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ANNUAL LETTER REPORT

ONR Contract N00014-83-K-0365

"Solar Flares and Magnetospheric Particles: Investigations Based Upon the ONR-602 and ONR-604 Experiments"

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For the Period Ending: 30 November 1988

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SOLAR FLARES AND MAGNETOSPHERIC PARTICLES: INVESTIGATIONS BASED UPON THE ONR-602 AND THE ONR-604 EXPERIMENTS

SUMMARY

A. ABSTRACT:

Data from the ONR-602 experiment, obtained in a low altitude, polar orbit are being analyzed to investigate the composition, intensity levels and time variations of energetic charged particles both trapped within the Earth's magnetosphere and incident upon the magnetosphere from interplanetary space, particularly solar flare particles. The effort involves both data analysis/interpretation and detailed modeling of the near-Earth environment. The research focusses on the "global zones" of low energy particle precipitation, including the South Atlantic Anomaly region from which access to the radiation belts is obtained, and the solar particle events of May-Nov., 1982. In addition, scientific/technical support is being provided to the ONR-604 experiment to be launched on the CRRES mission. The results of these investigations will enhance our understanding of the geospace radiation environment and its effects on men, materials and electronic systems in space.

B. OBJECTIVES:

The objectives of this research are to investigate the nature and origins of the particle populations in near Earth space by focusing on their spatial distributions, composition, energy spectra and temporal variations and to look at couplings between interplanetary (solar flare generated) and magnetospheric populations. The goal is to understand the Geospace environment in which men and spacecraft must survive and function.

C. PROGRESS DURING PRECEDING PERIOD:

In the past year we have (i) developed the Source Attenuation model to explain the altitude dependence, (ii) used the telescope efficiency calculation to compare Phoenix-1 and EI-92 intensities in both models for the altitude dependence, (iii) investigated the energy ranges/particles involved in the SS counting rate, (iv) looked at electron signatures and (iv) analyzed solar particle access to the magnetosphere. Review papers on particle astrophysics and solar flares appeared in print and a paper was accepted for publication in J.G.R. Further, planning for the final ONR-604 accelerator calibration and equipment preparation are in process.

D. PLANS FOR THE COMING YEAR:

During this next year we will focus upon (i) electron precipitation events, (ii) 1982 solar flare time profiles and comparisons to interplanetary spacecraft, (iii) particle composition in the SAA, (iv) the accelerator calibration of ONR-604 for CRRES, (v) development of the solar flare database and (vi) software development for the CRRES analysis.

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"SOLAR FLARES AND MAGNETOSPHERIC PARTICLES: INVESTIGATIONS BASED UPON THE ONR-602 AND THE ONR-604 EXPERIMENTS"

ONR Contract N00014-83-K-0365

Annual Letter Report

I. INTRODUCTION:

This report covers the period to 30 November 1988 for the contract cited above. The research consists of fundamental investigations of the charged particle component in the Geospace environment. The project involves analysis of the data returned from the ONR-602 (Phoenix-1) experiment on the S81-1 mission in 1982, correlation of the Phoenix-1 dataset with other measurements, modeling the processes and the environment to understand the data, and scientific planning for the launch and operation of a "sister experiment," ONR-604 on the CRRES mission. During the past year significant progress has been made in interpreting the ONR-602 dataset with respect to the low-energy protons observed in the equatorial belt and the solar energetic particle observations.

II. PERSONNEL:

The personnel engaged in this analysis effort consist of the principal investigator; Assistant Research Professor, Dr. T. G. Guzik working part-time on the analysis; Senior Research Associate, Dr. J. Cooper, working on the solar flare access questions and electron events; Research Associate, Dr. J. W. Mitchell who works part-time on the interpretation and modeling; and several undergraduate students to help with programming and data handling.

Our graduate student, M. A. Miah has completed his Ph.D. work this past year and has obtained a position at the University of Arkansas at Pine Bluff. He will be replaced by a new graduate student as soon as a suitable candidate is available. For the coming year, Mr. James Pitts, a B.S. in Physics, will be employed as a researcher to help with the project. Mr. Pitts will leave us for graduate school at the end of summer, 1989. He has had previous experience with the project, working on much of the software development and the early analysis, and will be able to make an immediate contribution to the analysis effort.

III. FACILITIES:

The majority of the ONR-602 data analysis is now handled on the Experimental Physics Data System (EPDS), a VAX-11/750 based system containing 450 Mbytes of disk, three tape drives, a line printer and a Calcomp plotter as peripherals. The EPDS replaced a small PDP-11/73 and has improved both our data handling/analysis capabilities and our compatibility with the data systems at other facilities with which we work, e.g. University of Chicago, Naval Research Laboratory, Lawrence Berkeley Laboratory, etc.

We have obtained "node status" on SPAN (Space Physics Analysis Network) and have installed the needed hardware and software. This national network provides access, from the EPDS, to most other space physics facilities in the country, including the NSSDC at Goddard, MSFC, University of Chicago, the Aerospace Corporation, and, through ARPANET, AFGL. This speeds communications with collaborators, provides for data transfer, and is already proving valuable for working the CRRES program, both pre-launch and post-launch.

During the past year we augmented the capabilities of the EPDS with the addition of a VaxServer 3500 and a VaxStation 3200, clustered with the 11/750. This has allowed the SPAN network load to be taken by the 3500 and has enhanced the capabilities of the system for detailed modeling studies and for the current and projected data analysis work. The EPDS remains a shared resource, but with the cluster, it should be usable for the analysis of the CRRES data over the next 3-5 years.

IV. PUBLICATIONS, REPORTS AND PRESENTATIONS:

1. The invited review paper prepared by J. P. Wefel has appeared in print:

   "An Overview of Cosmic Ray Research: Composition, Acceleration and Propagation," in Genesis and Propagation of Cosmic Rays, eds. M. M. Shapiro and J. P. Wefel, NATO ASI Series C, Vol. 220 (D. Reidel and Co., 1988, Dordrecht, Holland), pp. 1-40.

2. An article describing our work, based upon a presentation by M. A. Miah, has appeared:

   "Phoenix-1 Observations of Equatorial Zone Particle Precipitation," by M. A. Miah, T. G. Guzik, J. W. Mitchell and J. P. Wefel, in Genesis and Propagation of Cosmic Rays, eds. M. M. Shapiro and J. P. Wefel, NATO ASI Series C, Vol. 220 (D. Reidel and Co., 1988, Dordrecht, Holland), pp. 339-355.

3. M. A. Miah finished and successfully defended his Ph. D. dissertation entitled, "Global Zones of Particle Precipitation." This work was based solely on the analysis of Phoenix-1 data from the S81-1 mission. A copy of the Dissertation Abstract is included as Appendix A. Mr. Miah was awarded the Ph.D. degree in Fall, 1988.

4. A paper on the modeling of the low energy proton precipitation at the equator was prepared, submitted and has been accepted for publication in the Journal of Geophysical Research:

   "Low Altitude Trapped Protons at the Geomagnetic Equator," T. G. Guzik, M. A. Miah, J. W. Mitchell and J. P. Wefel, J.G.R., in press (1989).

   A preprint is attached as Appendix B.

5. Mr. M. A. Miah was selected to receive support for attendance at the Yosemite 1988 Conference on Outstanding Problems in Solar System Plasma Physics: Theory and Instrumentation, 2-5 February 1988, Yosemite National Park, CA. He presented a paper entitled, "A Method for Mapping the Pitch Angles of Magnetospheric Particles onto a Detector Telescope: Detector Efficiency."

6. John P. Wefel presented an invited paper entitled "Nucleosynthesis, Nuclear Physics, Supernovae and Cosmic Rays" to a NATO Advanced Study Institute, the 6th Course of the International School of Cosmic Ray Astrophysics. The school was held during April, 1988 at the Ettore Majorana Centre in Erice, Italy.

7. John F. Cooper represented our group at the Second Workshop on "Impulsive Solar Flares" held in September, 1988 at the University of New Hampshire, Durham, NH. He presented a poster paper on our work entitled "ONR-602 Results from 1982 Flares."

8. Two abstracts have been prepared for presentation at the fall, 1988 meeting of the American Geophysical Union in San Francisco, CA. Dr. M. A. Miah will give a poster presentation entitled "Altitude Dependence of Quasi-Trapped Protons in the Equatorial Zone," and Dr. J. F. Cooper will give an oral presentation entitled, "S81-1 Measurements of Low-Altitude MeV Ions." Copies of these abstracts are included as Appendix C.

V. RESEARCH HIGHLIGHTS:

During the past year we have (a) completed the analysis and modeling of the low energy precipitating protons observed near the geomagnetic equator, (b) started investigating multiple particle effects in the higher particle intensities encountered during polar passes, (c) cross-calibrated the Phoenix-1 data with IMP-8 results, (d) begun a study of the solar particle access conditions, comparing IMP-8 (interplanetary) to Phoenix-1 and (e) initiated a program for special calibrations for the ONR-604 experiment to be launched on the CRRES mission. The effort in these areas is summarized below.

A. Low Energy Protons at the Equator

The interpretation of magnetospheric particle data, particularly comparison of observations made by different instruments and/or over different time periods, requires the determination of the absolute intensity of the particles. At a particular altitude and longitude, the trapped particle population is characterized by an equatorial pitch angle distribution to which different instruments may not have the same response. Thus it is necessary to unfold the effects of the pitch angle distribution from the raw counting rates.

Previously, we developed a procedure to calculate telescope efficiency as a function of pitch angle and used it to compare the absolute intensities measured for the ~1 MeV precipitating protons observed by the Phoenix-1 and the EI-92 instruments in 1982 and 1969-70 respectively. The absolute flux values were found to be in good agreement for a wide range of values of "q" (for a pitch angle distribution described by $\sin^q \alpha_E$, where α_E is the equatorial pitch angle). The difficulty here is that the EI-92 measurements were made at altitudes ≥450 km while the Phoenix-1 results were for altitudes ≤277 km and showed a marked (power law, exponent of 5) dependence on altitude (see Figure 1). Extrapolating the Phoenix-1 results to 450 km gave a large difference between the two epochs, 1969-70 and 1982.

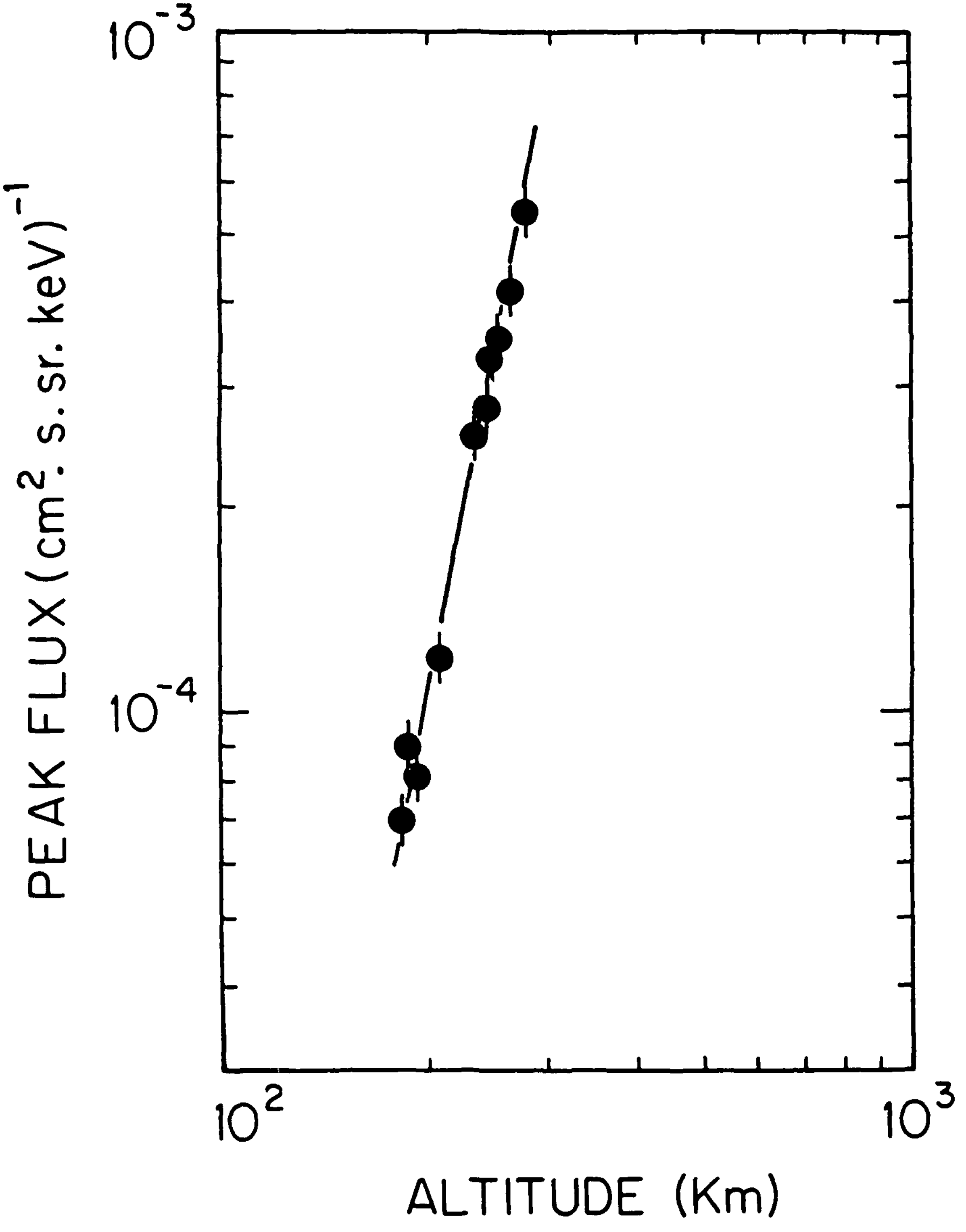

Figure 1. The altitude dependence of the proton flux measured by the Monitor telescope in Phoenix-1. The line is a power law in altitude (h^5) normalized to the measured flux at 185 km.

Resolving this difficulty, and obtaining an accurate assessment of any difference in flux between the two epochs, involves modeling the processes contributing to the altitude dependence in order to perform the proper extrapolation from the Phoenix-1 to the EI-92 altitudes. This has been accomplished in the past year with the development of a Source Attenuation (SA) model for the low altitude proton flux.

The SA model assumes the same double charge exchange ring current source as used in previous investigations but incorporates, in addition, all of the loss processes in the atmosphere which have not been treated in detail previously. At large altitudes, the atmospheric column density is so low that there is little attenuation of the neutral hydrogen flux from the source. In this region an altitude independent analysis is a good approximation. At lower altitudes, however, the column density both changes rapidly with altitude and is sufficiently large so that there is a large attenuation. The division between these regions is in the 300-400 km altitude range, just between the regions explored by Phoenix-1 on S81-1 and EI-92 on Azur.

The flux attenuation is illustrated in Figure 2 which shows the calculated attenuation curves, from only charge exchange processes, as a function of altitude for different particle energies. Note the strong altitude dependence at low altitudes. While actually exponential in nature, the curves can be fit by a power law over the Phoenix-1 altitude range. The cross sections have an energy dependence, leading to the different curves on Figure 2, and this implies that the model calculations must be averaged over the energy spectrum of the observed particles.

Other sources of particle loss must be included. These involve ionization energy loss for the charged protons and pitch angle diffusion into the loss cone. Further, the source geometry, i.e. what fraction of the ring current source that can contribute to the flux at a particular altitude, must also be considered. An analysis of each of these effects has been performed, combined with the attenuation of Figure 2, and averaged over an $E^{-2.55}$ power law spectrum, the spectrum determined from a compilation of existing measurements. The calculated altitude dependence is shown in Figure 3 as the solid line. A power-law fit (dashed line) to the calculations yields an altitude dependence of $h^{4.6\pm0.3}$, consistent with the measured dependence over the Phoenix-1 altitude interval. With the Phoenix-1 data, it is impossible to observe the small difference between the solid and the dashed curves in Figure 3.

Figure 4 shows the comparison of the absolute flux measured by Phoenix-1 in 1982 with that measured by EI-92 in 1969-70. The extrapolation of the Phoenix-1 results to the EI-92 altitude via the power paw altitude dependence shows an order-of-magnitude larger flux in 1982, too large a change to be reconciled with a ring current source. The new SA model extrapolation, however, shows a flux increase in 1982 by a factor of ≤1.5 depending, weakly, upon the exact value of the index of the pitch angle distribution. Thus, there is some evidence for a small, long term temporal variation in this population, due either to an enhanced source, e.g. the ring current, or to differing atmospheric conditions which effect the production and loss of these low energy protons.

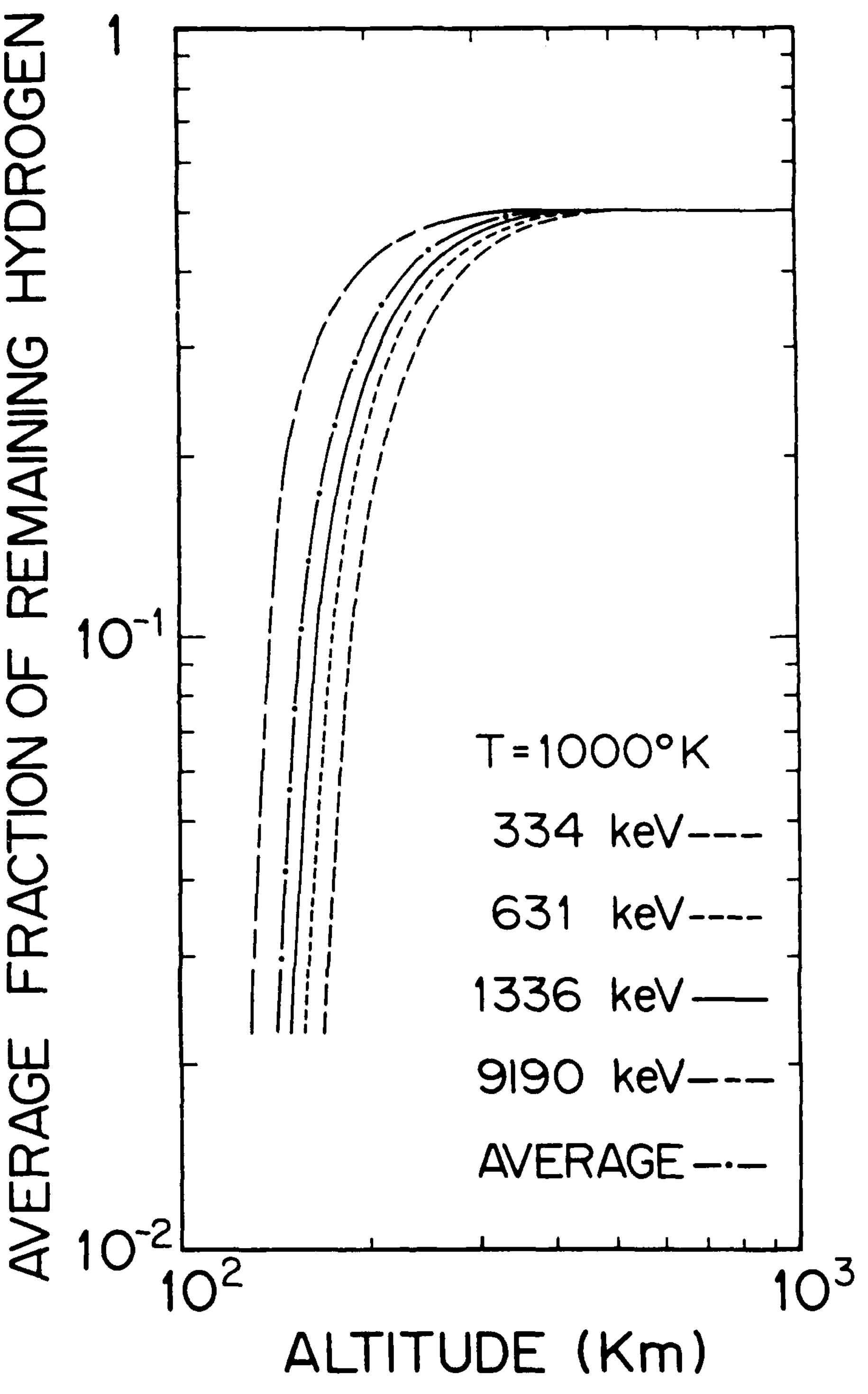

Figure 2. Source attenuation due to charge exchange in the atmosphere as a function of altitude for different energies of the precipitating protons.

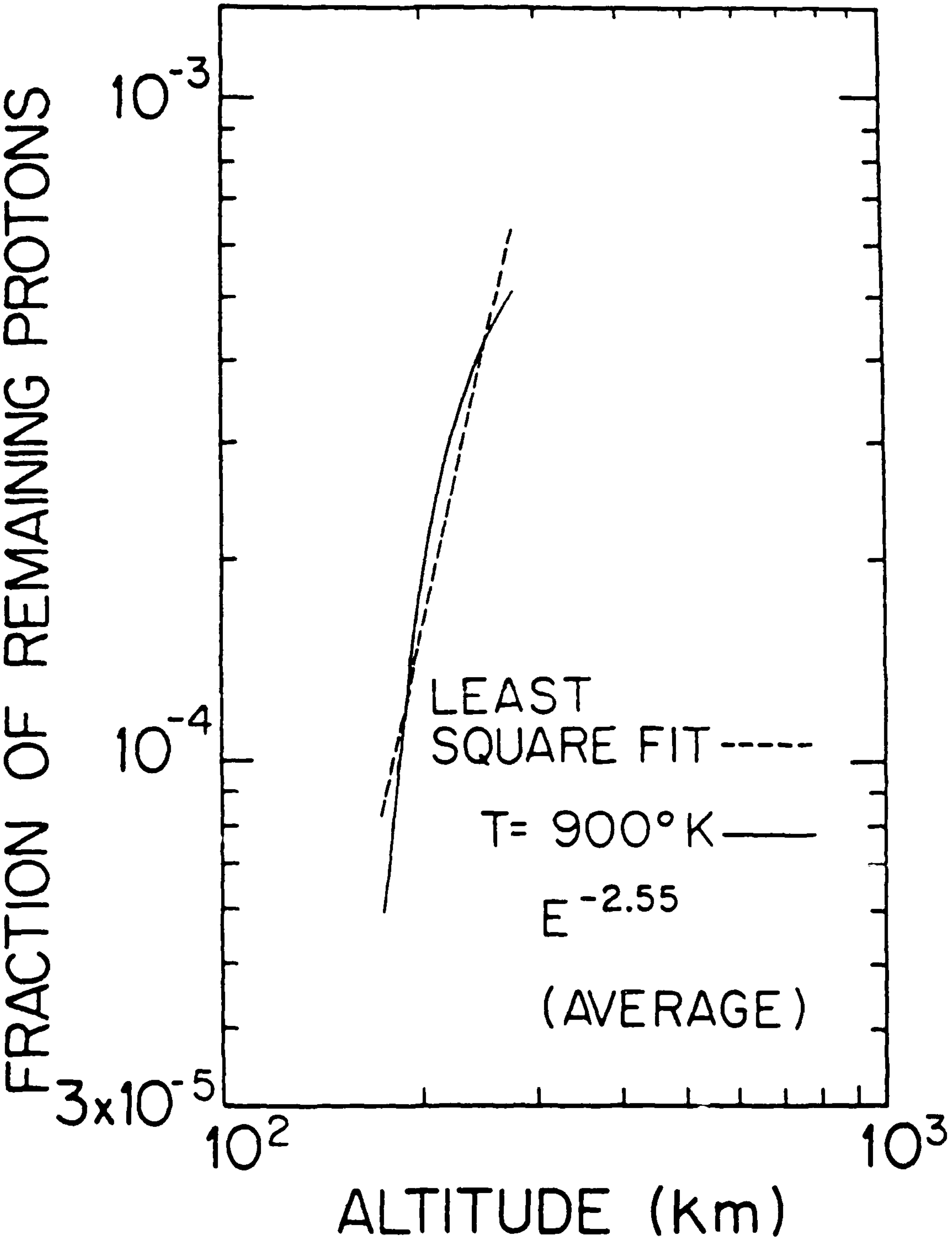

Figure 3. Calculated altitude dependence for the SA model (solid) compared to a power-law fit to the calculations (dashed) for an average atmospheric temperature of 900 °K. The results are averaged over an $E^{-2.55}$ differential energy spectrum for the protons.

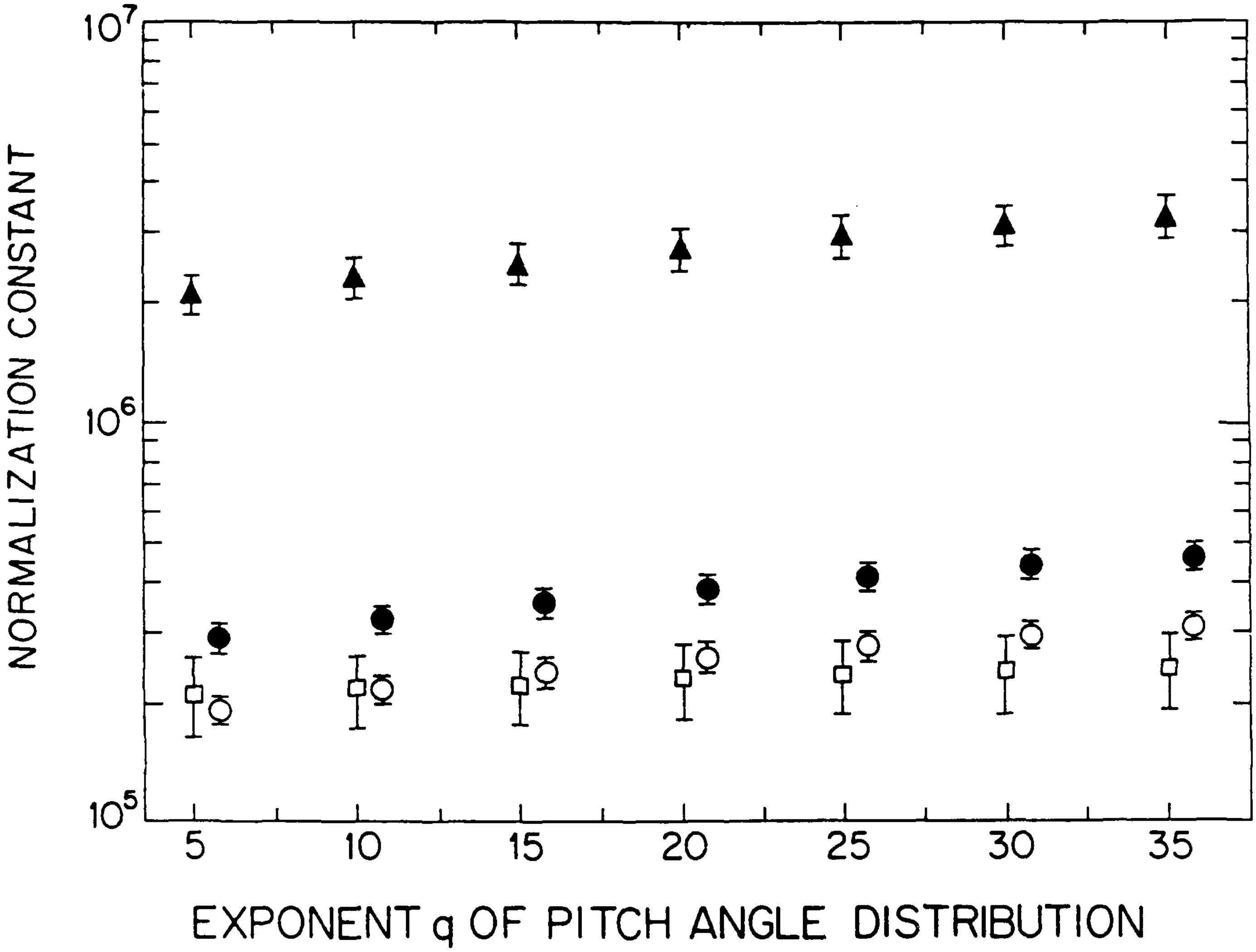

Figure 4. Comparison of the particle intensity, represented by the flux normalization constant, for Phoenix-1 at 277 km (O) and EI-92 at 450 km (□) as a function of the index of the pitch angle distribution. Results are also shown for Phoenix-1 extrapolated to 450 km using the power law altitude dependence (▲) and the SA model altitude dependence (●).

B. Solar Particle Access to the Magnetosphere

The question of the access of solar energetic particles to the polar cap regions of the magnetosphere can be investigated with the Phoenix-1 instrument in polar orbit combined with an instrument in interplanetary space to provide an absolute normalization. Figure 5 shows several orbits of the S81-1 spacecraft during day 255, a period of moderate solar activity. Plotted is the ML counting rate corresponding, nominally, to ≥ 0.5 MeV protons. The equatorial belt, discussed in the previous section, is indicated as are the polar cap regions. A large precipitation spike is observed just to the side of the polar cap regions, and this is discussed in the following section. The sharp onset of the increased intensity in the polar caps provides a means for studying the access questions.

An interplanetary monitor is provided by the low energy telescope on the IMP-8 spacecraft which has a channel, L1NL2, nominally identical to the ML rate from Phoenix-1. A comparison of the two rates is provided in Figures 6 and 7 showing polar cap averages from Phoenix-1 compared to IMP-8 hourly averages in interplanetary space. The correlation is remarkably good both for the overall solar activity during 1982 (Figure 7) and for the June, 1982 flare period shown expanded in Figure 6. The correlation time scale is generally ≤ few hours, however, the data for day ~163 suggest periods where correlation times may be as long as 10-12 hours, perhaps due to access from the extended magnetotail.

With these results, we confirm that the ML detector is observing interplanetary particles over the poles, and we can use the data to study more details of the process. Figure 8 compares the ML and MM counting rates during a North pole pass (top) and a South pole pass (bottom) for day 203 of 1982. The time resolution is 4 seconds corresponding to ~30 km spatial resolution. The wide region of relatively low flux observed across the North pole on the night side indicates inhibited access of interplanetary particles into that zone except at large distances down the magnetotail, perhaps due to the orientation of the interplanetary magnetic field at that time which may have provided preferential access to the southern polar region. Note that proton and helium counting rates show approximately the same polar cap structure, indicating that we are indeed observing interplanetary particles.

The sharpness of the proton trapping boundary corresponding to the last closed field line is illustrated in Figure 9 for proton, helium, and heavy ion counting rates from the Monitor telescope for a period of especially high solar particle intensity. The dropoff in counting rate within one four-second interval gives a plasmapause boundary thickness less than 30 km, which is comfortably wider than the sampled particles' gyroradii which are in the 3-6 km range. Note that the stormer cutoffs for the geomagnetic field at the boundary are ~13 MeV for protons and ~3 MeV/nucleon for helium, an order of magnitude larger than the proton and helium energy thresholds. It may be possible that the helium and heavy ion channels have a significant proton pileup component considering the high proton fluxes at this time. This possibility must be investigated before the counting rates can be used to determine relative particle composition during these flare periods.

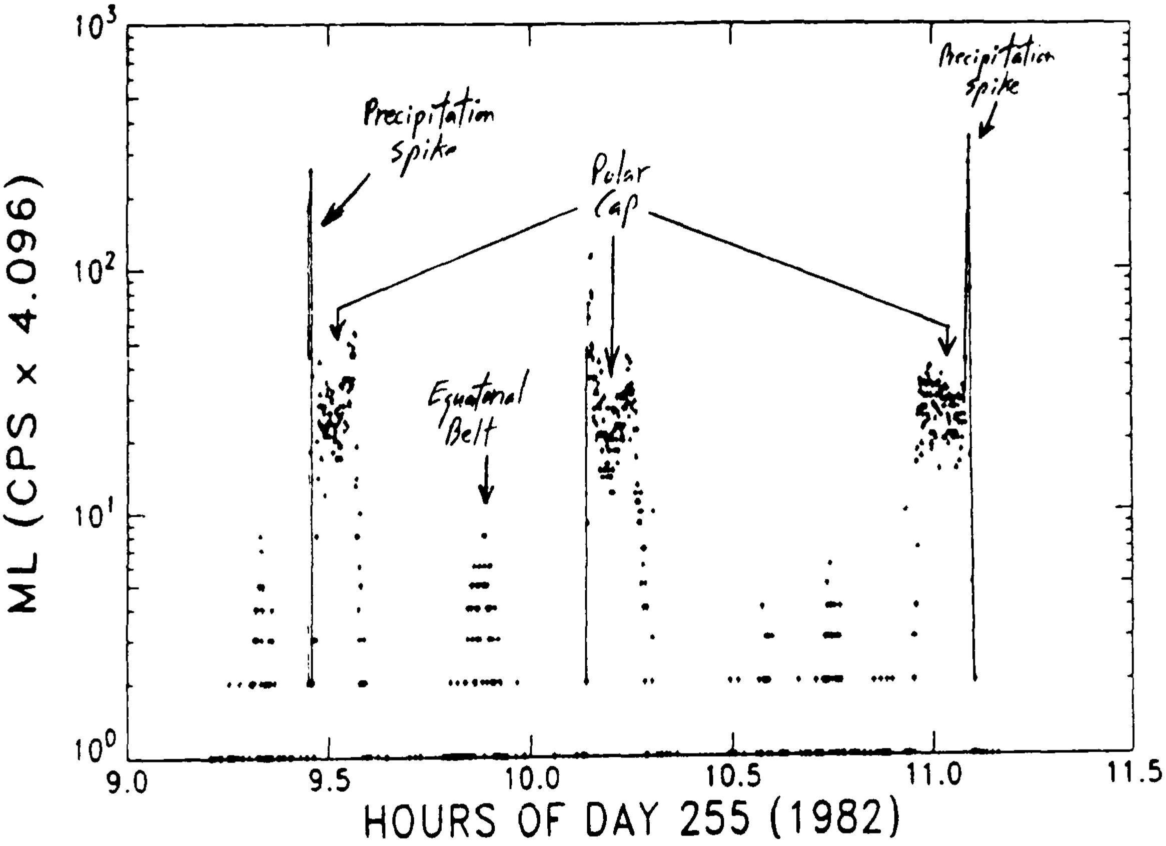

Figure 5. ML counting rate for part of day 225.

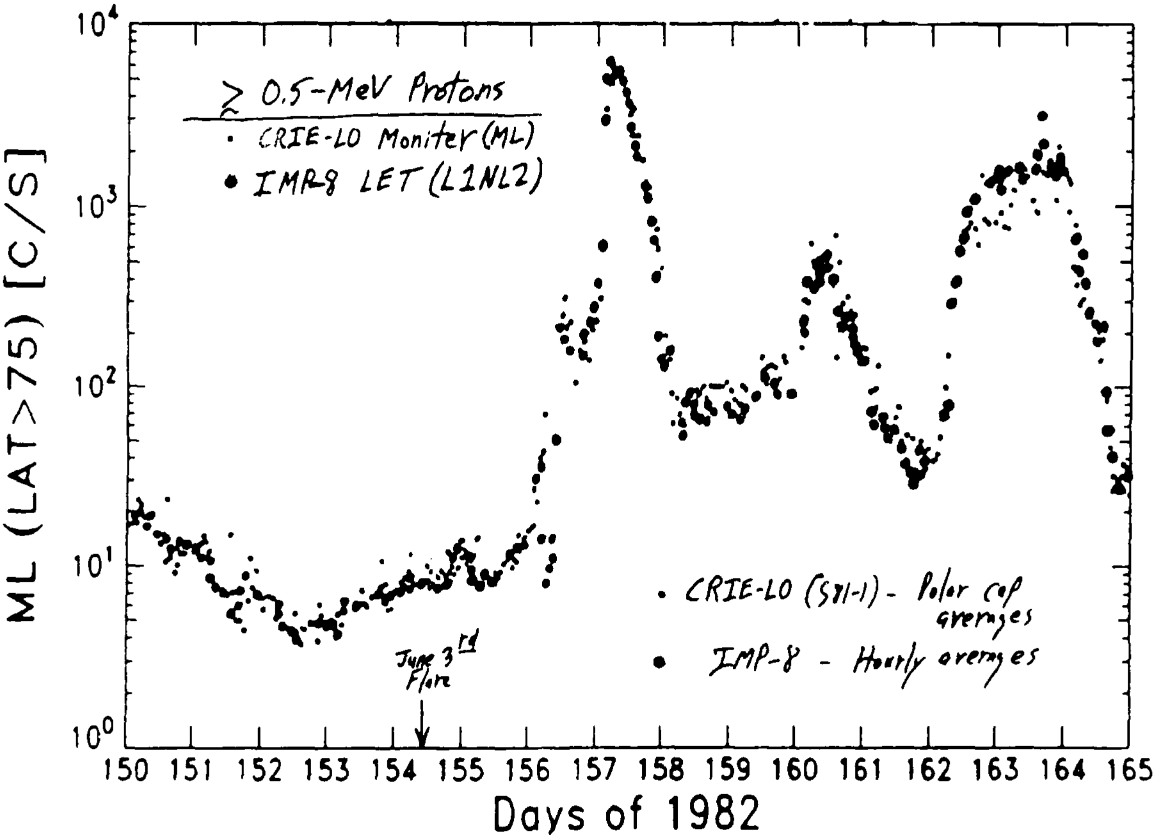

Figure 6. Comparison of Phoenix-1 and IMP-8 counting rates.

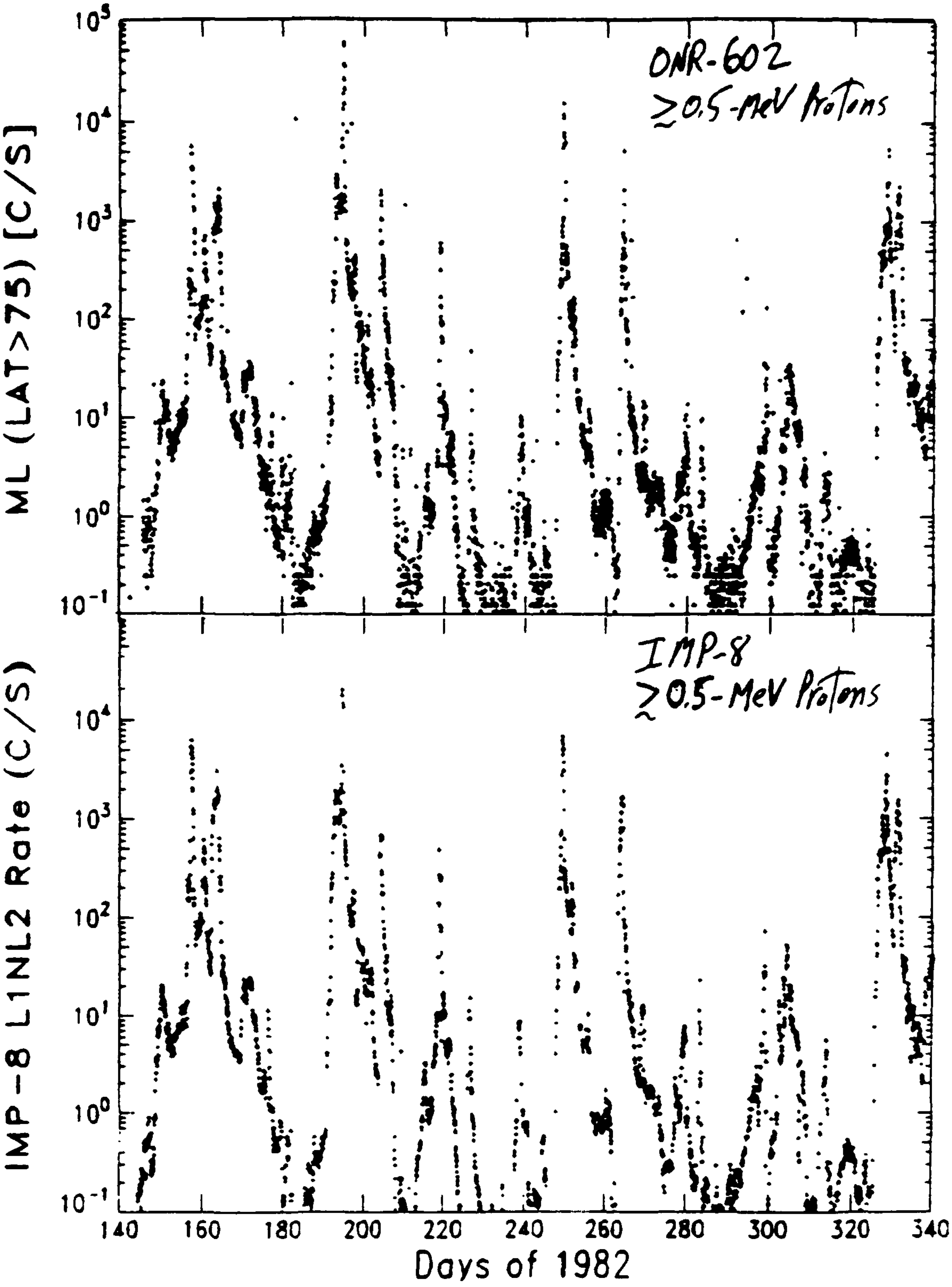

Figure 7. Comparison of Phoenix-1 monitor rate ML with IMP-8 L1NL2 rate, both nominally ≥0.5 MeV protons. The ML data is for polar passes, latitudes >75°.

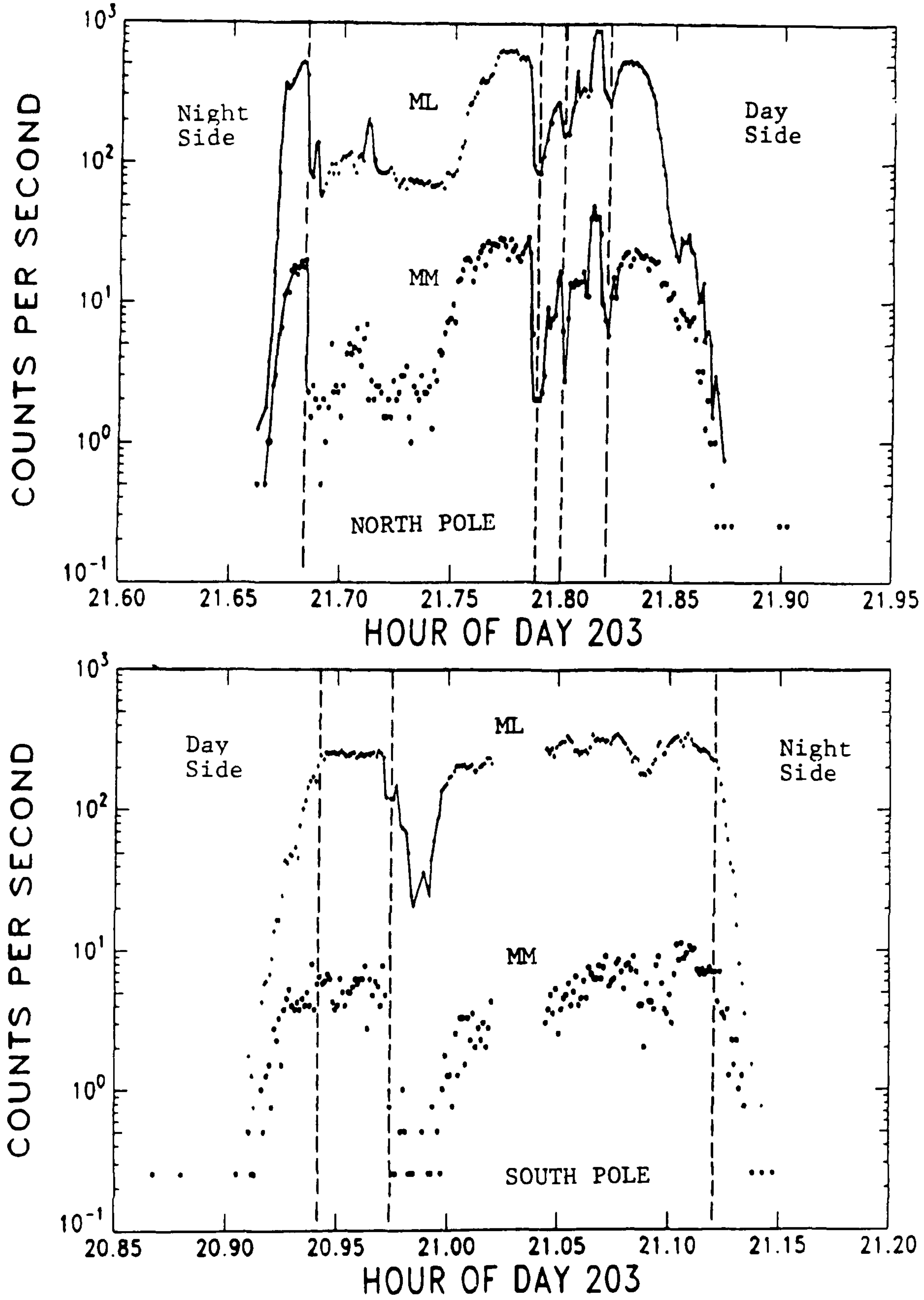

Figure 8. ML (proton) and MM (helium) counting rates during a polar cap crossing over the North pole from the night side to the day side (top) compared to the previous South pole crossing from the day side to the night side (bottom). Note the sharp spatial gradients resolved for solar proton and helium access to the polar cap region. Interplanetary solar particle fluxes are rapidly increasing at this time.

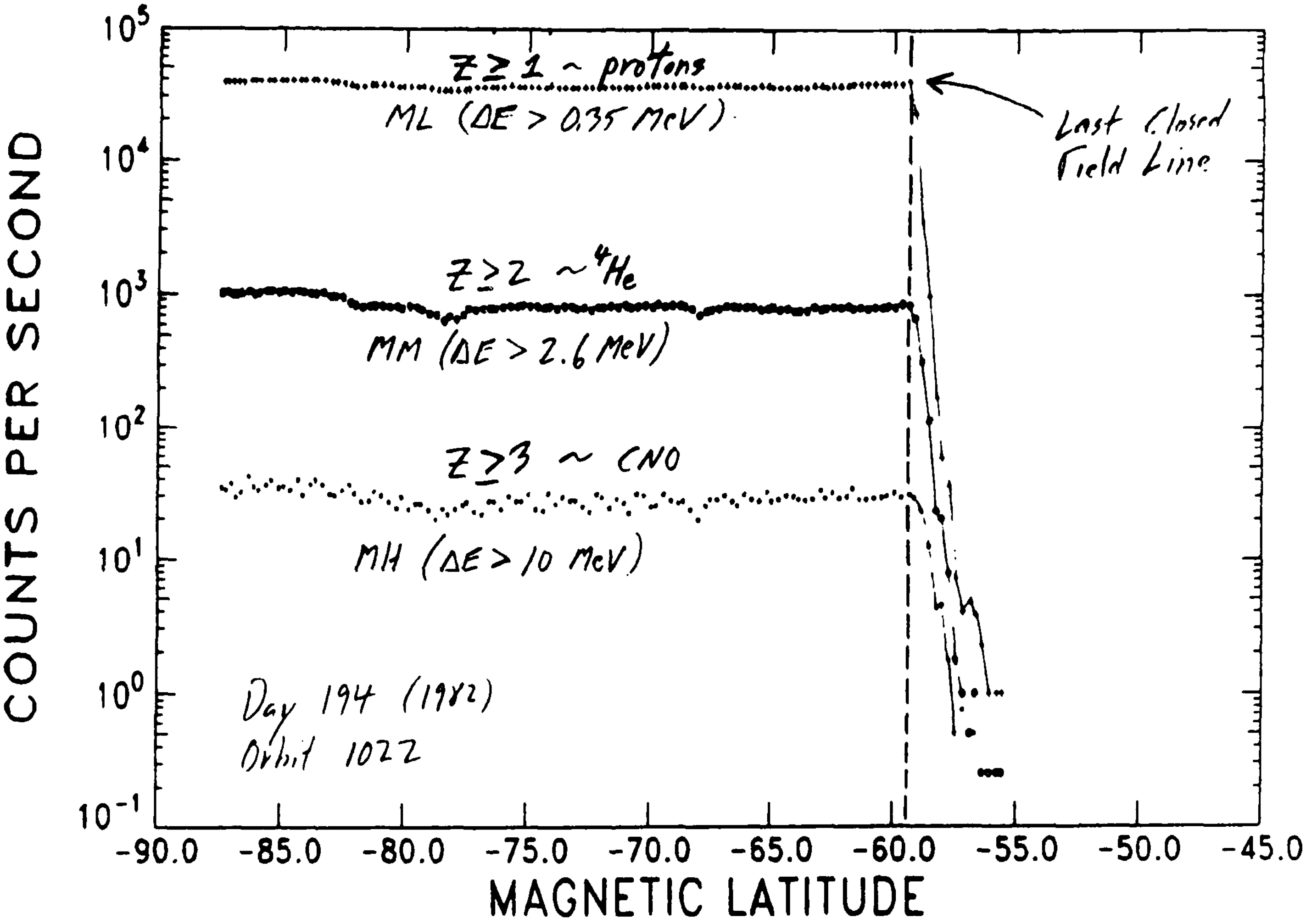

Figure 9. ML (proton), MM (helium), and MH (heavy ion) counting rates across a polar cap during a period of very high solar particle flux. The trapping boundary dropoff occurs within one four-second interval at L = 3.97 and invariant latitude of 59° for all three rates. The corresponding Stormer cutoffs are 13 MeV for protons and 3.0 MeV/nucleon for ions in a dipole magnetic field model.

C. Electron Precipitation Spikes

Figure 5 indicated sharp precipitation spikes near the plasmaspheric boundaries of the last closed field line just adjacent to the polar cap region. One of the largest spikes is shown in expanded time scale in Figure 10. Note that no corresponding spike (or any significant level of events) was recorded in the helium channel, which strongly suggests that the spikes originate from nonsolar energetic particle populations. A check of simultaneous data from the LPARL medium energy electron spectrometer on S81-1 shows that this was a period of intense electron precipitation at ~100 keV. The LPARL instrument was in saturation during most of this period. Thus, it is probable that electron pile-up in the 40 μm thick monitor detector is most likely responsible for the ML spikes. Note that the L = 5.67 location of the spike would be consistent with a large increase in energetic electron flux and/or strong pitch angle scattering near geosynchronous orbit. A possible correlation to the hard, field-aligned electron component above 600 keV observed in this L-region is an investigation which will be undertaken in the coming year.

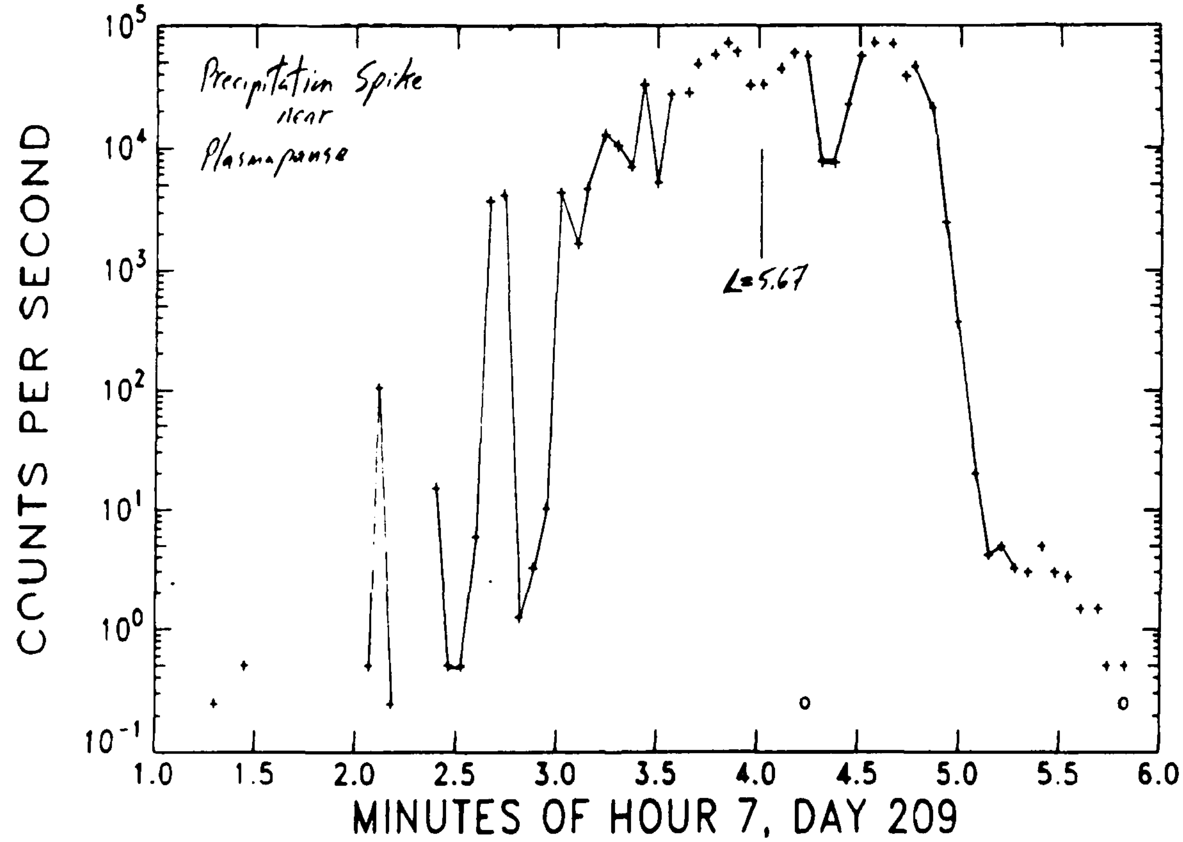

Figure 10. Expanded time scale of precipitation event observed in ML counting rate.

D. Solar Particle Monitoring

The average intensity of MeV protons over the polar caps (>75 degrees magnetic latitude) are well-correlated to hourly averages of counting rates from the University of Chicago low energy telescope onboard IMP-8 as shown in Figures 6 and 7. In addition to the monitor telescope, the main telescope of the Phoenix-1 package contains a well shielded guard scintillator (SS) whose rate can provide a solar particle monitor. Nominally, the passive shielding around SS should make it immune to electrons ≤4 MeV and protons ≤40 MeV. Thus, the SS rate may be able to provide a higher energy monitor for flare particles.

To investigate this possibility further, the SS rate profile over the poles was compared to different counting rates from the IMP-8 instrument in interplanetary space. Figure 11 shows the comparison for the June, 1982 flare period. Careful comparison of the profiles in Figure 11 shows that the ONR-602 SS rate reflects the rise seen in the IMP-8 Cherenkov counter for >100 MeV protons with, possibly, some admixture of >MeV electrons. The fact that the fall off after the flare peak is less rapid than the >100 MeV proton rate indicates the presence of either MeV electrons or lower energy protons, but not as much as would be expected by just adding one of the top two curves to the Cherenkov counter rate, since the fall is more rapid than either of the top two plots. This is a qualitative indication that SS can be used as a tracer of the relativistic protons, but care must be taken since there is a possible contamination by high energy electrons. More detailed studies are in progress to try to determine more quantitatively the energy ranges for the particle response of SS.

The use of the SS rate is illustrated in Figure 12 which shows mission plots for SS compared to the pulse height analysis trigger rate, P3. This latter rate corresponds to helium (~5-9 MeV/nucleon) plus CNO plus heavier nuclei selected for pulse height analysis by the main telescope. The correlation between the rates is quite good indicating that SS provides a tracer of the heavy ion component among the flare particles. This is important since the P3 rate is generally quite low while SS can be employed for small flares not observed in the P3 rate.

Figure 13 shows the results of a survey of the charge coverage for the pulse height analyzed events (top). Note that this top plot can be compared to the results of Figure 12. The charge values are determined from dE/dx vs residual energy plots, such as is illustrated on the bottom of Figure 13, after correcting for the angle of incidence of the particles using the information provided by the two-dimensional position sensing detectors in the Phoenix-1 main telescope. Note that the charge resolution in this T1-T2 mode is quite good. This provides an opportunity to compare the heavy ion content of the different flare periods during 1982 for correlation with other observations and to look at ion time profiles during the flares.

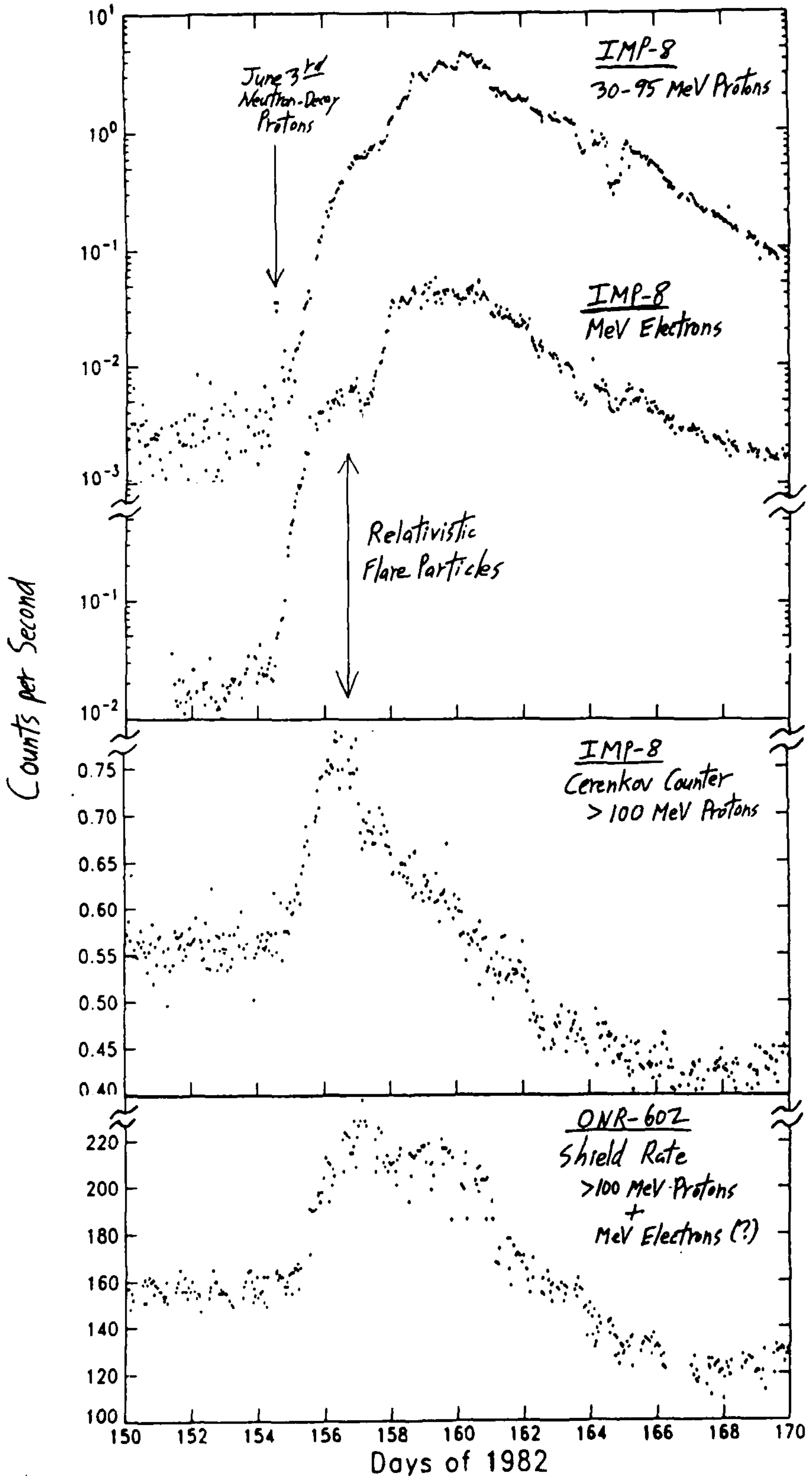

Figure 11. Comparison of Phoenix-1 shield (SS) rate with various counting rates from IMP-8 for the June, 1982 flare period.

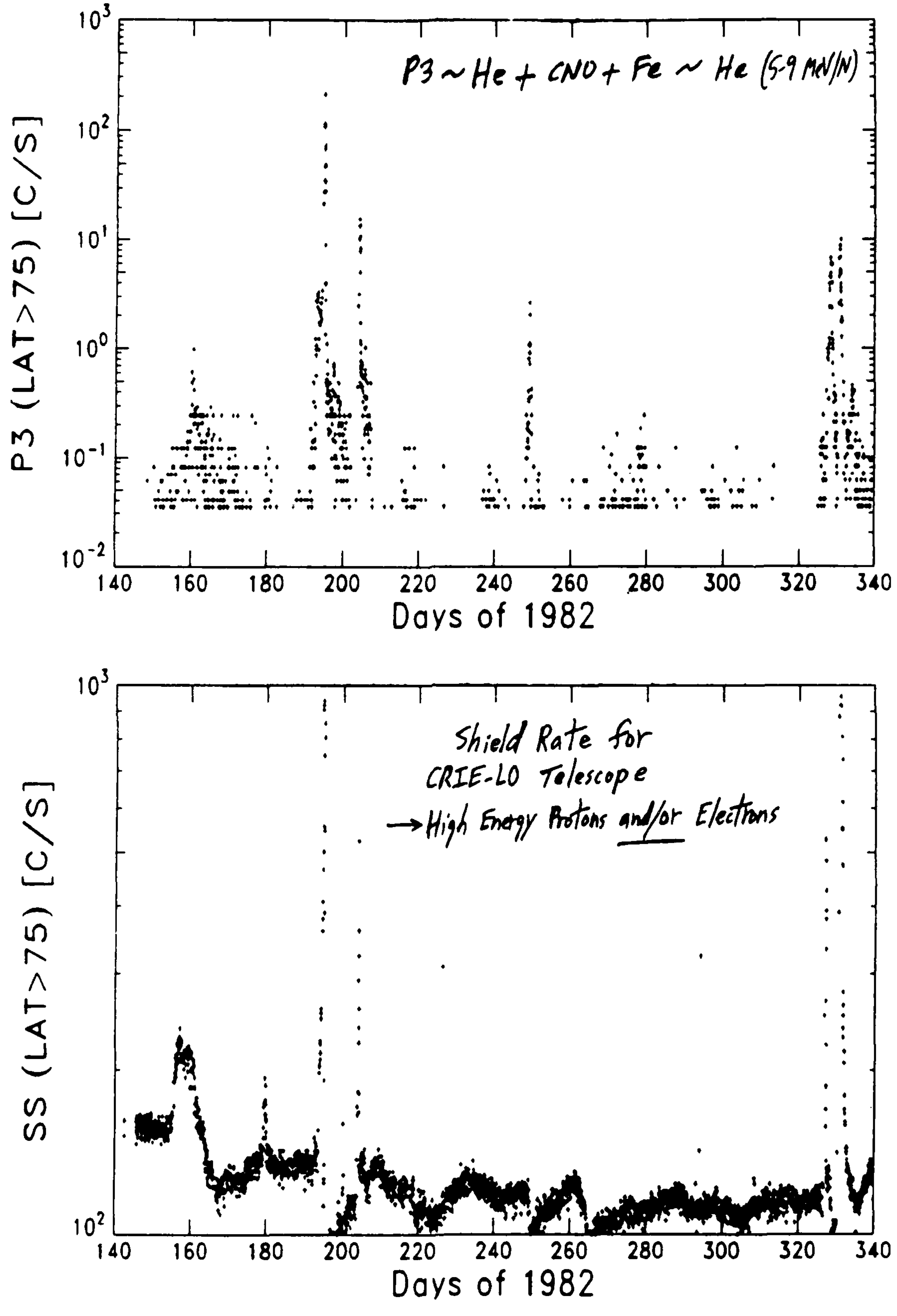

Figure 12. Polar cap averages of the SS rate compared to the P3 (pulse height analysis) rate for the S81-1 mission.

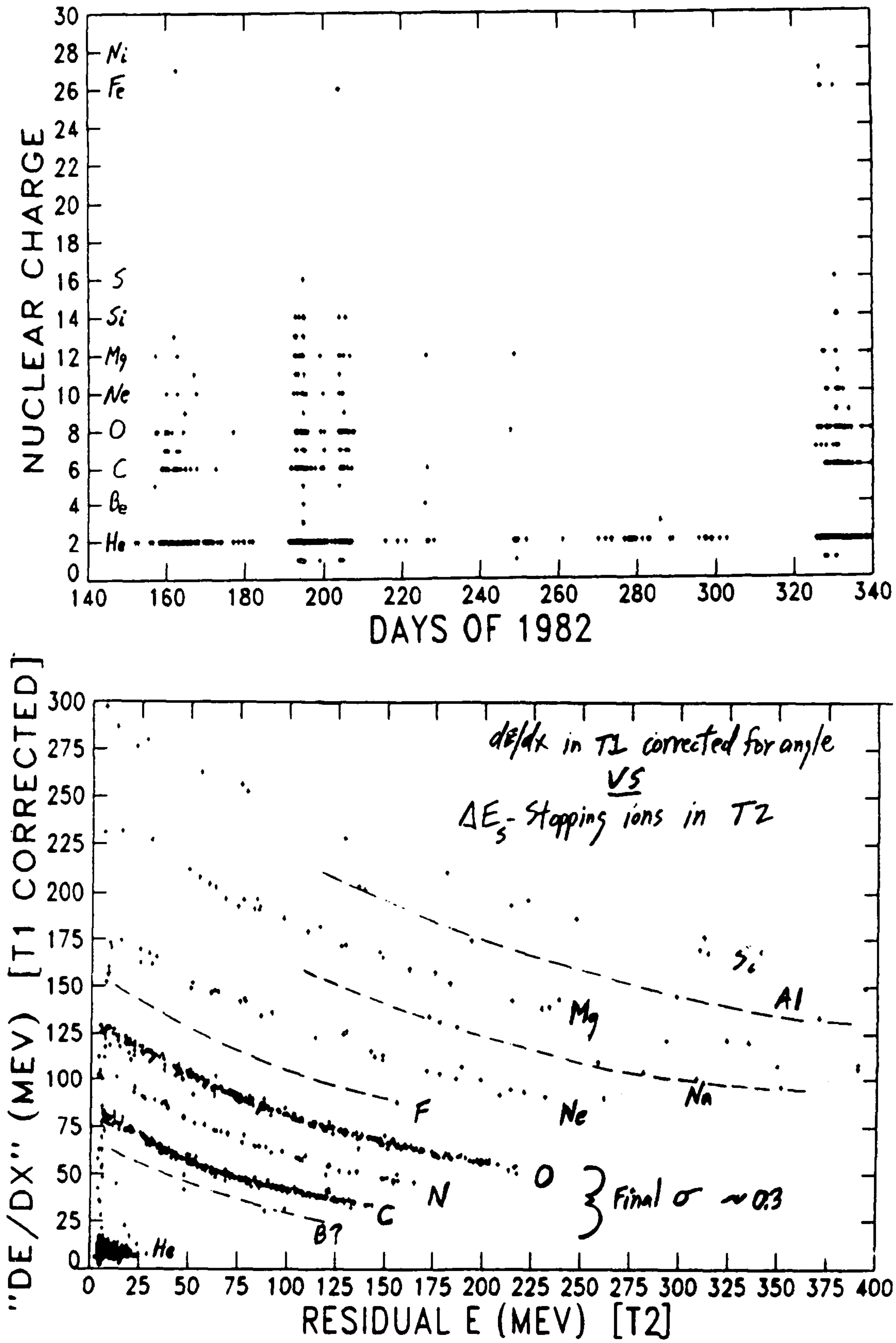

Figure 13. Charge coverage for flares during the S81-1 mission (top). The T1-T2, dE/dx-E matrix used for charge identification (bottom).

E. ONR-604 Calibration

The ONR-604 instrument, the "sister" experiment to Phoenix-1 (ONR-602), is scheduled for launch onboard the CRRES mission in 1990. The ONR-604 package has been in storage at the University of Chicago and its performance has been monitored on a periodic basis through bench tests. It is still functioning nominally. However, the storage has been so extended that the pre-storage heavy ion calibration of the instrument can no longer be considered valid and must be re-done. Delivery to Ball Aerospace for re-integration of ONR-604 into the CRRES satellite is scheduled for May/June 1989, so that the accelerator calibration must be performed in the next few months.

This accelerator calibration will involve personnel from both the University of Chicago and Louisiana State University, a co-investigator on the project. We are tentatively scheduled for the last two weeks of February at the LBL Bevalac facility. Much of our effort in the past several months has been devoted to planning and equipment acquisition for this calibration experiment.

The LSU responsibilities include general setup, operations and experiment monitoring with the Chicago group. In addition, we have accepted responsibility for a special test to try to simulate the high background environment which will be encountered during the perigee passes through the inner magnetosphere. There are two questions to be answered.

1) What is the effect of a background of electrons and gammas on the pulse height analysis resolution for heavy ions?

2) What is the effect of such background on the counting rates and the instrument triggering logic in both "proton" and "heavy ion" operating modes.

The environment will be simulated by exposing the telescope to a large β-γ flux from a radioactive source both while the instrument is recording heavy ion events from the accelerator and while it is operating in "quiet" mode. The intensity of the radiation from the source will be varied to search for threshold effects in the operation.

LSU has purchased a ^{144}Ce source and designed a holder to allow control of the particle intensity. Detailed set-up for the source runs will be done at the accelerator in consultation with the Chicago group. Fabrication of the source holder and ancilliary equipment is in progress.

VI. RESEARCH PLANS FOR THE COMING YEAR:

The effort to understand the low energy precipitating protons at the geomagnetic equator has revealed many facets of the ONR-602 instrument and of the dataset. As this effort is concluded, new areas have opened up. One example is the question of electron precipitation spikes as suggested by Figure 5 and 10. These events are clearly magnetospheric in origin but their exact explanation is still unknown. There are many examples of such events and the detailed time profiles must be analyzed. The possible connection to energetic electron events observed in geosynchronous orbit is fascinating and must be followed up through time correlations and modeling of the processes.

Our solar flare analysis has taken a step forward in the past year with the development of a correlative database with IMP-8 and its use to study the particle access question. The demonstration that S81-1 gets direct access to interplanetary space during the polar passes can now be used to study the time profiles of the 1982 flares in detail to determine limits on the acceleration and transport processes. Comparison of ions and electrons as well as composition variations are part of our plan for continuing this research.

The SAA region of the orbit must be investigated in more detail. The demonstration that SS provides a tracer of high energy protons (and, possibly, electrons) can now be employed to analyze the structure of the SAA, comparing the three monitor counting rates and looking for excess counts as a function of location within the anomaly. This will provide important information for the analysis of the ONR-604 data from CRRES.

The most immediate experimental effort for the coming year is the CRRES calibration at LBL. We must complete the hardware construction, develop a monitoring procedure and design the exposure geometry (support stands, etc.). Wefel and Cooper are tentatively scheduled to spend the last two weeks of February performing this vital calibration.

Finally, we will continue with the development of the solar flare database, attempting to obtain additional datasets for correlative studies. In addition, the launch of CRRES is fast approaching and significant effort will be needed for software development in order to be prepared for the analysis of the data. Overall, next year promises to be quite busy!

APPENDIX A

MIAH, Muhammad Adel, B.Sc., Rajshahi University, 1972
M.Sc., Rajshahi University, 1974
Doctor of Philosophy, Fall Commencement, 1988
MAJOR: Physics (Space Physics); Minor: Internal (Astrophysics)
Global Zones of Particle Precipitation
Dissertation directed by Professor John P. Wefel
Pages in dissertation, 287. Words in Abstract, 333.

Magnetospheric particles are precipitated at low altitude all over the globe. The study of the physics of the equatorial global zone is important for geospace environment modeling, for knowing the loss processes of radiation belt particles and for the Space Station Project. The equatorial global zone was investigated by the Phoenix-1 experiment on board the S81-1 mission in May through November, 1982. The global profile of the peak flux of quasi-trapped protons follows the line of minimum magnetic field strength, with a FWHM of ~ 13° in latitude. The pitch angle distribution anisotropy index is found to be 19 ± 2, and the protons show no statistically significant longitude dependence.

Contrary to an earlier observation (Moritz, 1972), we find a strong altitude dependence. Within the altitude range of observation (~ 160-285 km) the proton flux varies as the fifth power of altitude. This altitude gradient indicates a strong depletion of source neutrals, coupled with charge exchange loss and ionization loss of protons. A power law fit to the flux values of the previous observations, yields an energy spectral index of -2.55 ± 0.11, implying that the mean energy of the protons observed by Phoenix-1 is 1.3 MeV.

For comparison of the observed proton population with the earlier observation, the response functions of both instruments -- the monitor telescope on the S81-1 mission, and the EI-92 telescope on the Azur mission -- have been calculated as a function of the satellite orbital parameters and instrument geometry, both in the dipole and real magnetic field models. The undepleted source model (altitude dependent power law valid up to 450 km) predicts a population enhancement by an order of magnitude, while the depleted source model (altitude dependece turns over beyond 300 km) predicts an enhancement by ~ 1.5, both indicating a possible temporal variation of the flux. The enhanced flux indicates either a local time effect, in which case the night time flux exceeds the daytime flux, or different solar conditions which cause an increased generation of energetic neutral hydrogen, or, possibly, some of both effects.

HEA-SS-88-02

APPENDIX B

LOW ALTITUDE TRAPPPED PROTONS AT THE GEOMAGNETIC EQUATOR

by

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LOW ALTITUDE TRAPPED PROTONS AT THE GEOMAGNETIC EQUATOR

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ABSTRACT.

Geomagnetically trapped protons in the 0.6 - 9 MeV energy range were measured at latitudes near the geomagnetic equator by the Phoenix-1 experiment on board the S81-1 mission from May - November, 1982. The protons show a distribution in latitude along the line of minimum magnetic field strength with a full width at half maximum (FWHM) of ~10° but no appreciable longitudinal variation. Between 170 and 290 km, the peak proton flux shows a fifth-power altitude dependence, in contrast to previous measurements at higher altitudes, possibly demonstrating source attenuation. The efficiency of the telescope is calculated as a function of particle pitch angle and used to investigate the time dependence (1969-1982) of the intensity.

INTRODUCTION

The existence of a low altitude trapped proton population in the vicinity of the geomagnetic equator was established by Hovestadt et al. (1972) and Moritz (1972) who reported observations of protons with energies between 0.25 and

In the present paper we report measurements of the quasi-trapped proton population at ~1 MeV made in 1982 with a solid state detector telescope on the polar orbiting S81-1 satellite. In the 170-290 km altitude range, the measurements show a marked altitude dependence.

SATELLITE AND INSTRUMENTATION

Our investigation of the low altitude equatorial region was performed with the Phoenix-1 instrument on the S81-1 mission from May through November, 1982. This three axis stabilized satellite was in a low altitude (170-290 km) nearly circular polar orbit, inclination 85.5°, with a sun synchronized orbital plane from 10:30 - 22:30 local time.

The Phoenix-1 experiment included two telescopes: the Monitor telescope and the Main telescope. The Main telescope provided information for the determination of the isotopic composition of solar energetic particles and is not used for the analysis presented here. The Monitor telescope, shown schematically in Fig. 1, was a passively shielded unit with a single, 40 μ thick, fully depleted silicon detector. It had an opening angle of 75 degrees, a geometrical factor of 0.5 cm^2-sr, and was mounted on the spacecraft with the telescope axis tilted at an angle of 2.35° to the local vertical in a plane perpendicular to the orbital plane. At the dipole equator, where the orbital inclination and the tilt of the telescope axis have little effect, the Monitor received particles of pitch angle ~55° - 129°.

The Monitor telescope returned three counting rates, ML, MM, and MH, all with an accumulation time of 4.096 seconds, corresponding to three different threshold settings for the pulse height from the detector. Rate ML had a threshold value of 0.36 MeV and could be triggered by protons in the energy

Fig. 2 were computed from the counting rates and the number of readouts included in each average.

A global plot of the location of the proton flux maxima in geomagnetic coordinates is shown in the top panel of Fig. 3, in which the horizontal bars indicate the width of each longitude bin and the vertical bars indicate the FWHM of the distributions. The bottom panel of Fig. 3 shows the location of the line of minimum magnetic field strength, B_{min}, (Stassinopoulos, 1970). A comparison of the two panels of Fig. 3 shows that the measured maxima follow the B_{min} line. This profile is expected from the geometry of the source if these protons reflect the ring current proton distribution.

To find the spatial extent of this radiation, the latitude distributions from individual longitude bins were superposed peak-to-peak. The FWHM of the resulting global distribution is ~10° in latitude, consistent with the profile measured by Hovestadt et. al. (1972).

To investigate any possible longitude dependence of the flux, satellite passes were grouped in three altitude ranges, ($180 \text{ km} \leq H \leq 215 \text{ km}$), ($225 \text{ km} \leq H \leq 255 \text{ km}$), and ($255 \text{ km} < H \leq 285 \text{ km}$), based on the altitude at which the measured flux was greatest for each pass. For each range, the passes were binned in 30° longitude intervals and the average rate was computed for each interval. Plots of the average rates for the three altitude ranges are shown in Fig. 4 and indicate no statistically significant longitude dependence, as expected from the short proton lifetime at these altitudes.

Altitude Dependence

The altitude range was binned in 5 to 15 km wide intervals in order to keep comparable numbers of passes in each altitude bin. Passes with peak values occurring in a given altitude bin were superposed, and the average peak

Over the altitude range covered by the current experiment, however, the atmospheric column density varies from about 2.8 x 10^{16} cm^{-2} at 185 km to 5.3 x 10^{15} cm^{-2} at 280 km. If the average electron loss cross-section for our energy interval is taken to be about 1 x 10^{-16} cm^2 then the hydrogen flux is attenuated to 60% of its initial value by 280 km and to 6% by 185 km. A simple power law fit to six points on this attenuation curve gives an exponent of order 5, consistent with our observed altitude dependence.

This calculation is strongly dependent on the details of the actual atmospheric density and composition encountered by the neutral hydrogen in reaching a particular altitude. In addition, the neutrals created by the loss of trapped protons by electron capture at a particular altitude act as a secondary source at other altitudes. A complete model of the proton population at low altitude must consider the detailed source geometry, both primary and secondary, as well as additional loss processes such as ionization energy loss and possibly pitch angle scattering. The estimate given above does indicate, however, that the charge exchange model can explain the gross features of the observed altitude dependence when attenution of the neutral hydrogen flux is taken into account. A detailed model of the quasi-trapped proton population incorporating all of these processes is currently being developed.

Differential Energy Spectrum

Figure 6 shows a compilation of the peak differential flux measured on previous missions (Moritz, 1972; Hovestadt et al., 1972; Mizera and Blake, 1973) and by Phoenix-1 in 1982. These flux values were obtained by dividing the observed peak counting rate by the quoted geometrical factor and energy range for each instrument. Results from quiet times and during geomagnetic this is not the case. Rather, the distribution is strongly peaked toward 90° equatorial pitch angle. Thus, in order to make the correct comparison between the Phoenix-1 results and previous missions, it is necessary to evaluate the telescope efficiency as a function of particle pitch angle.

In general, the counting rate R of a particle telescope in sec^{-1} can be expressed as:

$$R(x,t_o) = \frac{1}{T} \int_{t_o}^{t_o+T} dt \int_S dS \cdot \hat{r} \int_{\Omega(p)} d\omega \int_{E_1}^{E_2} dE\ j(E,\omega,x,t) \qquad (2)$$

where j is the differential directional flux in (sec^{-1} cm^{-2} sr^{-1} MeV^{-1}), T is the sampling time, S is the area of the detector, E_1 and E_2 are the limits of the energy response of the instrument, $\Omega(p)$ is the domain of ω as a function of location p on the detector, x denotes the location in space, and $\hat{r}$ is the unit vector in the direction ω (c.f. Sullivan, 1971).

At low altitudes near the equator, the proton population can be represented by a differential directional flux which is axisymmetric about the magnetic field direction and has the form:

$$j(E,\omega,x,t) = A(x,t)\ E^{-\delta}\ \sin^q \alpha_o \qquad (3)$$

where A(x,t) is a normalization constant in units of (sec^{-1} cm^{-2} sr^{-1} $MeV^{\delta-1}$) and α_o is the equatorial pitch angle.

The response of a telescope to this highly directional flux depends strongly on the geometry of the telescope and the detector(s). We will consider the case of a telescope such as the Phoenix-1 Monitor (or the EI-92 telescope of Moritz, 1972) in which the detector(s) are planar and in which shielding and/or coincidence conditions define the aperture.

$$f(\alpha) = \frac{1}{2\pi} \int_S dS \int_{\beta_1(p,\gamma,\alpha)}^{\beta_2(p,\gamma,\alpha)} d\beta \, (\sin\gamma \sin\alpha \cos\beta + \cos\gamma \cos\alpha) \tag{7}$$

as the pitch angle dependent instrument directional efficiency or response function, then:

$$R(x,t_o) = 2\pi \, A(x,t_o) \int_{E_1}^{E_2} E^{-\delta} dE \int_o^{\pi} \sin^{q+1}\alpha \, f(\alpha) \, d\alpha \tag{8}$$

Thus, in order to derive the flux measured by different instruments from their measured counting rates, the instrument response function must be determined, and this requires knowing the direction of the detector normal relative to the local magnetic field (γ) as well as the variation of the limits of β integration as a function of α, γ and p.

The approach which we have taken to find $f(\alpha)$ is to divide the detector area into a large number of elemental subareas. For each of these subareas we determine the limits of β as a function of α and γ (in practice we replace the α integration in Eq. 8 by a sum, so we deal with discreet values of α). Using these limits we evaluate the β integral and sum over elemental areas.

The response function depends strongly on γ and thus, for a satellite such as S81-1 which is not magnetically aligned, on geomagnetic latitude. Near the equator, however, $\gamma \approx 90°$ for Phoenix-1 and the response function becomes:

$$f(\alpha) = \frac{\sin\alpha}{2\pi} \int_S dS \int_{\beta_1(p,\alpha)}^{\beta_2(p,\alpha)} \cos\beta \, d\beta \tag{9}$$

The function $f(\alpha)$ from Eq. 7 was calculated along the $B=B_{min}$ line in a real geomagnetic field model (IGRF 1975 extended to 1982) and was found to peak at an average ~92° pitch angle as compared to 90° for Eq. 9. Thus, to chosen to investigate the possible effect of a variation in pitch angle anisotropy at lower altitudes from the values previously reported. Figure 7 shows the results of these calculations for (open circles) the highest S81-1 altitude bin (277 km), and (squares) the EI-92 data (lowest altitude ~450 km). Also shown are the Phoenix-1 values extrapolated to 450 km under the assumption that (triangles) the power law altitude dependence shown in Fig. 5 holds to this altitude, and (filled circles) the simple source attenuation model discussed above can be applied.

It is clear from Fig. 7 that within the uncertainties the flux measured by Moritz (1972) at 450 km and by Phoenix-1 at 277 km are indistinguishable even if there is a small change in the pitch angle anisotropy at lower altitudes.

The comparison of the Phoenix-1 values extrapolated to 450 km to the EI-92 values suggests that the flux measured on the S81-1 mission may reflect an enhancement of the proton source compared to that measured on Azur. This is certainly the case if the power law extrapolation is valid in this altitude range. The source attenuation extrapolation also supports this conclusion although the required enhancement is much less and variations in atmospheric density/composition must be taken into account. Assuming a reduction of the neutral hydrogen flux to 80% at 277 km, due only to atmospheric attenuation and not to a change in the ring current source, then the extrapolated Phoenix-1 flux and the EI-92 measurement would be consistent for an atmospheric column density (at 277 km) of 2.2 x 10^{15} cm^{-2}, which is 42% of the estimate given earlier. Such a density reduction would not, however, give the observed altitude dependence below 277 km. Therefore, the best explanation of the difference between the EI-92 and extrapolated Phoenix-1 measurements is an enhanced neutral hydrogen flux during the S81-1 mission in 1982.

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FIGURE CAPTIONS

Figure 1. Diagram of the monitor telescope from the Phoenix-1 experiment. The cross hatched region represents the passive shielding surrounding the telescope.

Figure 2. Average ML counting rates as a function of latitude bin (1° wide) for the geomagnetic longitude range $180° \leq \phi < 185°$.

Figure 3. The location of the peak ML counting rate (top) compared to the line of minimum magnetic field strength (bottom: Stassinopoulos, 1970) in geomagnetic coordinates. The vertical bars in the top panel are the FWHM of the peaks.

Figure 4. The longitude dependence of the average peak counting rate for three altitude intervals.

Figure 5. The altitude dependence of the proton flux measured by Phoenix-1. The line is a power law in altitude (h^5) normalized to the measured flux at 185 km.

Figure 6. Differential energy spectrum of protons compared to previous measurements, for both quiet (prestorn, average) conditions and geomagnetically disturbed (poststorm) conditions. Data are: circles, Mizera and Blake (1973); triangles, Moritz (1972); inverted triangles, Hovestadt et al. (1972) and squares, this experiment.

Figure 7. Normalization constant A(h,t) in (sec^{-1} cm^{-2}-sr^{-1}-$keV^{\delta-1}$) for $\delta = 2.55$: open circles, Phoenix-1 at 277 km; squares, EI-92 (Moritz, 1972) at 450km; triangles, Phoenix-1 extrapolated to 450 km using h^5 power law; filled circles, Phoenix-1 extrapolated to 450 km using source attenuation model.

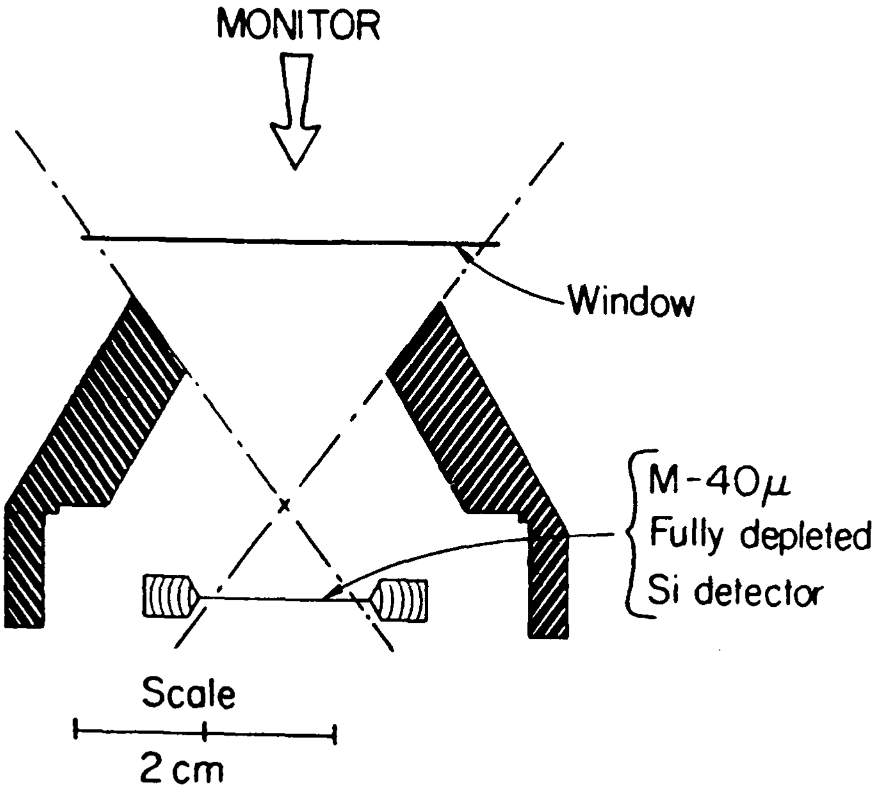
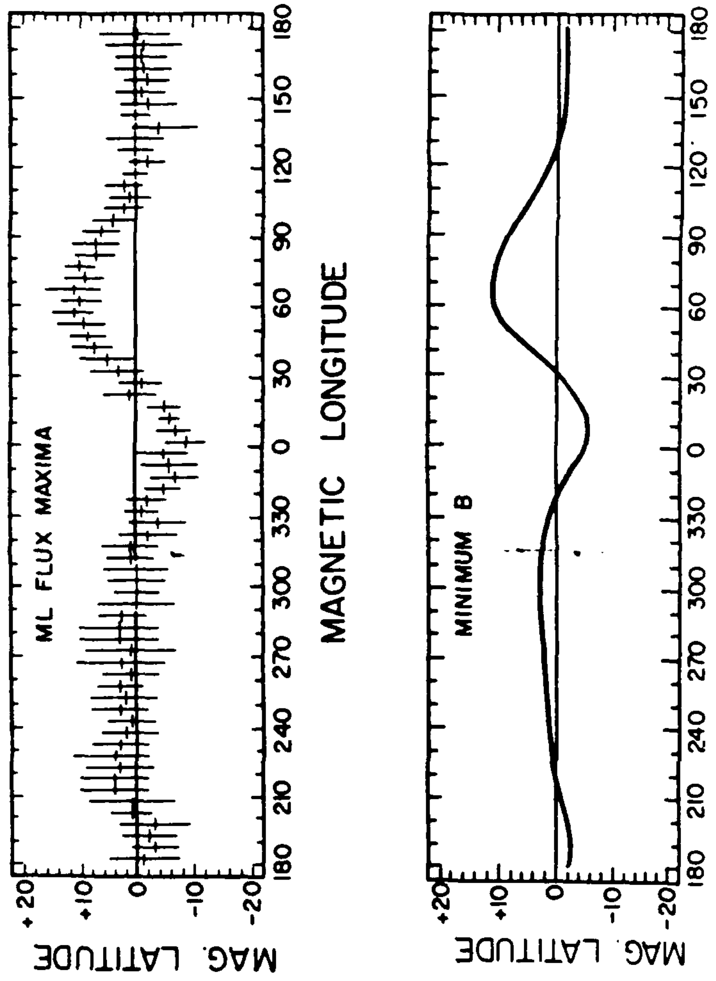


Figure 1


ML FLUX MAXIMA
MINIMUM B
MAG. LATITUDE
+20
+10
0
-10
-20
MAGNETIC LONGITUDE
180
210
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60
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120
150
180

Figure 3

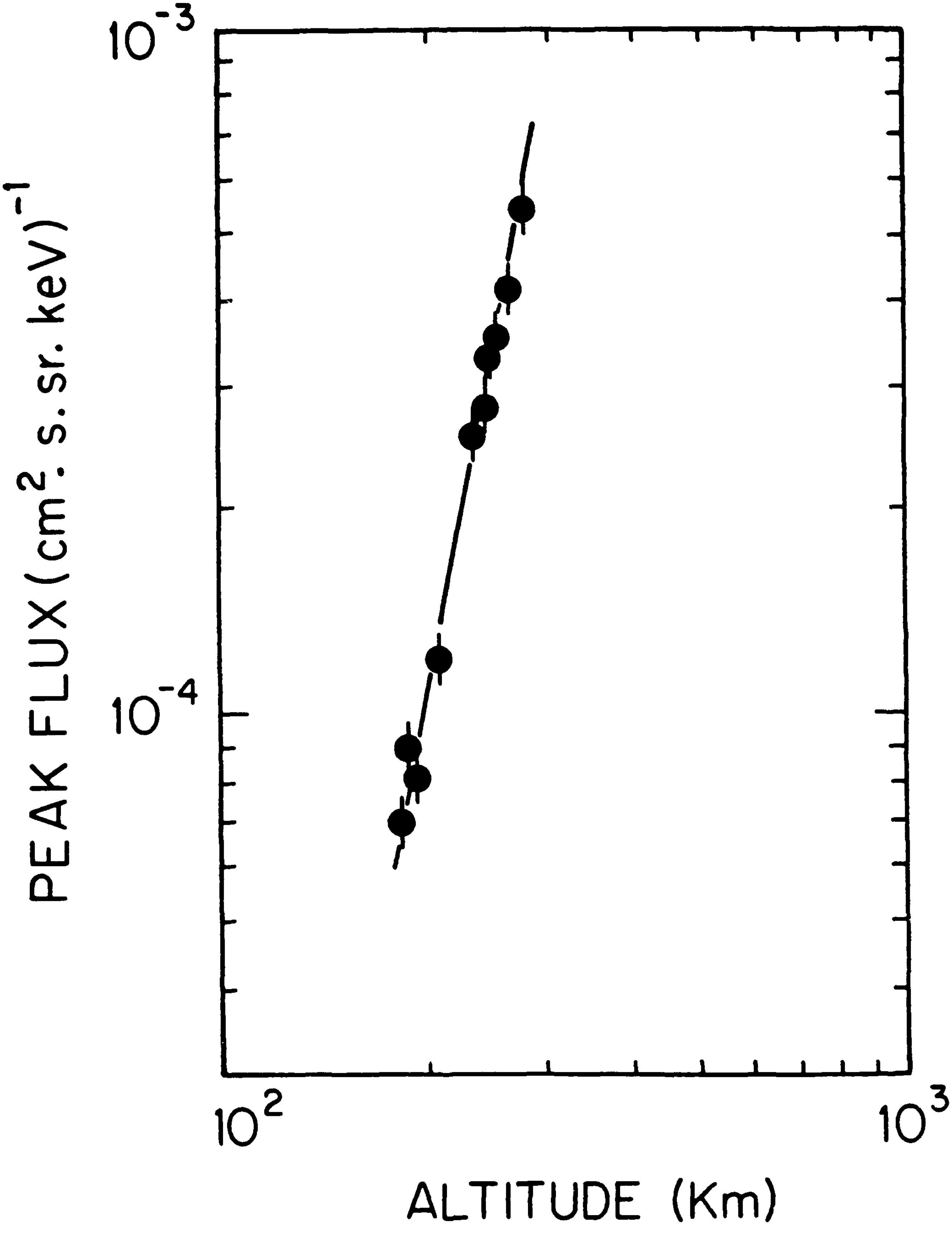

Figure 5

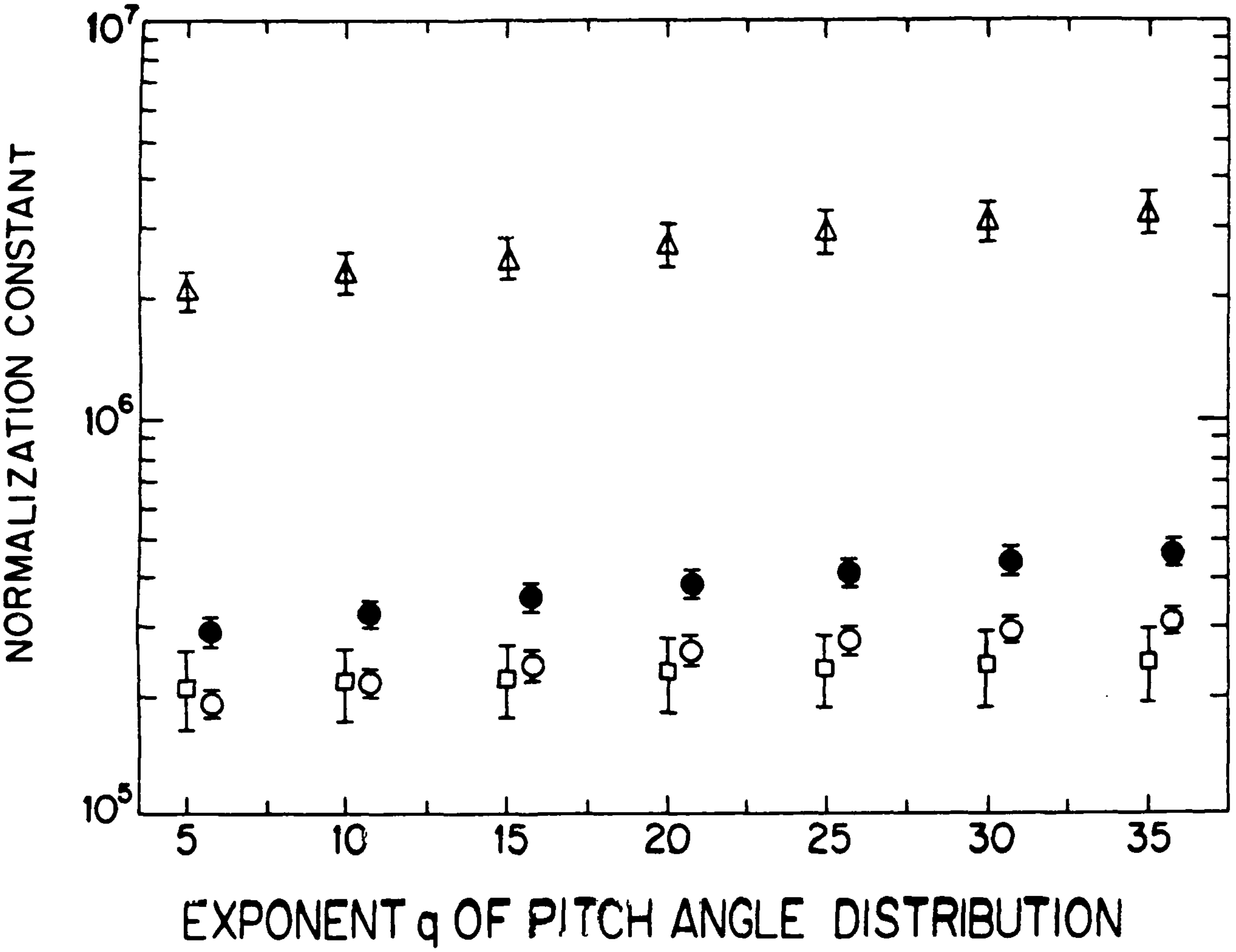
10^7
10^6
10^5
NORMALIZATION CONSTANT
5
10
15
20
25
30
35
EXPONENT q OF PITCH ANGLE DISTRIBUTION

Figure 7

APPENDIX C

U51-101 0830 POSTER

Altitude Dependence of Quasi-trapped Protons in the Equatorial Zone

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The Phoenix-1 experiment on board the S81-1 mission investigated the precipitation of protons at low altitutes (< 300 km) in the equatorial region. The satellite had an active life-time of May through November of 1982. The orbits of the satellite were polar and the orbital planes were 10:30-22:30 LT. One of the important discoveries of the observation was the fifth power altitude dependence of the quasitrapped protons in the equatorial zone. Early observation at a higher altitude range (450-1000 km) found altitude independence of proton flux.

A model has been developed to explain both the altitude dependence below ~400 km and altitude independence above ~ 450 km of the quasitrapped proton flux. It is found that, mainly, a strong depletion of the source neutrals coupled with neutralization and ionization loss of protons can account for the observed altitude gradient of proton flux.

SM31B-10 1100

S81-1 Measurements of Low-Altitude MeV Ions

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The Phoenix-1 experiment onboard the S81-1 satellite measured energetic ions at MeV energies in a sun-sychronous, polar orbit at altitudes of 170-290 km during the period May 25 through December 5, 1982. The large latitude coverage of the polar orbit allowed measurement of trapped particles near the magnetic equator and of precipitating particles at higher latitudes. A unique result of the low-altitude orbit was the first measurement of a large positive radial gradient in fluxes of equatorially trapped protons at MeV energies. This gradient arises from atmospheric attenuation of the neutral source atoms ejected by charge exchange from the ring current region and was not observed at the higher altitudes (above 400 km) of previous experiments. At high latitudes access of magnetospheric and interplanetary charged particles to magnetospheric precipitation zones and the polar cap region was sampled during quiet times and periods of high solar flare activity. Strong latitudinal structure appeared in the measured intensity ratios of different ion species at these latitudes. For flare periods the time profiles of Phoenix-1 measurements have been correlated to solar energetic particle (SEP) measurements outside the magnetosphere to study the dependence of SEP access into the magnetosphere and polar cap regions on particle species. Finally, we present measured flux limits for trapped heavy ions in the SAA (South Atlantic Anomaly) region. This work was supported by the Office of Naval Research under contract No. N00014-83-K-0365.