnetic latitude. These locations, between the auroral zones and the geomagnetic poles (and near the cusp latitude), present a unique opportunity for high-latitude magnetospheric investigation. The measurements have been conducted with 30-MHz and 50-MHz riometers. The use of several years of data continuously collected from the stations allows investigation of seasonal effects. The study of these data and correlation with simultaneous satellite data provides information on the source of the particles that are causing absorption and their acceleration process. The events selected were not associated with solar flares, were generally small (on the order of 0.5 dB), and were usually of short duration (averaging about 1 hour). These events occurred at a rate of approximately 14 per month. The study was concerned with the diurnal distributions of these events throughout the year and their correlation with three other types of data: those obtained by other ground stations; electron "island" intensities observed by particle detectors on IMP I, II, and III; and direct particle measurement by polar-orbiting satellites. Most of the large events occurred near local magnetic midnight, which is 0700 UT. When the much larger number of events above 0.1 dB are included, the peak occurs near 1900 UT, which is local magnetic noon. It is also found that the large events, which occur near midnight, tend to be of short duration, whereas the noon group includes those often lasting longer than 2 hours. These studies were reported by Satterblom and Masley (1967); Satterblom, Masley, and Santina (1967); and Satterblom and Masley (1968).

5.2 MAGNETOSPHERE MODELS

A general method for determining the shape of the magnetopause for all angles of incidence of the solar wind upon the geomagnetic dipole was developed (Olson, 1968). In this model, the magnetopause is found where the dynamic solar wind pressure is equal to the pressure of the total magnetic field just inside the boundary. To accurately determine this field, it is necessary to calculate the contribution from the magnetopause current system. This made necessary the use of a self-consistent field model similar to the one developed by Mead and Beard (1964). Unlike their procedure, here the "pressure balance" equation had to be solved simultaneously at several points. The model results are compared and found to be in good agreement with the final surface values of Mead and Beard for perpendicular incidence of the solar wind upon the geomagnetic dipole. For oblique incidence angles the results of the present model are exactly the same as those obtained by Spreiter and Briggs (1961) for the cross-section of the boundary in the plane containing the dipole and solar wind direction vectors.

The nose of the magnetopause, for all "tilts," resembles a hemisphere with its center displaced from the earth's center. Cross-sections of the boundary in the tail region are almost circular. The angle between the earth-wind line and the neutral points (points on the boundary where the total magnetic field is zero) varies annually from 45° to 115°. One of the neutral points is always closer to the earth (from 9.5 to 8.3 earth radii) than any other point on the boundary. The magnetopause cross-sections in the solar-magnetospheric equatorial plane are almost completely independent of the tilt angle.

Havirg determine the shape of the boundary for all "tilts" the magnetopause current system can be computed. Integration over this current system (using the Biot-Savart law and several coordinate transformations) yields the magnetic field produced by these boundary currents. The model can therefore be used to study the temporal variations in these magnetic fields. It predicts both annual and semiannual variations in addition to the daily variations produced by the older models.

An improved model of the currents flowing in the neutral sheet and magnetospheric tail was developed (Olson and Cummings, 1968). The tail currents flow across a neutral sheet and return on an approximately cylindrical boundary. The neutral sheet is hinged to the geomagnetic equatorial plane and parallel to the solar-magnetospheric equatorial plane. This model, too, is under the influence of the changing angle between the solar wind and the geomagnetic dipole axis.

The magnetic fields from these two current systems can then be added to the earth's main field to yield the magnetic fields anywhere in the magnetosphere. At geocentric distances larger than about 9 earth radii, the combined magnetic field of the boundary and tail current system is larger than the dipole field. It is, therefore, important to include these fields in the calculation of the motion of charged particles, e.g., solar cosmic rays and geomagnetically trapped radiation. Generally, these fields must play an important role in the dynamics of the magnetosphere.

A quantitative model of the near earth total magnetic field which includes the contribution for distributed currents has been developed. Work on the tail field has indicated that the neutral sheet currents are small and that the field line geometry in the tail of the magnetosphere can best be explained in terms of diamagnetic effects - currents flowing on the boundary of the plasma sheet. Diamagnetic currents should also be strong near the plasmapause. Gradient and curvature drifts also contribute to the currents in the outer magnetosphere. A model of the magnetospheric magnetic field, with distributed currents included, was compared with the ΔB contours empirically determined (Sugiura et al., 1971) and found to be in excellent agreement. This model has also been used to examine field line geometry and cosmic ray cutoffs (Olson, 1972a; Masley, Olson and Pfitzer, 1973a). Preliminary comparison of model results with observed cosmic ray cutoffs reveals a difference of about 2° in latitude on the midnight meridian. Older models are 6° to 8° in error (Masley, Olson and Pfitzer, 1971). The model has also been used to study the shape and location of the trapping boundary and is in good agreement with observations (Pfitzer, 1972).

A quantitative model of the distributed magnetospheric currents (Olson, 1974) has been used together with a model of the magnetopause currents (Olson, 1969) and a dipole representation of the earth's main field to represent the total magnetospheric magnetic field (Olson, 1972, 1973a, b; Olson and Pfitzer, 1973, 1974; Pfitzer, 1972). For one of a kind calculations (constant $\vec{B}$ contours, ΔB contours, S_q patterns, etc.) $\vec{B}$ is accurately determined by direct integration over the current systems. However, for repeated usage (calculation of particle trajectories, field lines, drift sheets, etc.) direct integration is too expensive and instead an analytic representation must be used with some base of accuracy (Olson, 1970).

5.3 SOLAR COSMIC RAY ENTRY AND PROPAGATION WITHIN THE MAGNETOSPHERE

Trajectories of solar cosmic rays were calculated to determine the cutoff latitude and entry and propagation paths for specific cases. This was done using the best field models available (Olson's tilted magnetosphere and a realistic tail model and the Fairfield-Mead empirical model) (Masley and Olson, 1971 a, b; Masley, Olson and Pfitzer, 1971). Over 200 trajectories were run for 5 MeV protons at noon and midnight. These theoretical results were directly compared to measurements by the MDAC experiment on OGO-6. The careful calculations gave cutoffs 6° higher at midnight and 8° higher at noon than observed, indicating that there was still much to be understood about solar cosmic ray entry and propagation in the magnetosphere.

Additional detailed analysis of the 2 Nov 1969 event was carried out (Masley and Satterblom, 1970 b, c, d; Satterblom and Masley, 1971). This event, which was one of the largest during this solar cycle, has quiet magnetic conditions throughout and high intensities of solar protons (Figure 6), α-particles, and electrons. The MDAC OGO-6 data provide detailed information on the entry and propagation of solar cosmic rays within the magnetosphere. The location of the first open field line at low latitude on the noonside has been directly measured.

This location was monitored for 30 crossings during the 2 Nov 1969 event during quiet magnetic conditions. The average value was 76° for the northern hemisphere and 75° for the southern hemisphere. The location of the first open field line is demonstrated by a sharp increase in the intensity of > 350 keV solar electrons (Figure 7 upper section). This location is then used as an onboard reference for interpretation of proton and α-particle measurements. During the 2 Nov 1969 event the earth was in a positive interplanetary magnetic sector. The northern hemisphere, with possible merging

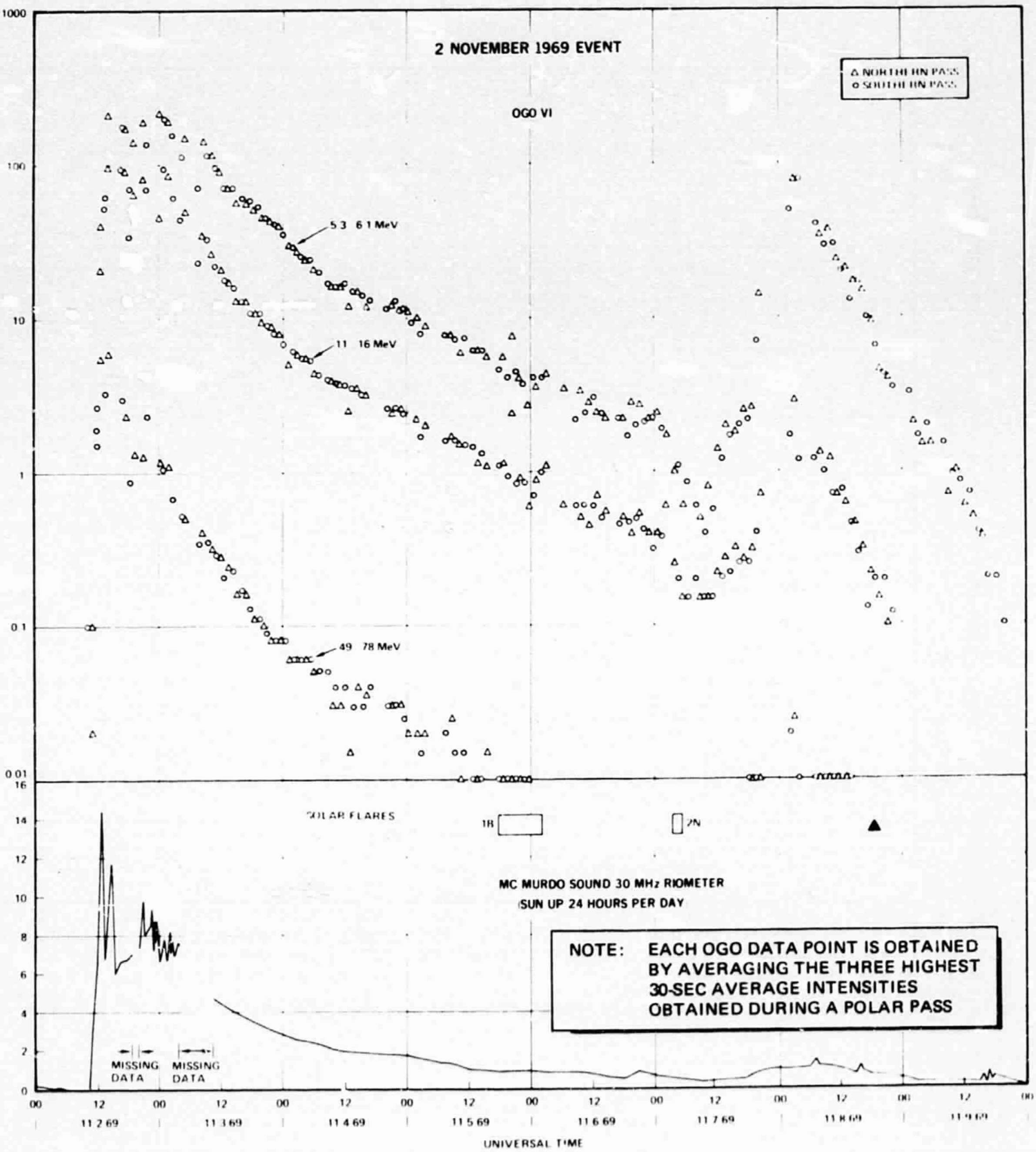

Figure 6. Event Profile for Three OGO Energy Intervals

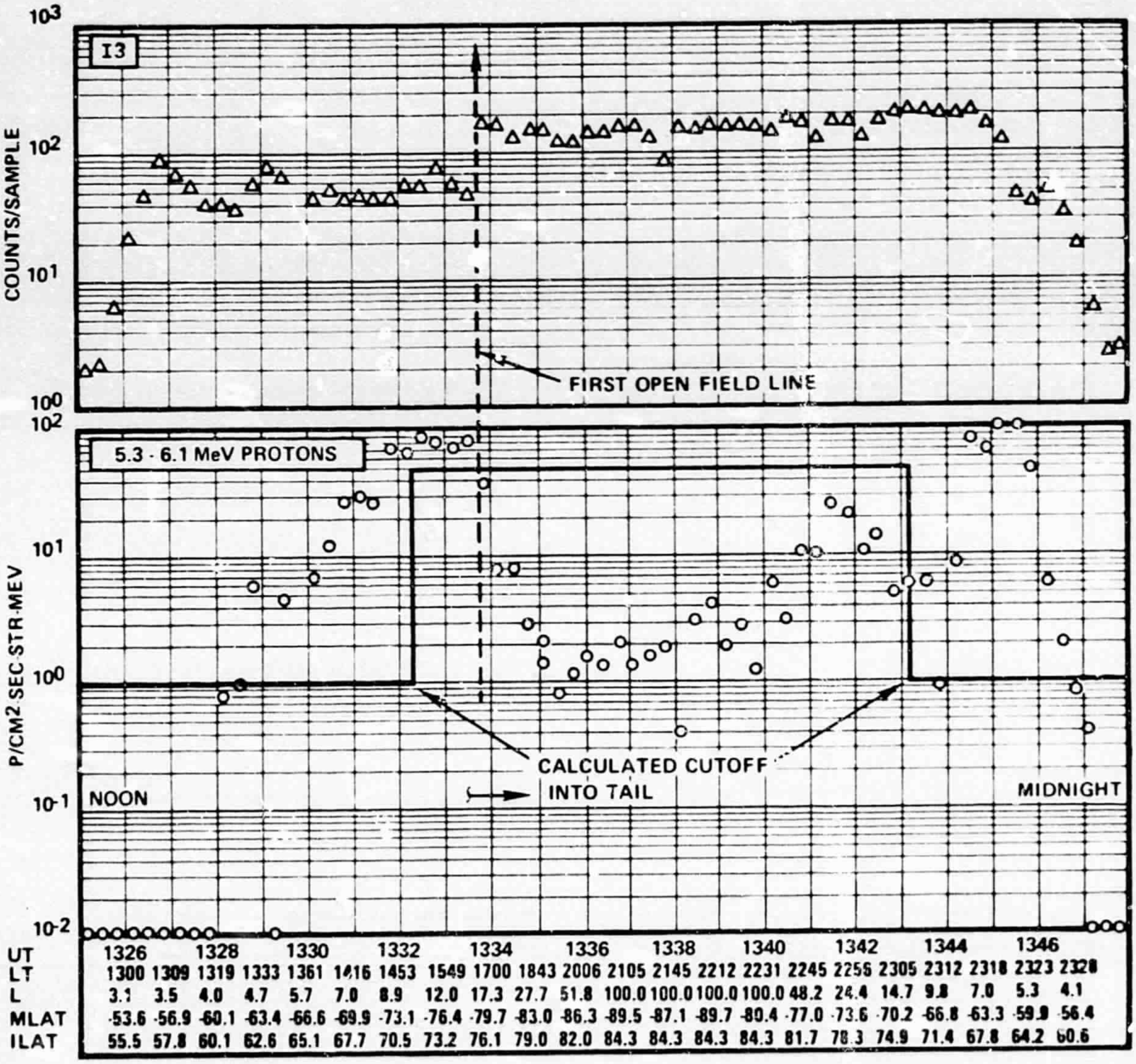

Figure 7. MDAC OGO-6 Observations and Theoretical Cutoff Results

along the tail, had a better connection to the interplanetary field than the southern hemisphere. There was a large variation in intensity across the southern polar cap for protons (Figure 7, lower section) and α-particles. The variation for 5 MeV protons in the south decreases from a maximum of 285:1 to 1.4:1 over a 20 hour period. In the northern hemisphere the variation ranged from 20:1 to 1.4:1 during the same period. The two low-latitude, high-intensity regions shown in Figure 7 are located below the predicted cut-off latitudes. Protons are nearly absent on the first open field line and the boundary of the southern tail.

5.4 AURORAL STUDIES

Photometers at 3914Å and 5577Å have been operating at the McMurdo Sound observatory since 1967 and at the Shepherd Bay observatory since 1968. Operation at a high-latitude station provides data on auroras inside the auroral zone. By comparisons of aurora between the two locations, much can be learned about the magnetosphere, acceleration mechanisms, particle types, and particle energies.

Studies of the ratio of 5577Å to 3914Å emission intensities in groups of events has shown that the ratio fluctuates frequently and with large amplitude, much more so than typical auroral zone emissions. Suggested causes for these differences are: differences in the type and energy spectrum of precipitating particles; frequent changes in the particle type and energy spectrum in the high latitude area; or a higher probability of proton precipitation in the high latitude area with increases in the local K index above 4. These studies were reported by Mukherjee (1969, 1970 a,b) and Mukherjee and Masley (1969, 1970).

Section 6
SATELLITE MEASUREMENTS

6.1 OGO-6

OGO-6 was launched on 5 June 1969, and the McDonnell Douglas experiment operated successfully and continuously from turn on until September 1970. On 7 June 1969, one day after turn on, the first solar cosmic ray event was recorded.

The general scientific objective was to perform a basic investigation of solar cosmic radiation and to relate the results to cosmic ray and ionospheric studies and riometer measurements. In particular the measurement of proton spectra between 5 and 80 MeV and alpha particle spectra between 18 and 84 MeV over the polar caps (see Table 1) and occasionally across the riometer antenna pattern permits a direct calibration of the riometer response to ionizing radiation in the most important energy ranges. The effect of a varying proton to alpha particle ratio can also be studied. Cases wherein a north-south absorption asymetry occurs can be studied for indications of effects on particle entry. Measurements were made by MDAC-W on the Polar Orbiting OGO-6 during passage over the north and south polar regions. A two-element solid-state detector telescope with a geometry factor of 0.545 cm^2-ster was used. One complete proton spectrum, one complete alpha particle spectrum, and several integral channels of information were determined every 0.86 seconds or 7 km along the polar trajectory. The experiment was designed to allow measurement of all events from the minimum-size to the largest ever recorded, a J_o of $10^5/cm^2$-sec-ster or $3 \times 10^4 > 5$ MeV. The data handling technique permitted the onboard accumulation of counts within channels of fixed energy increments rather than telemetering the pair of amplitudes resulting from each particle. The experiment included a complete electronic inflight calibration system and a radioactive source. The inflight calibration was a preprogrammed pulse generator modulated by a precision voltage ramp, which separately checked the threshold level of each discriminator on each detector and measured the differential linearity of the pulse height analyzer. The flight unit was environmentally laboratory tested and also calibrated by

Table 1

OGO-6 CHANNEL ENERGY BOUNDARIES

Channel No.	Kinetic Energy (MeV)	
P1	5.3 to 6.0	Protons
P2	6.0 to 8.2	
P3	8.2 to 10.5	
P4	11.0 to 12.7	
P5	12.7 to 16.0	
P6	16.0 to 20.7	
P7	20.7 to 24.5	
P8	24.5 to 29	
P9	29 to 35	
P10	35 to 41.5	
P11	41.5 to 49	
P12	49 to 59	
P13	59 to 70	
P14	70 to 78	
A1	17.5 to 20.0	Alpha particles
A2	20.2 to 21.8	
A3	21.8 to 26	
A4	26 to 34.2	
A5	34.2 to 46	
A6	46 to 53	
A7	53 to 62	
A8	62 to 72	
A9	72 to 84	
11	Protons 5 -78 MeV	Integral channels
	Alpha particles 20.2 - 125 MeV	
13	Protons greater than 78 MeV	
	Electrons greater than 270 keV	

protons and alpha particles from accelerators.

6.2 RIOMETER - OGO-6 STUDIES

Proton energy spectra and proton/α-particle ratios measured on OGO-6 at the times of passes close to the geomagnetic field line terminating at the McMurdo Sound riometer station were used in the computer program H067 to calculate the 30 MHz riometer absorption expected (Adams and Masley, 1965b, 1966a, b). Figure 8 shows the results for the largest event of that period, 2 November 1969. During the first six hours of the event, the particle intensities measured on OGO-6 varied by as much as two orders of magnitude during a single polar pass. The relatively large differences between the calculated and measured absorption during this period (even at the near overpass at 1158 UT) are easily explained by this spatial variation; a difference of only a factor of 2.6 in particle intensity would account for the largest discrepancy seen. In general, the curve illustrates good agreement and follows the relationship $A = KJ^{1/2}$ with K = 0.32. This is discussed in more detail in Section 6.5. All significant events during the period when OGO-6 was active were studied. The results were very satisfactory and support the use of riometer measurements to deduce solar proton intensities (Baker et al., 1972b, 1973a, 1973b).

6.3 SOLAR PARTICLE CUTOFF OBSERVATIONS

Direct measurements of charged particles entering the polar cap were made by the McDonnell Douglas Experiment on OGO-6 from June 1969 through August 1970. The solid state telescope measured a 14 channel proton spectrum from 5 to 80 MeV, an α-particle spectrum from 18-84 MeV and electrons > 270 MeV every 0.86 seconds. A study of the complex parameters related to charged particle access was carried out (Masley and Satterblom, 1973). Six of the larger events were chosen; 3 observed near noon-midnight local time and 3 near dawn-dusk local time. The study includes 650 polar cap boundary crossings. The dependences of the cutoff latitude on K_p, daily and seasonal tilt, interplanetary field polarity, local time, north and south polar regions, and S.C. effects were investigated. The relationship between the cutoff and K_p, and the zero K_p cutoff latitude were determined for the four local times for 5, 20, and 70 MeV

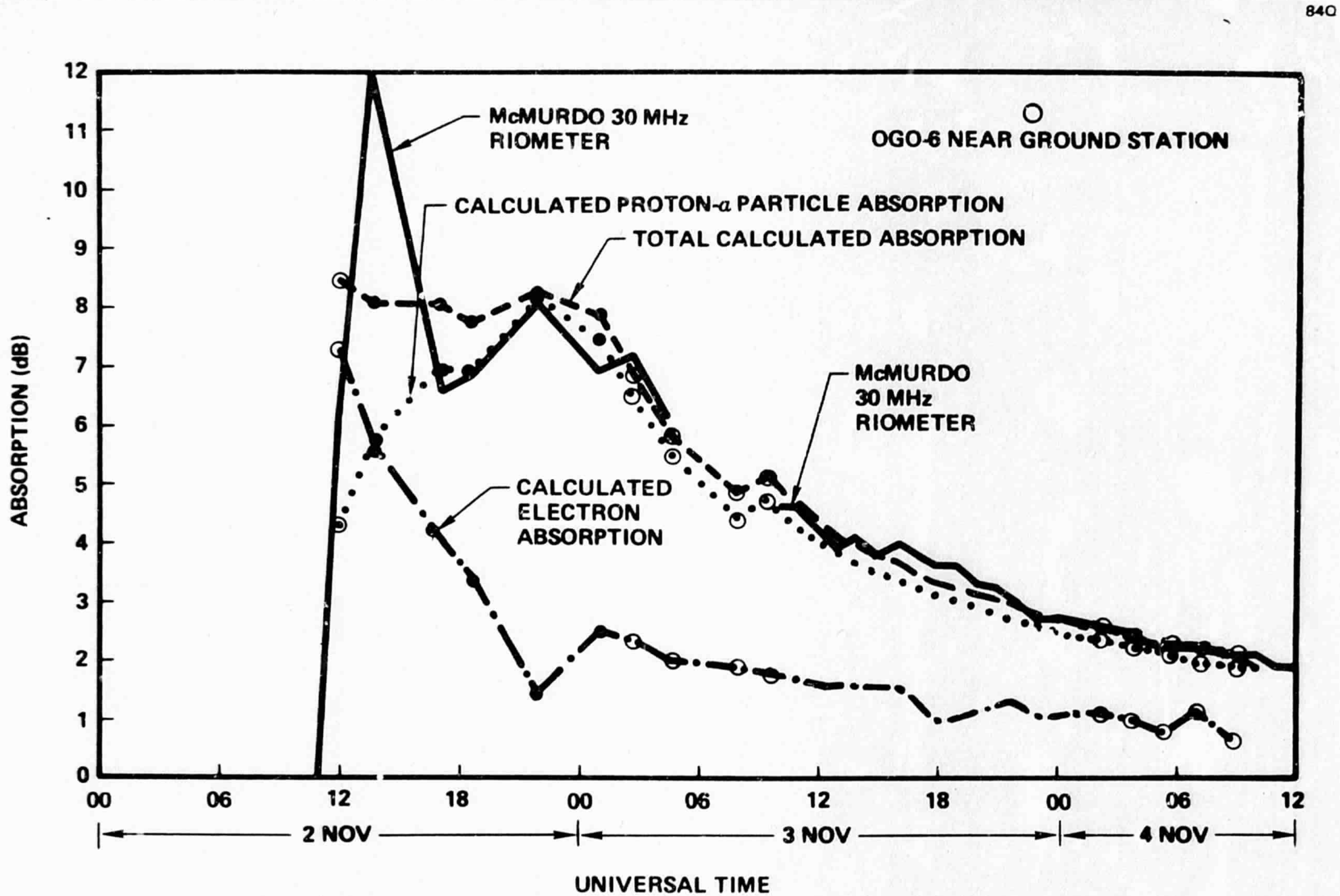

Figure 8. Calculated (OGO-6) and Measured 30-MHz Absorption, 2 November 1969 Event

protons. A cutoff dependence on tilt was observed during several of the events especially at dawn and dusk.

The measured geomagnetic cutoff (Invariant Latitude) for 5, 20, and 70 MeV protons at the four local times is shown in Table 2 along with more recently calculated cutoffs.

Table 2

PROTON CUTOFFS

	5 MeV			20 Mev			70 Mev	
	Calculated $\perp$	Calculated $\parallel$	Measured $\parallel$	Calculated $\perp$	Calculated $\parallel$	Measured $\parallel$	Calculated $\parallel$	Measured $\parallel$
Noon (Direct)		73			71		68	
Noon (Drift)	68	69	69.9 $\pm$0.7	68	68	65.8 $\pm$1.0	66	63.4 $\pm$3.3
Midnight	65	66	66.7 $\pm$0.4	64	65	65.2 $\pm$0.7	62	63.4 $\pm$0.9
Dawn	69	70	67.6 $\pm$0.8	67	68	65.5 $\pm$2.0	67	62.1 $\pm$7.0
Dusk	70	71	67.3 $\pm$0.6	67	68	67.5 $\pm$1.7	67	61.0 $\pm$7.4

6.4 SOLAR PARTICLE ENTRY CALCULATIONS

Particle trajectories were calculated in Olson's 1972 distributed current model of the magnetosphere in order to identify the source region for particles which reach specific locations in the polar cap (Masley, Olson, and Pfitzer, 1973a). This was done for 5, 20, and 70 MeV protons for a series of latitudes on the noon-midnight meridian and the dawn-dusk meridian. Particles which define the cutoff in the low latitude drift around region enter the magnetosphere at $\sim 325°$ (35° toward dawn from earth sun line) and within about 10° of the ecliptic plane and not up the tail neutral sheet as suggested by previous authors. Furthermore, good agreement between calculated and measured cutoffs has been obtained for the first time without involving complex entry mechanisms.

Trajectories were calculated for 1000 km altitude for 5, 20, and 70 MeV protons. A latitude series was carried out on the noon-midnight meridian and the dawn-dusk meridian. This was accomplished in 5° latitude steps at the higher latitudes and in 1° intervals near the cutoff latitude and the boundaries between regions of different access mechanisms. Most runs were made at 0° pitch angle, although selected runs were made at 90° and other pitch angles in order to investigate a possible pitch angle dependence on the cutoff. About 300 trajectories were run in this series.

6.5 RELATIONSHIP BETWEEN POLAR RIOMETER AND SPACE MEASUREMENTS - A JOINT STUDY WITH DR. S. R. KANE, UNIVERSITY OF CALIFORNIA, BERKELEY

Observations by the Minnesota ion chamber on OGO-3 and the MDAC Polar Riometer were used in this analysis. Regression plots were prepared for each of the eight events investigated. In general, hourly values were used for the comparison. The data agree well with the relationship $A = KI^{1/2}$ where A is the riometer absorption in dB, I the ion chamber rate in the units of NPPS x 10^3 and K is a constant. For the largest four of the events studied here, the average value of K is $(1.0 \pm .05) \times 10^{-2}$. This value is also consistent within 20 percent for the smaller events where it is more difficult to determine the value of K. If it is assumed that protons > 12 MeV are nearly isotropic, then $I = 728\ J(>12\ \text{MeV})$ where J is in units of particles $cm^{-2}\ sec^{-1}\ ster^{-1}$. Hence $A = 0.3\ J(>12\ \text{MeV})^{1/2}$ Figure 9 illustrates the excellent agreement during the increasing and decreasing portions of the 28 January 1967 events. The good correlation between the OGO ion chamber and polar riometer absorption suggests that riometer absorption is due primarily to solar particles in the energy range 12-32 MeV per nucleon for typical spectra. To further verify this conclusion regression plots were made of the riometer absorption and the hourly averages of the integral proton intensity J above 10, 30 and 60 MeV observed by the IMP-F satellite (Solar Geophysical Data) during three solar particle events. For protons > 10 MeV the relationship between the absorption A and proton intensity J can be well represented by $A = K_1\ J(>10\ \text{MeV})^{1/2}$ where $K_1 = 0.32$, A is in dB, and J is in protons cm-sec^{-1} $ster^{-1}$. Since the

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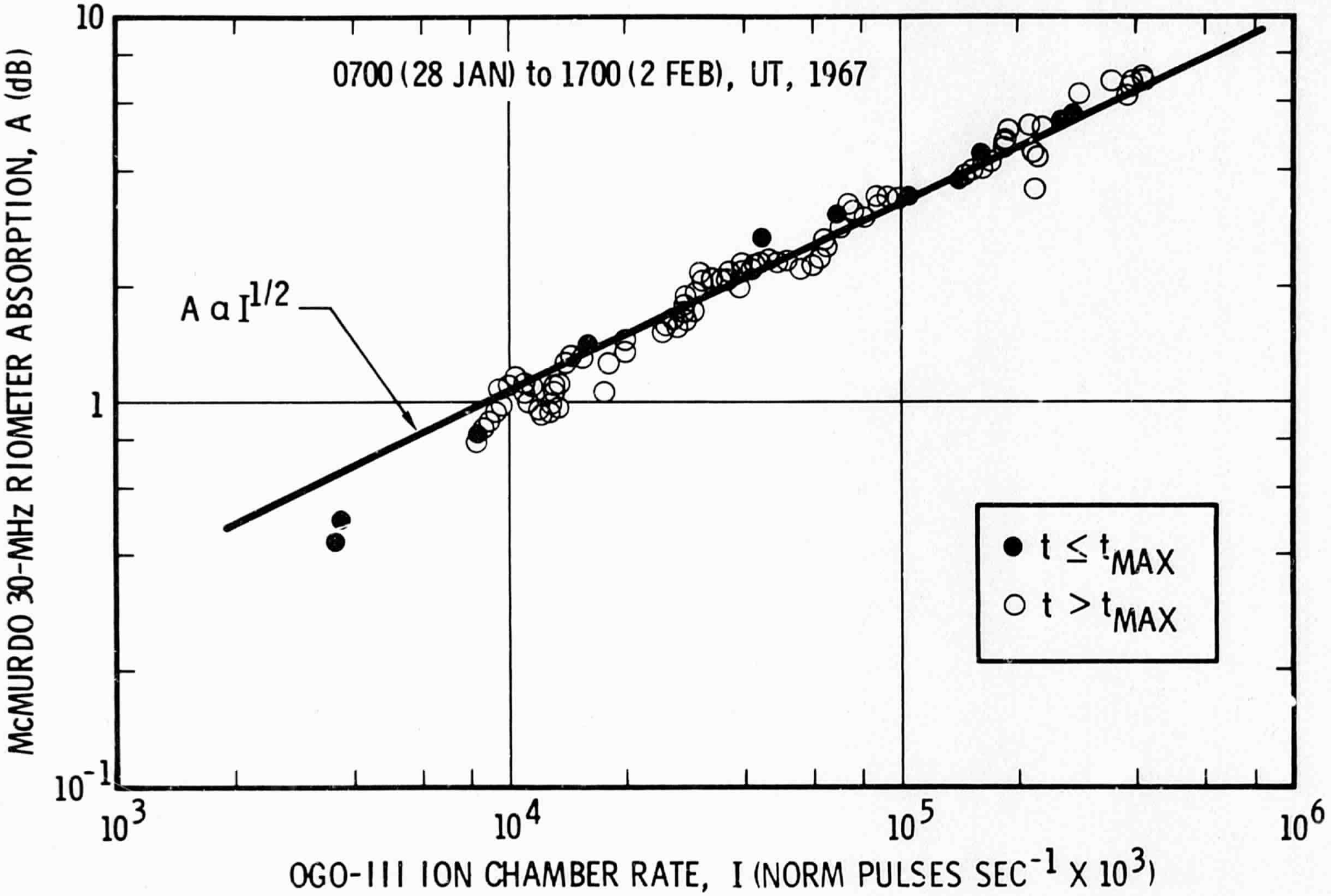

Figure 9. Solar Particle Event of 28 January 1967

relationship holds throughout the event and over a range of spectral distributions, it indicates that K_1 is independent of the energy distribution for greater than 10 MeV protons. For intensities greater than other minimum energies such as 30 MeV or 60 MeV, K_1 is dependent on the energy distribution. (Kane and Masley, 1973).

Section 7
INTERNATIONAL PARTICIPATION

From the beginning of this program to the present we have participated in numerous international programs, projects and data exchanges.

A. We were requested to submit a report of our measurements made during the August 1972 solar cosmic ray events for inclusion in a compendium on those events published by World Data Center A (Masley and Baker, 1973a). During the August events we passed our data within hours to both the World Data Center and to the Air Force.

B. Our data for the 28 May and 16 June 1972 events were submitted to the Campaign for the Integrated Observation of Solar Flares (CINOF) at their request, and were published by them (Masley and Baker, 1974).

C. The adoption of a Solar Proton Classification System at a recent IAGA-COSPAR meeting in the U.S.S.R. This system was presented by Shea and Smart of AFCRL. They used our riometer data for the 20th solar cycle in the study and in the proposal for classification. A significant amount of the data was furnished to them, to provide comprehensive coverage for this cycle, at their request.

D. Data on all events occurring during a two year period was provided to Dr. Rao of India and Dr. McCracken of Australia to enhance their studies and interpretation of Pioneer observations.

E. Our preliminary unpublished data during the 7 July 1965 event was provided to Dr. Hakura of Japan who was preparing an international summary of this event. His report indicates that our station has the highest sensitivity, was the first ground station to observe the onset of the event and the only station to see the critical part of the event of interest for his study.

F. Our program was part of the IQSY.

G. We regularly present results at key international meetings thereby sharing our data and research with all of the participating countries of the world. Our results were presented at the "Invitation only" closed International Cosmic Ray Conferences in Calgary, Budapest, Hobart, and Denver and an invited paper at the IQSY meeting in London. We regularly present results at the International Cospar Meetings.

H. Presented Invited Survey of Solar Phenomena to the Polar Cap Panel of COSPAR meeting at Alpbach, Austria in 1963. Also contributed to writing the document which outlined recommendations for future polar cap research.

J. We have served on numerous international scientific committees including COSPAR, IAGA, URSI, IUCSTP.

K. Our data or our research results have been used in M.S. and Ph.D. theses at a number of Universities including University of California, Berkeley, University of Iowa, and the Air Force Academy.

Section 8

1974 RESEARCH

8.1 SOLAR ACTIVITY

Since this is solar minimum, the period of four to five years when the sun is very inactive, the three sizable solar cosmic ray events observed by the MDAC Geophysical Observatories were somewhat unexpected. However, this is in keeping with the sporadic nature of these events and the general lack of understanding of their causes. The July 1974 event is shown in Figure 10. It is a very ordinary event, exhibiting some absorption at 30 MHz on July 4 and rising rapidly to a peak of 3.8 db on the 5th. It decayed rather rapidly with little evidence of absorption on the 7th. It should be noted that these measurements were made at the southern station at McMurdo Sound, Antarctica, where the sun was below the horizon continuously. It is well known that absorption is surpressed under these conditions, so the values shown are minimal. The northern station (at Shepherd Bay, Canada) was in continuous sunlight at this time, but unfortunately the experiment was inoperative at that time.

The second significant event occured in September. Preliminary analysis of the Shepherd Bay 30 MHz riometer data indicate a moderate event starting on 11 September and reaching about 2.6 db on the 13th, after which the event decayed rapidly. The third event started on 20 September, and reached a peak absorption of 2.6 db that same day. It showed no unusual characteristics and slowly decayed until 25 September. Detailed analysis of the May and June 1972 solar cosmic ray events were made as part of a widespread cooperative effort to observe these particular events as thoroughly as possible (Masley and Baker, 1974).

8.2 ATS-6 STUDIES

The MDAC ATS-6 experiment was first operated on 14 June 1974 and has been in continuous use since that date. Three periods of high solar activity have been observed. The first was during the central meridian passage of Solar Active Region 433. This region with 12 flares of importance 1B or greater was

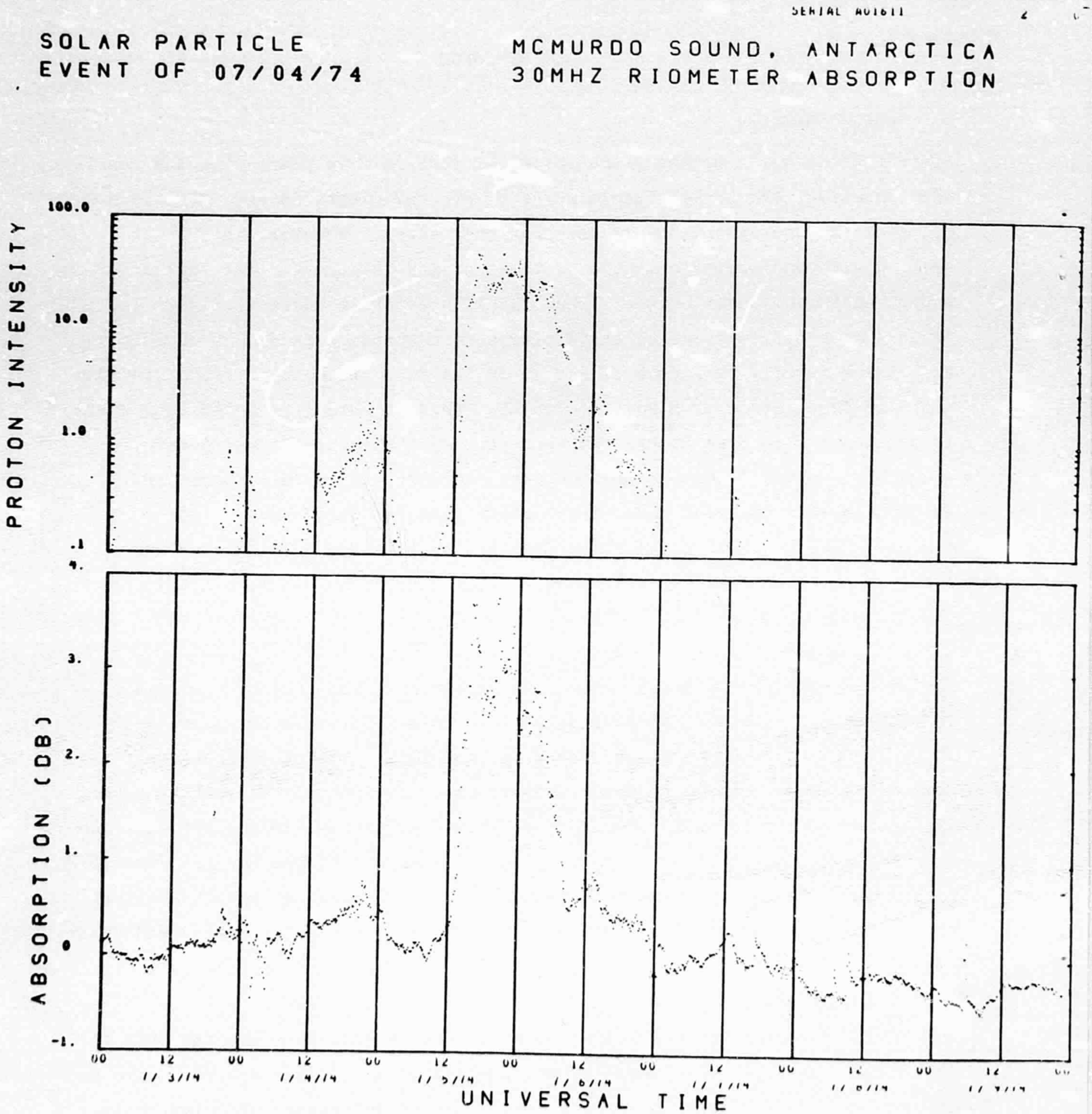

Figure 10. Solar Partical Event of 07/04/74

detected at synchronous orbit by the arrival of protons and α-particles with energies up to 30 MeV/Nucleon. The other solar active periods are 11-15 September and 18-22 September 1974. This latter activity is from the same 433 region two solar rotations later.

The experiment uses two orthogonal magnetic electron spectrometers to measure 50-1000 keV electron intensities in four differential channels. With the lowest energy proton channel (.3 - 1.2 MeV) and a high energy electron channel (>1.5 MeV), these compose a data set which show the effects of substorm injection of fresh particles and their subsequent gradient drifts. Effects of sudden field inflation are evident by the non-energy dependent intensity changes. Drifting electrons show energy dispersion in their profiles, the higher energy particles arriving earlier at ATS-6. Data from the on-board magnetometer are used to determine the local field direction and magnitude.

The excellent time resolution of the MDAC ATS-6 experiment allows studies of wave particle interactions from periods of 1 second to hours. Initial studies limited by the 32 second time resolution of the computer graphics have demonstrated many particle waves at synchronous orbit in the 1-5 minute frequency domain. The wave structure covers the entire observed electron energy band from 50 keV - 1 MeV. Preliminary analysis gives no specific tendency in local time distribution, energy distribution, or phase relationship. The observed waves demonstrate both broad band as well as narrow band phenomena.

ATS-6 experimental results have been reported by Satterblom and Masley (1974), Masley et al. (1974), and Pfitzer et al. (1974).

8.3 MAGNETOSPHERIC PHYSICS

Quantitative representations of the magnetic fields associated with the magnetopause currents and the distributed currents (tail and quiet time ring currents) have been developed. These fields are used together with a dipole representation of the main field of the earth to model the total vector magnetospheric magnetic field. The model is based on quiet time data averaged over all "tilt angle" values. The weak field in the equatorial region of the inner magnetosphere and the tail field structure are included in the model. The depressed field region in the inner magnetosphere is essentially important for the accurate modeling of several observed particle and magnetic field phenomena. The field representation is analytic and given in Cartesian coordinates with power series and expotential terms. It is valid from the subsolar magnetosphere to beyond lunar orbit. This series expansion allows the magnetic field to be accurately modeled over an extended region of the magnetosphere and permits the representation of the field in the same region as its source currents. The model has been tested by using it to calculate several observed magnetospheric particle and field properties. The latitude cutoffs for solar cosmic rays and the trapping boundary of the low energy particles computed from the model agree well with observations. Model calculations also yield field line shapes in agreement with barium cloud observations (Olson and Pfitzer, 1974a).

The solar wind is an electrically neutral plasma. The charged particles that comprise it are deflected when they encounter the geomagnetic field. These motions produce electrical currents whose fields modify the geomagnetic field. The magnetosphere is formed by this interaction and is described in terms of these particles and fields. Recent observations of the high latitude dayside magnetosphere have shown that some of the solar wind particles penetrate down to the atmosphere where they influence the density of both neutral and ionized particles. The solar wind "carries" with it a magnetic field. This interplanetary magnetic field interacts with the geomagnetic field and controls the magnitude of magnetic storms that intermittently disrupt the near earth environment. It has also been recently demonstrated that these high latitude phenomena influence the earth's surface weather. Many features of the interaction of the solar wind with the geomagnetic field are now understood. However, several important phenomena that exert important influences on the near earth environment are not well understood. A general description of the state of our knowledge of the magnetosphere and upper atmosphere was presented with emphasis on recent observations of the high latitude atmosphere and magnetosphere (Olson, 1974a).

The shape of a planetary magnetosphere as described by pressure balance formalism has been quantitatively determined for the case of solar wind incidence parallel to the planetary magnetic dipole axis. The planet Uranus may posses such a magnetosphere during part of its orbit around the sun. This magnetosphere possesses only one cusp (around the sunward pole), the other having been removed to infinity. Shocked solar wind particles penetrate through this cusp directly into the planetary ionosphere. The magnetic field, B, has been found throughout the magnetosphere by integrating over the magnetopause currents. An analytic representation of B has been developed. The magnetic equator, as defined by the local minimum field, is not planar, but extends down the tail. It divides the tail into two concentric cylindrical regions, one containing field lines with a tailward direction, the other with the returning segments of those lines. Field lines surrounding the tailward pole (corresponding to field lines in the sunward cusp region) connect with the interplanetary field at large distances down the tail (Baker and Olson, 1975).

8.4 STATION OPERATION

In December, 1974, operation of the MDAC Geophysical Observatory at McMurdo Sound Antarctica, was terminated. All usable equipment was packed and an agreement reached among AFOSR, NSF, MDAC, and the New Zealand DSIR regarding its disposition. DSIR will use most of the equipment to continue measurements at their locations at Arrival Heights and Scott Base, Antarctica. The remainder was either scrapped or, if usable, returned to MDAC. The shipment arrived at MDAC in March, 1975.

In February, 1975, operation of the MDAC Geophysical Observatory at Shepherd Bay, N.W.T., Canada, was terminated. All equipment was packed and placed in storage at Shepherd Bay, pending possible renewal of operation in conjunction with the International Magnetospheric Study commencing in 1976.

Section 9

PERSONNEL

Principal Investigator:

A. J. Masley, Assistant Chief Scientist (prior to August 1975)

M. B. Baker, Senior Engineer/Scientist (after August 1975)

Biotechnology & Space Sciences Department

Senior Scientists:

- Dr. N. R. Mukherjee
- Dr. W. P. Olson
- Dr. K. A. Pfitzer

Operators-in-Charge:

McMurdo Sound: B. P. Smith

Shepherd Bay: J. R. Biggers

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Section 10

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