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INVESTIGATION OF RING CURRENT / STORM DYNAMICS: PRELIMINARY RESULTS

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This report outlines the achievements of the second year of work on data acquired by the Lockheed Ion Mass Spectrometer (IMS-LO), one of the space radiation group of instruments on the Combined Release and Radiation Effects Satellite (CRRES). The purpose of IMS-LO is to study the low energy (110eV-35keV) ion component of the current plasma. The primary data processing is almost complete, as is the construction of databases of validated low energy ion data. A preliminary version of a static model of low energy ion composition in the ring current has been constructed. This shows the average equatorial energy and pitch-angle distributions of ion fluxes organized by L and local time. Non-equatorial distributions can be obtained by adiabatic mapping. A number of events from both quiet and disturbed times have been selected for special studies. The quiet time convection electric field was estimated using the Liouville's Theorem method. Several events were studied which suggest that induced electric fields can be important in the acceleration and loss of ions.

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1. Introduction

The effort consists of three Tasks in support of one of the major goals of the Combined Release and Radiation Effects Satellite (CRRES) which is to develop a time-dependent model of the magnetospheric radiation environment that presents a hazard to the performance of spacecraft electronic systems. This effort will model the low energy ion species. H^+, O^+, He^+, and He^{++}.

There is no question regarding the need for such modeling. These heavy-ion species – especially the ones in the ring current with energies extending to 300 keV/e range [Gloeckler et al., 1985] – contribute appreciably to the degradation of spacecraft thermal control surfaces, optical coatings and filters, and other sensitive surfaces. Moreover, these ions are fundamental to the dynamic modeling of the radiation belt: (1) the low energy ions strongly effect the dynamics of the magnetosphere at distances greater than about 7 R_E in the magnetotail, and they become strongly affected by the magnetospheric dynamics inward of about 6 R_E – thereby offering a means of modeling the stormtime geoelectric and geomagnetic fields and their effects on all the trapped radiation; (2) these ions are the principal source which is eventually accelerated to become much higher energy particles in the inner radiation belt; and (3) these ions strongly affect the redistribution of inner belt ions – in species type as well as spacially and temporally – and loss through multiple charge-exchange processes and multi-species instabilities and wave-particle interactions.

For example, Wrenn [1989] has recently reported that the rate of recovery of magnetic storms is related to solar cycle. He attributed the change in recovery rate to changes in the ion composition which strongly influences the rate of charge exchange, one of the principal loss processes. Another important ring current loss process is pitch angle diffusion by ion-cyclotron waves. Kozyra et al. [1984] showed that the generation of these waves by the interaction of plasmaspheric plasmas with the ring current is strongly dependent on the composition, densities and temperatures of the interacting plasmas.

The development of a comprehensive and accurate model of the ring current and radiation belts requires a thorough understanding of ring current dynamics, which in turn requires detailed knowledge of the particle source contributions, transport phenomena, energization processes, and scattering and loss mechanisms.

The low energy plasma plays a major role in the dynamics of the inner magnetosphere. A critical component of this plasma is the composition of the ion component. These low energy ions, which originate in the solar wind and the ionosphere serve as a source for the ring current and radiation belts. The principle tracers of plasma origin in the magnetosphere are measurements of ion flux ratios and charge state density ratios.

Because of limitations in available satellite instrumentation, measurement of ion composition in the ring current and radiation belts has begun only fairly recently. The comprehensive data required for an environmental model were not available before CRRES [Williams, 1987] and earlier efforts at modeling the behavior of the low energy ions were imperfect, as evidenced by the number of unanswered question that they raised [Delcourt et al., 1989]. A principal objective of this experiment is to provide a database suitable for modeling efforts.

Task 1 is to process the raw Lockheed ONR-307-8 Ion Mass Spectrometer (IMS) data from the agency tapes to provide the basic data base of quality controlled calibrated in situ measurements of ion composition upon which the scientific studies are based. The other two Tasks make use of this database. Task 2 is to construct an empirical, statistical model of the plasma composition and distribution function as a function of magnetospheric location for quiet and disturbed magnetospheric conditions. During magnetic storms the model is to be organized by storm phase in order to reflect the development of the ring current plasma. Task 3 is to investigate aspects of magnetospheric dynamics by making a specialized study of magnetic storm events selected from the Lockheed IMS database. For each event it will: 1) Determine time dependent models of geomagnetic and geoelectric fields consistent with the transport of the measured ions between observation points on successive legs of the CRRES orbit. 2) The transport of ions from typical sources of up-flowing ionospheric ions will be computed and compared with the CRRES in situ measurements of magnetospheric ions. The ion transport will also be compared with possible storm predictors.

We will make use of observations of ion species, principally H^+, O^+, He^{++} and He^+, in the energy range 100 eV/e to about 100 keV/e. These ions become strongly affected by the magnetospheric dynamics thereby offering a means of modeling the stormtime geoelectric and geomagnetic fields and their effects on all the trapped radiation. They are the principal source of ions which are eventually accelerated to become much higher energy particles in the inner radiation belt and they strongly affect the redistribution and loss of inner belt ions through multiple charge-exchange processes and multi-species instabilities and wave-particle interactions.

To achieve these objectives ONR 307-8-1,2 (IMS-LO) is designed to measure plasmas that are the sources of radiation belt particles, and to provide data on the origin and acceleration of these plasmas. To achieve these objectives IMS-LO measures energy and mass spectra covering the ranges of E/q from 0.1 to 35 keV/e and M/q from 1 to 32 AMU/e with good coverage of pitch angles throughout the orbit.

2. Experiment Status and Operations

CRRES was successfully launched on July 25 1990 and initialization operations of the ONR 307-8 instruments, which provide data that are used for this contract, began shortly thereafter. Both instruments continued to work perfectly until contact with the satellite was lost on October 12 1991. Almost the only other non-scheduled loss of data occured as a result of the loss of synchronization caused by the dropouts in the vehicle clock. These caused the instruments to lose synchronization but they were able to recover within a couple of minutes.

The failure of battery 2, on December 22 1990 led to duty cycling of the ONR 307-8 instruments during eclipses in order to conserve the limited battery power. Similar duty cycling of the fluxgate magnetometer resulted in loss of pitch-angle information on occasions.

Data analysis has been proceding steadily and all the scientists took part in a CRRES science working group meeting which was held during the American Geophysical Union's Fall Meeting in San Fransisco in December 1991. Three papers were presented during the American Geophysical Union Fall Meeting: 'A Preliminary Statistical Model of Low Energy (110eV-35keV) Ring Current Ions', by H. L. Collin, J. M. Quinn, and J. B. Cladis, 'CRRES Energetic Particles and Ion Composition Measurements During the March 1991 Storm', by R. M. Robinson, H. L. Collin, H. D. Voss, R. R. Vondrak, R. W. Nightingale and W. L. Imhof, and 'Observations of a Quiet Magnetosphere and Polar Cap by CRRES, DE-1, and DMSP', by A. M. Persoon, R. R. Anderson, W. K. Peterson, H. L. Collin, R. M. Robinson, H. J. Singer, K. Kerns, D. A. Hardy, W. F. Denig, N. C. Maynard, J. R. Wygant, J. A. Slavin, C. J. Pollock, and T. E. Moore. Abstracts of these papers are in Appendix 1.

3. Progress and Current Activities

3.1 Generation of Lockheed IMS Database

3.1.1 Database Production

A description of the CRRES data processing sequence is included in the the first Scientific Report on this contract, Collin et al. [1991]. The data processing produces two principal data products, the High Resolution Database which is used as the basis of all other analysis and the Survey Plot Library of full orbit survey plots for all orbits. Special event studies and dynamic modeling which need maximum resolution and flexability make direct use of the High Resolution Database while the Survey Plot Library forms an important intermediate data product which displays IMS-LO data in a form which is compact and also sufficiently detailed to enable periods of scientific interest to be selected for specialized study under Task 3 or for other purposes. The survey plots are also an important tool for the assessment of instrument performance.

Processing of agency tapes has been completed and all tapes recieved to date have been processed. Reprocessing those tapes where problems had been encountered has also been completed. Any further agency tape processing is expected to consist only of reprocessing data where unexpected problems are encountered. Production of the Summary Plot Library has continued.

3.1.2 IMS-LO Calibration

We have made use of IMS-LO data alone to make a relative alignment of the calibration of the three heads which make up each of the ONR 307-8-1,2 instruments and between the two instruments ONR 307-8-1 and ONR 307-8-2. Adjustments did not exceed 10% between any pair of heads.

A number of data intervals were selected for cross calibration with the LEPA instrument. Intervals were required to have high ion fluxes which consisted almost entirely of H^+, which filled the energy range of the instruments and which were free of substantial spacial and temporal variations, to have very low background, and to have good pitch-angle coverage. IMS-LO data from several of these intervals have been compared with those from the LEPA instrument. This comparison proved very encouraging and helped to refine the alignment of the three heads making up each of the ONR 307-8-1,2 instruments.

The fluxes of H^+ measured by IMS-LO and LEPA during several hours on orbits 482 and 561 is shown in Figure 1. These are averages over the pitch-angle range 60° to 120°. The determination of the IMS-LO fluxes made use of the revised inter-head alignment. The measurements by the two instruments correspond quite closely.

Figure 2 shows the energy dependent mismatch between IMS-LO and LEPA as the ratio of the flux measured by IMS-LO to that measured by LEPA. It uses the same data that is shown in Figure 1. Comparisons of fluxes were made at both IMS-LO energy steps and at LEPA energy steps. In each case one of the fluxes was measured directly by one instrument while the other flux was interpolated from measurements made at nearby energies by the other instrument. The interpolated values are shown in Figure 1 as small dots. The mismatch beteen the instruments was less than 30% over most of the energy range. The vertical dashed lines indicate the boundaries between the three heads which make up each of the IMS-LO instruments. We are investigating the source of this residual mismatch and hope to be able to account for much of it.

3.2 Empirical model of ring-current ion composition

3.2.1 Model Definition

The preliminary static version of the Empirical Model of Low Energy Ring Current Ion Composition consists of a set of average equatorial energy and pitch-angle distributions of fluxes of H^+ and O^+. The distributions are binned by energy and pitch-angle with fifteen energy bins covering the whole of the IMS-LO energy range, 110 eV to 35 keV, and nine, 10°, pitch angle bins which cover the full range of 0° to 180°, assuming pitch-angle symmetry. The model contains a $H^+$and O^+distribution for each of a number of spacial regions. These regions are defined by dividing the equatorial plane into six local time sections each four hours in width and into six radial sections between L = 2.5 R_E and L = 8.5 R_E each 1.0 R_E in width. Associated with each flux value is an estimate of its statistical uncertainty and for developmental purposes a measure of the background rate and number of data samples used to determine that flux value. The model can be used to determine the average ion distributions away from the equatororial plane, assuming the absence of parallel electric fields and wave-particle interactions, by mapping the equatorial distributions down the field lines to the location of interest.

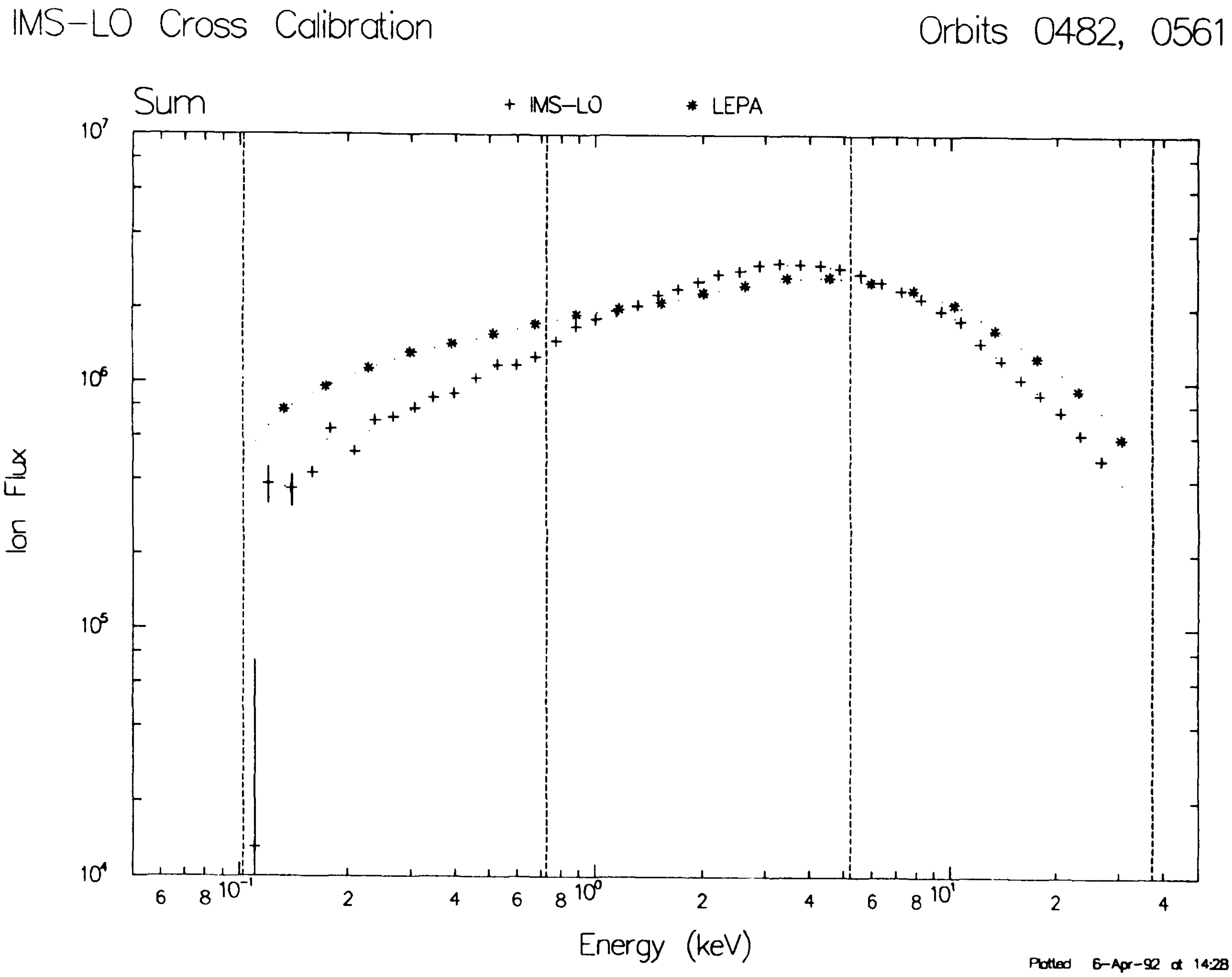

Figure 1. The fluxes of H^+ measured by IMS-LO and LEPA on parts of orbits 482 and 561.

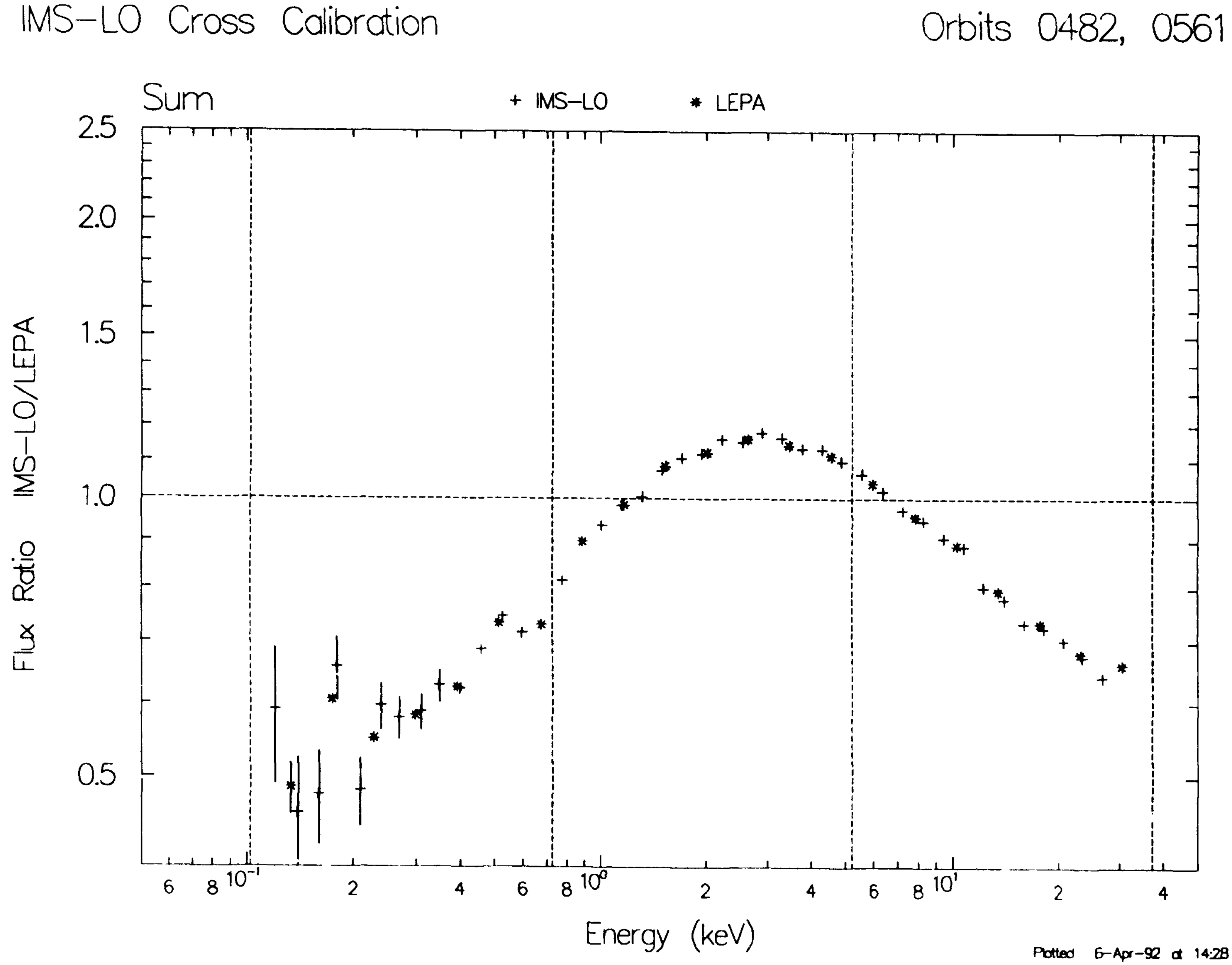

Figure 2. The mismatch between IMS-LO and LEPA from the data of Figure 1.

3.2.2 Construction of the Model

3.2.2.1 Summary Database

Increased understanding of the behaviour of the storm-time magnetosphere is likely to produce improvements in the models used to describe the geomagnetic field and so to require changes in the mapping of ion trajectories between CRRES and the equator and thus revision of the empirical model of ring-current ion composition. In order to avoid the computational burden of having to generate the model from the High Resolution Database each time a revision is needed, an intermediate database is being constructed. This IMS-LO Summary Database is a compact, partially processed database consisting of averages, over 262 seconds, of IMS-LO ion and electron data sorted by energy and pitch angle. Data from both IMS-LO-1 and IMS-LO-2 are combined. Supporting data include time, background count rate, status information, measured magnetic field and ephemeris information. The ion and electron data are recorded as count rates in order to make the database independent of revisions to the instrument calibration which cross calibration studies are expected to indicate. Calibrations are applied to the count rates when the database is accessed. This Summary Database is also suitable for rapid retrieval of energy spectra, pitch angle distibutions or survey plots when the full resolution is not required, and as a basis for statistical studies.

The IMS-LO Summary Database now contains over 80% of the data acquired from CRRES. Some of the remainder will be added later, but a substantial section, from orbit 365 to orbit 410, has no science magnetometer data and so no pitch-angle information. In principle, the engineering magnetometer could be used to provide pitch-angle, but its sensitivity is inadequate over most of CRRES's orbit.

3.2.2.2 Assembling the Model from the Summary Database

The model's average equatorial distributions are constructed by accumulating and averaging equatorial distributions from many orbits. There the data are binned by their energy and equatorial pitch-angle and sorted into ranges of L and local time. Equatorial ion flux distributions are derived from the summary database ion measurements which were taken along the CRRES orbit. In the absence of substantial parallel electric fields and wave-particle interactions, these distributions are mapped adiabaticly from the satellite location to the equatorial plane, which is taken to be the minimum B surface. The mapping makes use of the modeled values of the local magnetic field strength and the minimum field on the same field line which are provided in the CRRES ephemeris files.

A problem which occurs when accumulating data in this way is how to minimize accumulated errors while avoiding the introduction of sampling biases. Errors arise primarily from background corrections and from the statistical nature of particle counting which results in the higher fluxes, since IMS-LO's sensitivity is energy dependent, the higher energies having relatively low errors. In consequence if data which has a high relative error is excluded there will be a tendency to include only high flux events, especially at low energies. Background also contributes to the error since it is a particle counting phenomenon. The background countrate is independent of IMS-LO mass and energy settings so it is also relatively more important at low fluxes and at low energies. The background correction is performed by subtracting the average background countrate from the raw ion countrate. This is successful over most of the orbit.

The background is produced by high energy radiation belt particles which penetrate the instrument structure. It is most pronounced in the inner belt. These particles are often strongly anisotropic, and since the IMS-LO's radiation sheilding, which includes its own structure and that of the satellite, is also anisotropic, the background countrate can have a noticable spin modulation. In consequence subtracting the average countrate is not always an adequate correction since the spin modulated component is not removed. In principle it would be possible to measure the spin modulation of the background as well as its average rate, but the irregular pattern of background sampling together with the very rapid changes in background as CRRES passes through the inner radiation belt make this impractical. The radiation belt particle intensity variations are related to magnetic activity and in consequence rejection of data on the basis of the background level can be expected to introduce an activity related bias. On the other hand, admitting data with a spin dependent residual background component would introduce an unreal feature into the model.

We have taken the approach of not rejecting any data on the basis of its error or background, but instead to limit the range of the model to $L > 2.5\ R_E$ where the background is generally less intense and to accumulate the errors and the background in the same way as the ion fluxes. This allows us to later assess the validity of the average equatorial fluxes at any energy and pitch-angle by comparing them with their corresponding average background and error and rejecting those which are not larger by a substantial margin and also allows different margins to be used for errors and backgrounds. The effectiveness of this approach is still being assessed, but it appears to be reasonably successful.

Another common cause of dubious ion data is spacecraft charging. Under certain conditions spacecraft can become charged relative to the surrounding plasma, occasionally to several kilovolts. Ions would be accelerated as they approached the negatively charged spacecraft and their measured energy would be higher than it would have been had the spacecraft not been charged. This can cause serious distortion of the ion spectra if CRRES is charged to a potential which is a substantial fraction of the original ion energy. The effect of charging is easily seen in the survey plots as an intense monoenergetic peak in the ions, which is the result of the spacecraft potential accelerating ambient thermal io plasma into the energy range of IMS-LO, and by the simultaneous reduction of low energy electrons which are unable to reach CRRES. The survey plots were scanned to identify charging intervals which were then excluded from the data used for the model.

3.2.3 The Static Model

As described in 3.2.1, the static model is a set of average equatorial energy pitch-angle distributions of fluxes of H^+ and O^+, binned by energy and pitch-angle, for each of a number of ranges of local time and L. Associated with each flux value is an estimate of its error, the background rate and the number of data samples which contributed to it.

Figure 3 is a condensed display of the static model. The layout is based on that of the IMS-LO ion survey plots. The top panel contains energy spectra, averaged over pitch-angle, of H^+ and O^+ and the center and bottom panels contain H^+ and O^+ pitch-angle distributions, averaged over bands of energy. These panels are divided horizontally by bold black vertical lines into six broad strips which correspond to six ranges of L. The leftmost of the broad strips, for example, corresponds to $2.5 < L < 3.5$. Each of the broad strips is itself divided into six narrow strips each of which corresponds to a local time range. For example, the leftmost narrow strip, in each broader strip, corresponds to 00:00 to 04:00 hours local time. Each of the narrow strips displays the average equatorial energy spectra and pitch-angle distributions for its own local time and L range. Thus the energy spectra in the top panel (or the pitch-angle distributions in the lower panels) can be regarded as being the energy spectra (or pitch-angle distributions) which would be obtained on each of a sequence of circular equatorial orbits with radii of 3, 4, 5, 6, and 7 R_E.

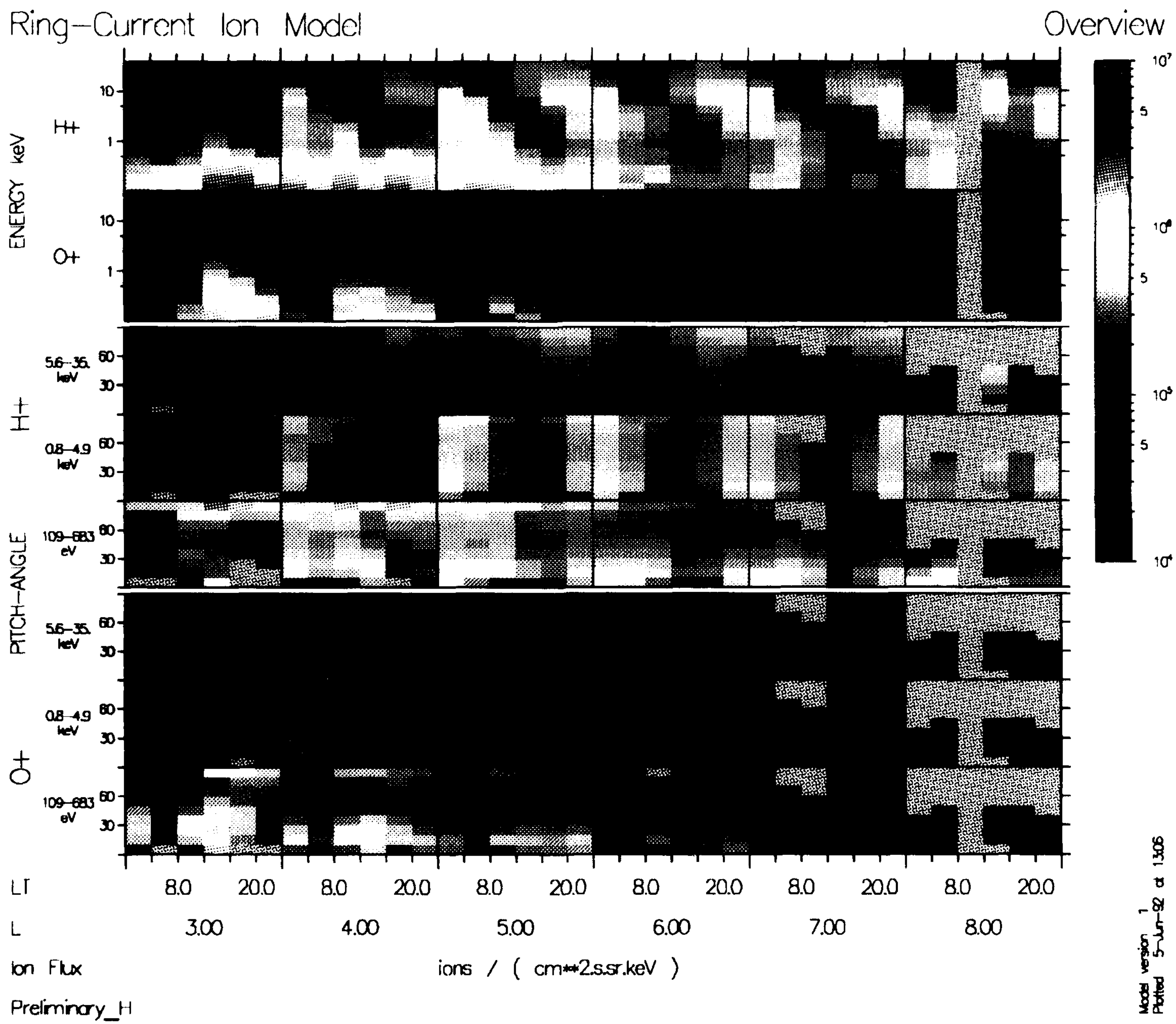

Figure 3. A condensed display of the model.

The errors, estimated from counting stastics, associated with the model flux distributions of Figure 3 are shown, in the same format, in Figure 4. The grey areas in Figures 3 and 4 indicate regions where insufficient good quality data was acquired. Some aspects of data quality were discussed in 3.2.2.2. An additional important cause of the empty grey regions and enhanced errors is inadequate sampling. This is the result of several factors: (1) Because CRRES did not complete a full local time precession there is little apogee data between 8 and 12 local time; (2) The region beyond $L = 7.5 R_E$ was not directly sampled so ions trapped there near 90° could not be measured and only those more nearly field aligned could be remotely sensed from lower L's; (3) At all L's equatorial 90° ions could only be measured when CRRES crossed the equator and field aligned 0° ions only when CRRES's spin axis and the magnetic field direction were so aligned that IMS-LO viewed directly along the field line; (4) CRRES spends little time near perigee so low L's are not as well sampled as high L's.

While Figure 3 gives a compact overview of the ion flux variations with local time and L it is hard to see details of the flux distributions at a particular location. Figure 5 shows detailed flux distributions at $4.5 < L < 5.5 R_E$. The upper two plots are of H^+ and the lower two are of O^+. The left hand plots are near dawn, local times between 4 and 8 hours, and the right hand plots are near dusk, local times between 16 and 20 hours. The fluxes from the original fifteen energy by nine pitch-angle bins have been smoothed using a linear interpolation algorithm in order to deemphasize the bin boundaries.

This static model represents the average magnetosphere during the period of CRRES operation. This was a magnetically active time, near solar maximum, and so this model can not be expected to be entirely representative of other time periods. Nor, since it incorporates data from both magnetically quiet and stormy times, does it usually provide an accurate description of the magnetospheric ions at any specific time. However, it does provide a reasonable representation of what is observed at a moderately active time. Figure 6 is a survey plot of IMS-LO data taken on orbit 723, shortly after a small storm whose minimum Dst was -103nT. The top four panels show energy spectrograms of H^+, O^+, He^+, and He^{++} and the lower six panels show pitch-angle distributions of H^+ and O^+ in three broad energy bands. For comparison, Figure 7 shows a similar survey plot for the same orbit using the model instead of observations. Fluxes from the model local time and L ranges were interpolated to the local times and L's along the orbit and mapped from the equator to the orbit's latitude. Figure 7 is in the same format as Figure 6 except that it

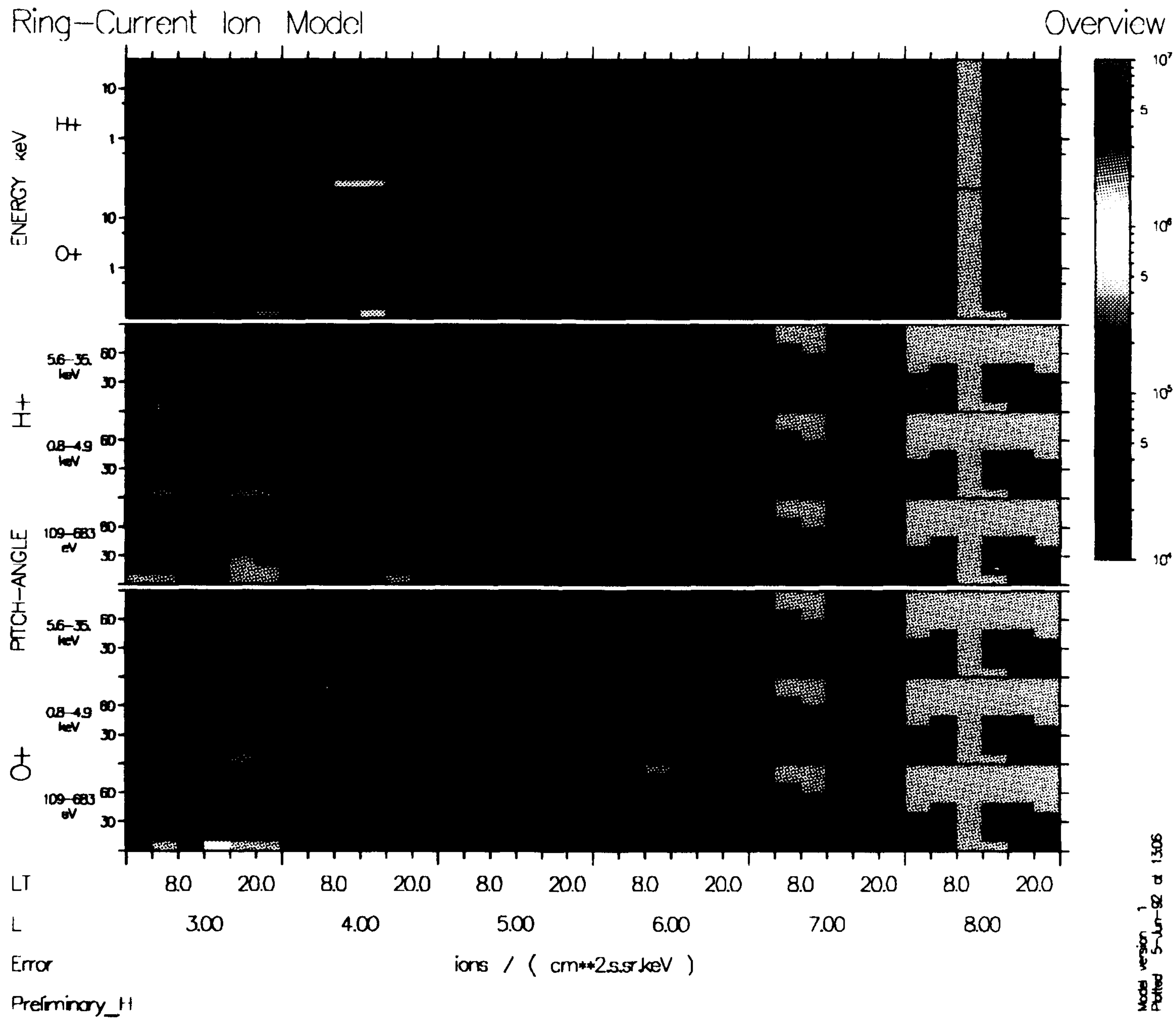

Figure 4. Estimated errors of the model fluxes.

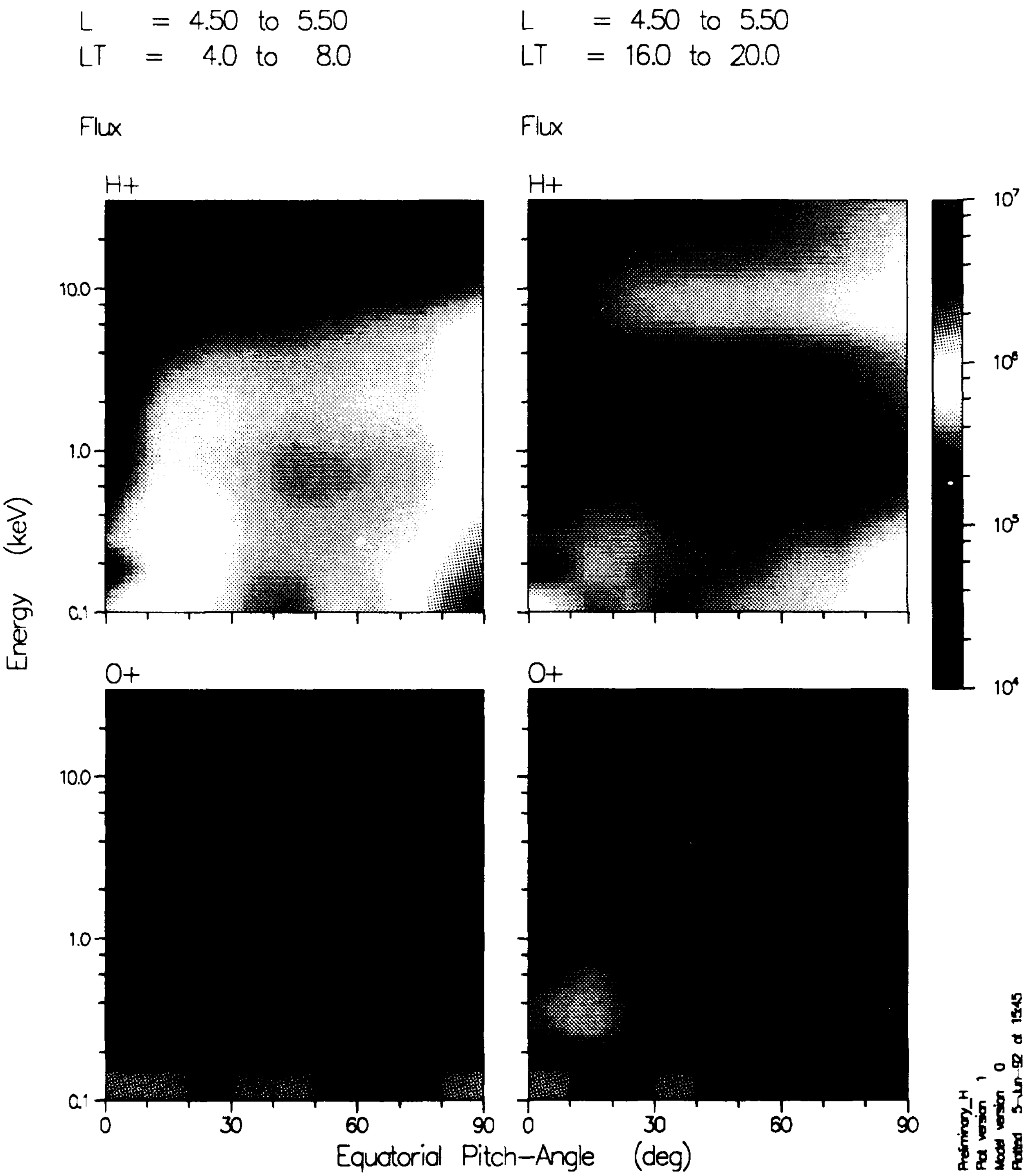

Figure 5. Morning and evening H^+ and O^+ flux distributions from the static model.

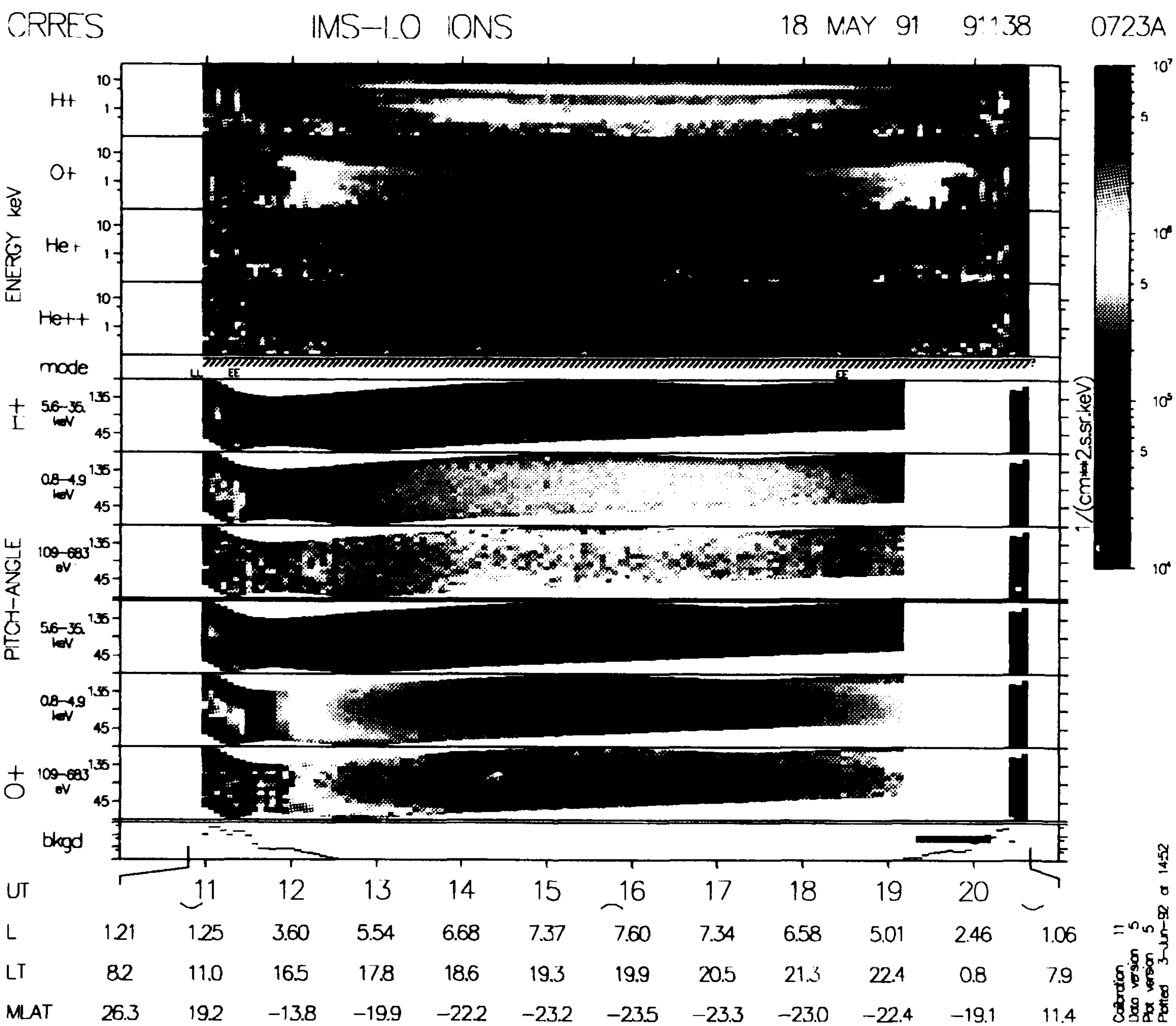

Figure 6. A survey plot of ion energy spectra and pitch-angle distributions measured on orbit 723.

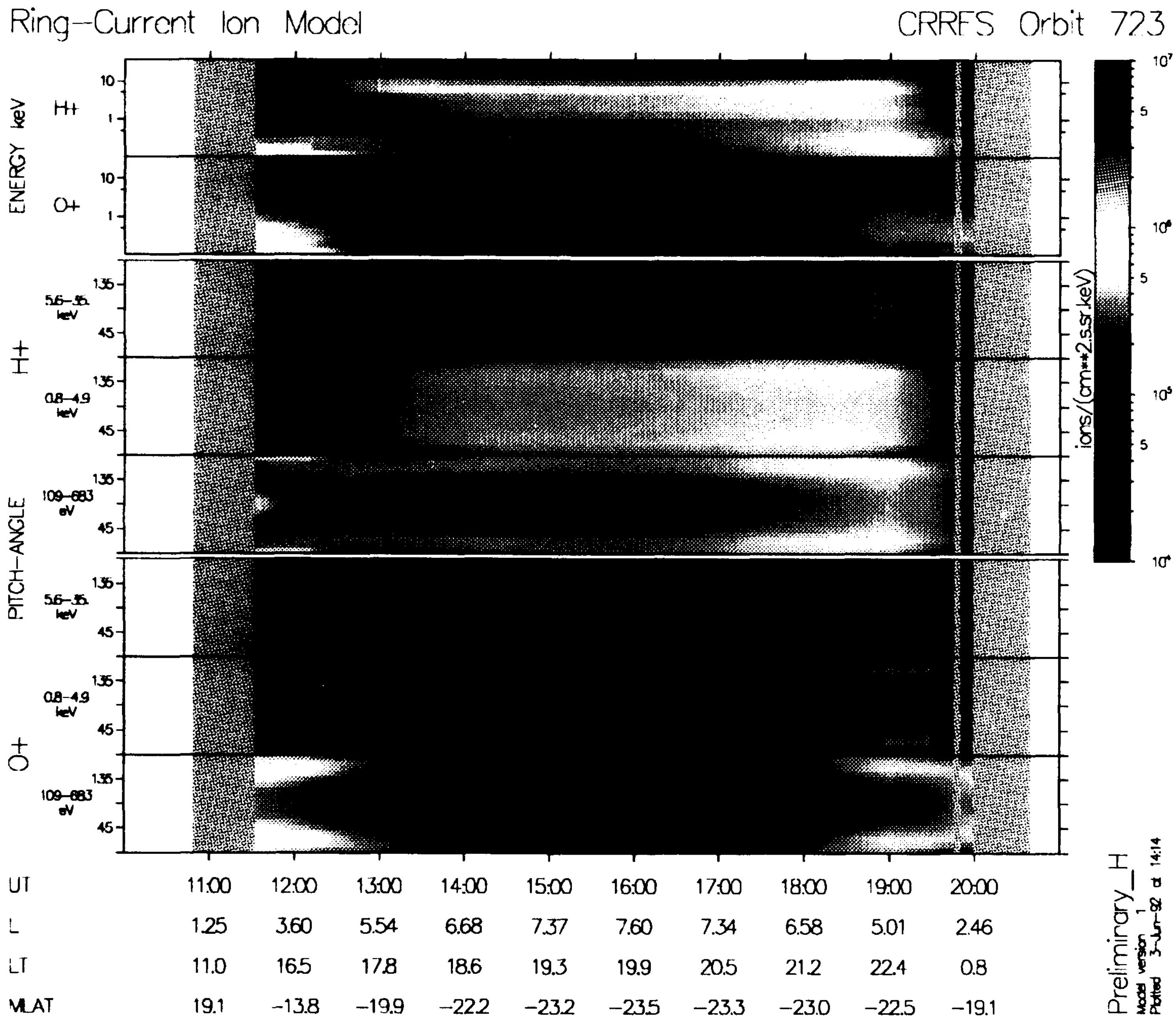

Figure 7. A survey plot for orbit 723 constructed from the static ion model.

does not include He^{+} and He^{++} energy spectrograms and its pitch-angle coverage is not limited by the satellite orientation or the operation of the magnetometer during the eclipse towards the end of the orbit. The modeled survey plot has a much smoother appearance, in part because of the interpolation, and also because the stocastic effects of counting statistics are not replicated. While the two spectrograms show a number of differences, mainly in the low energy H^{+}, the correspondence is generally quite close with the model energy spectra and pitch-angle distributions varying along the orbit in the same way and at closely similar flux levels as the observations. This ability to match the model, which is in effect an average of all orbits, with an individual orbit implies that the ion population of the magnetosphere is sufficiently reproducible that there is a good probability that a magnetic activity dependent model will be able to predict the distribution of the low energy ions with considerable confidence.

3.3 Magnetospheric Dynamics Event Studies

Under Task 3 the following progress was made on studies of particular events: (1) the convection electric field in the nightside magnetosphere during a quiet time was estimated using the Liouville's Theorem method, (2) further evidence was found that induced electric fields along the magnetic field are responsible for the occurrence of "clipped-wing butterfly" pitch-angle distributions of ions that persist for several hours, and (3) a moderate magnetic storm (1 February 1991) was selected for a detailed study of various dynamic processes and conditions that may be inferred from the behavior of the IMS-LO ions. These topics are described below.

3.3.1 Convection Electric Field

The Liouville's Theorem method was applied to estimate the convection electric field in the nightside magnetosphere during quiet times using IMS-LO data alone. The data were obtained on orbit 458, January 29-30, 1991, when apogee was near midnight.

As described previously, the Volland potential

$$\Psi = AR^{\nu} sin(\phi + \delta)$$

in the minimum-B plane is used to generate the trial electric fields. The coefficient A, exponent ν and phase-angle δ are the variable parameters. Here, ϕ is the magnetic local time (MLT) in degrees measured from magnetic local midnight. Numerous trajectories of ions that generally drift eastward were computed for various values of A in the range 0.121 to 0.815 kV/R_E^2, keeping ν and δ constant at their most probable values for quiet times at high L values, viz., $\nu = 2$ and $\delta = 0$. Near apogee success was achieved using A = 0.334 kV/R_E^2: The drift trajectory of an ion with an initial energy of 2.5 keV crossed the inbound CRRES orbit at two points at which the measured phase-space densities of the ions were approximately the same. The initial point (B, L, MLT) was at (136.8 nT, 6.23, 16.8°) at 4.08 hr UT, January 30, and the second point was at (203.8, 5.40, 26.9°) at 4.92 hr UT. The three-hourly Kp index was 2- from 21 to 24 hr on January 29, 0− from 00 to 03 hr and 0− from 03 to 06 hr on January 30. Several more connected trajectories were found that crossed the CRRES orbit at lower L values. The analysis based on these trajectories has not yet been completed because the charge-exchange rate was high.

Figure 8 shows, in L,T coordinates, the drift paths of ions of initial energies 2.5 keV (solid line) and 3.5 keV (dashed line) and the CRRES orbit (dot-dash line). The time T is measured from the initial point at L = 6.23. At T = 1 hr the energies of the 2.5 and 3.5 keV ions increased to 4.1 and 5.8 keV, respectively. Using the same coding of the lines, Figure 9 shows the ion drift paths and the CRRES orbit in MLT,T coordinates. Note in Figure 8 that the L values of the 2.5 and 3.5 keV ions versus time are nearly identical, but that the MLT values of these ions (Figure 9) increasingly diverge beyond MLT = 21.5°; along the MLT coordinate the drift path of the 2.5 keV ion remaines close to the CRRES orbit. In Figure 10 the solid line shows the ratio of the directional flux at $\alpha = 90°$ divided by energy $E = 2.5(B/B_0)$ versus L, and the broken lines show the standard deviation of this ratio. Therefore, this ratio is proportional to the phase-space density of the ions which, according to Liouville's Theorem is constant along a charged-particle trajectory. The horizontal line drawn through the intial point shows that indeed the phase-space density is nearly same — within the accuracy of the measurements — at the two points at which the ion crosses the orbit. At the equatorial crossing point of the field line drawn from the initial point, the electric field components in solar-magnetospheric coordinates (GSM) inferred from this analysis are $E_{X_{GSM}} = 0.090$ mV/m and $E_{Y_{GSM}} = 0.354$ mV/m.

Because of the high charge-exchange loss rate of the ions that crossed the orbit legs at the lower L values, much more computer running time will be required to complete the analysis for those trajectories. The analysis will be completed, however, because of the importance of testing the consistency of method and of estimating the variation of the

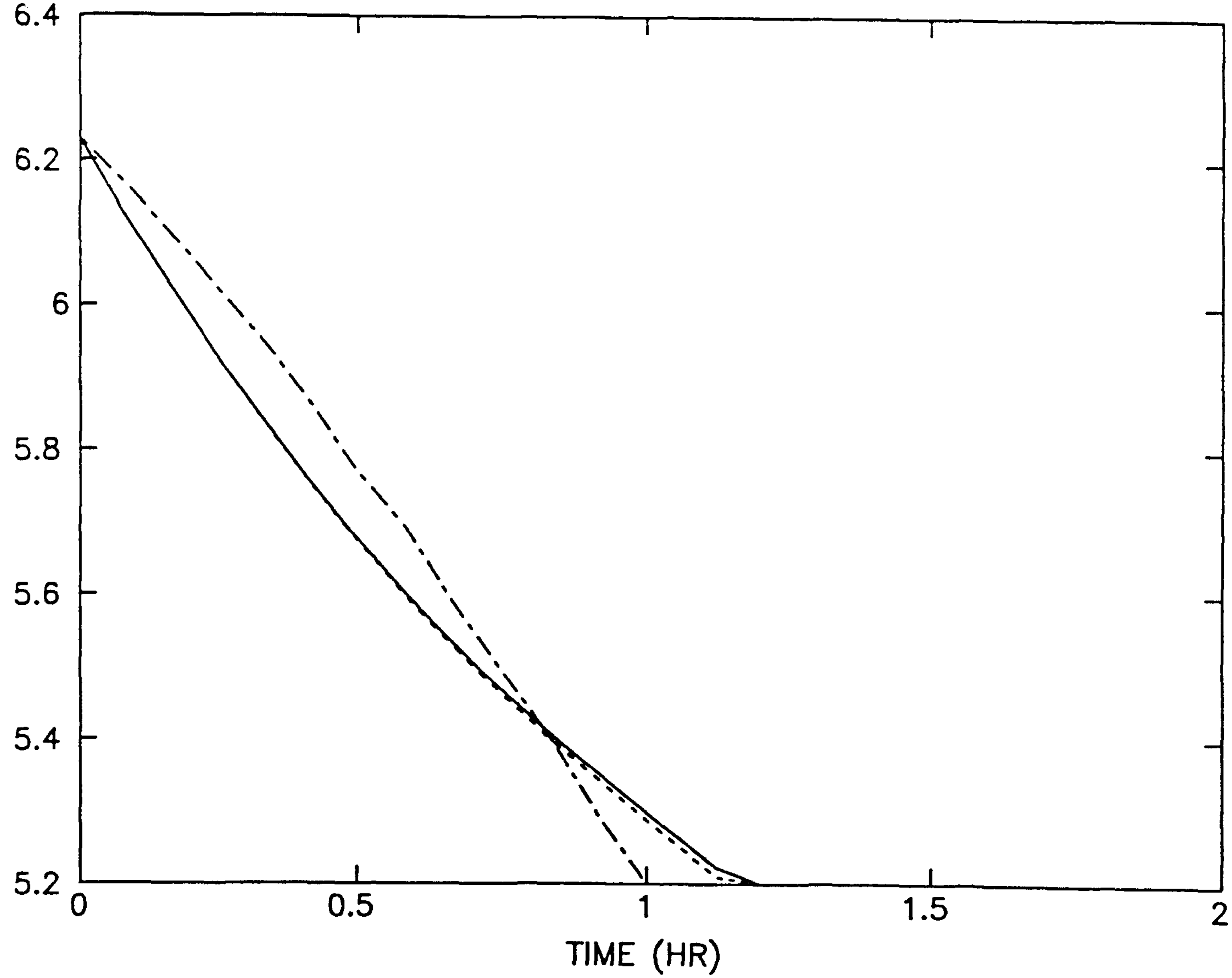

Figure 8. Drift-paths of ions of initial energies of 2.5 keV (solid line) and 3.5 keV (broken line) and CRRES orbit (dot-dash line) in L,T coordinates. (Orbit number = 0458A, ion pitch angle = 90°, A = 0.334 kV/R_E^2)

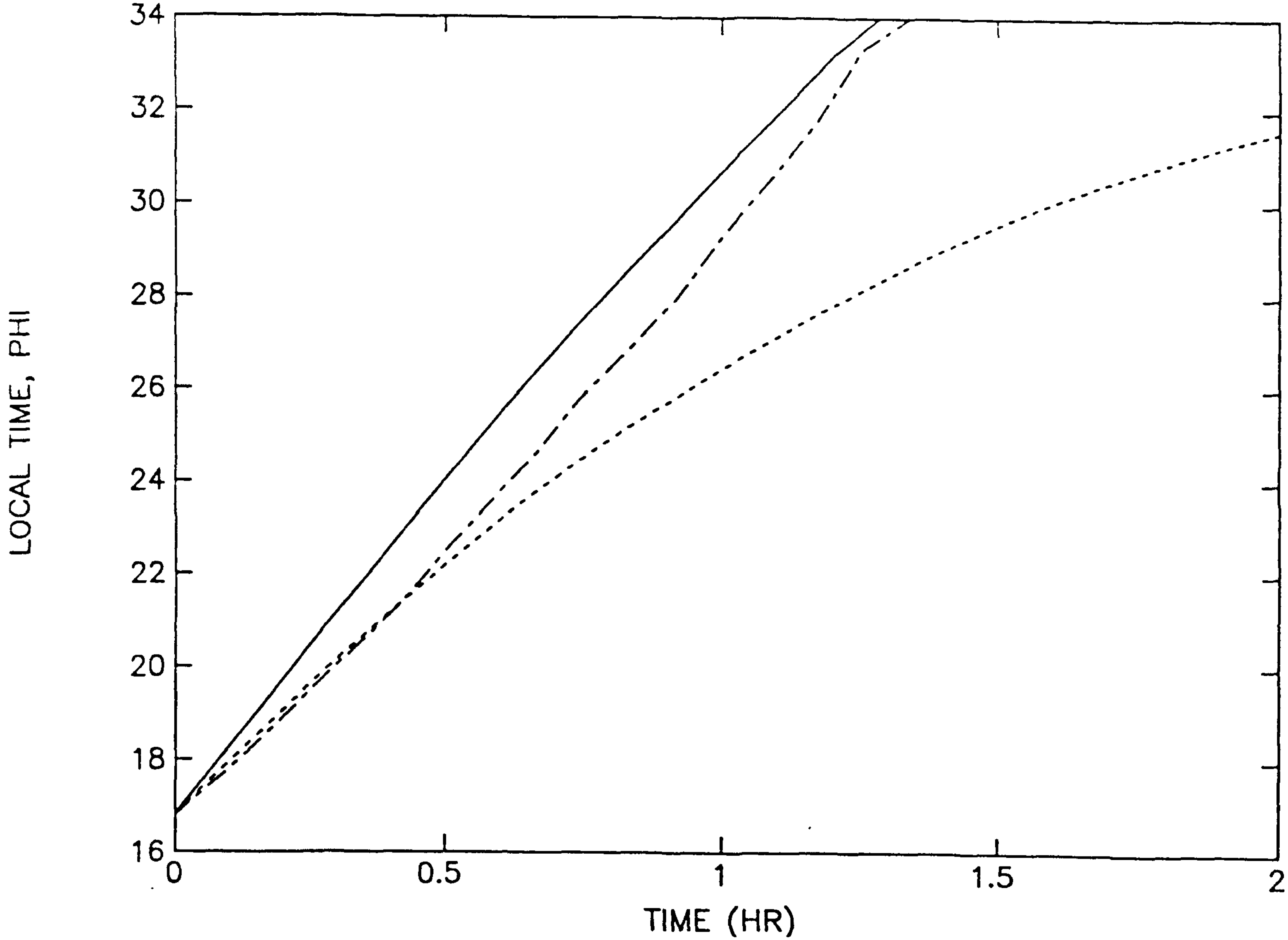

Figure 9. Drift-paths of ions of initial energies of 2.5 keV (solid line) and 3.5 keV (broken line) and CRRES orbit (dot-dash line) in MLT,T coordinates. (Orbit number = 0458A, ion pitch angle = 90°, A = 0.334 kV/R_E^2)

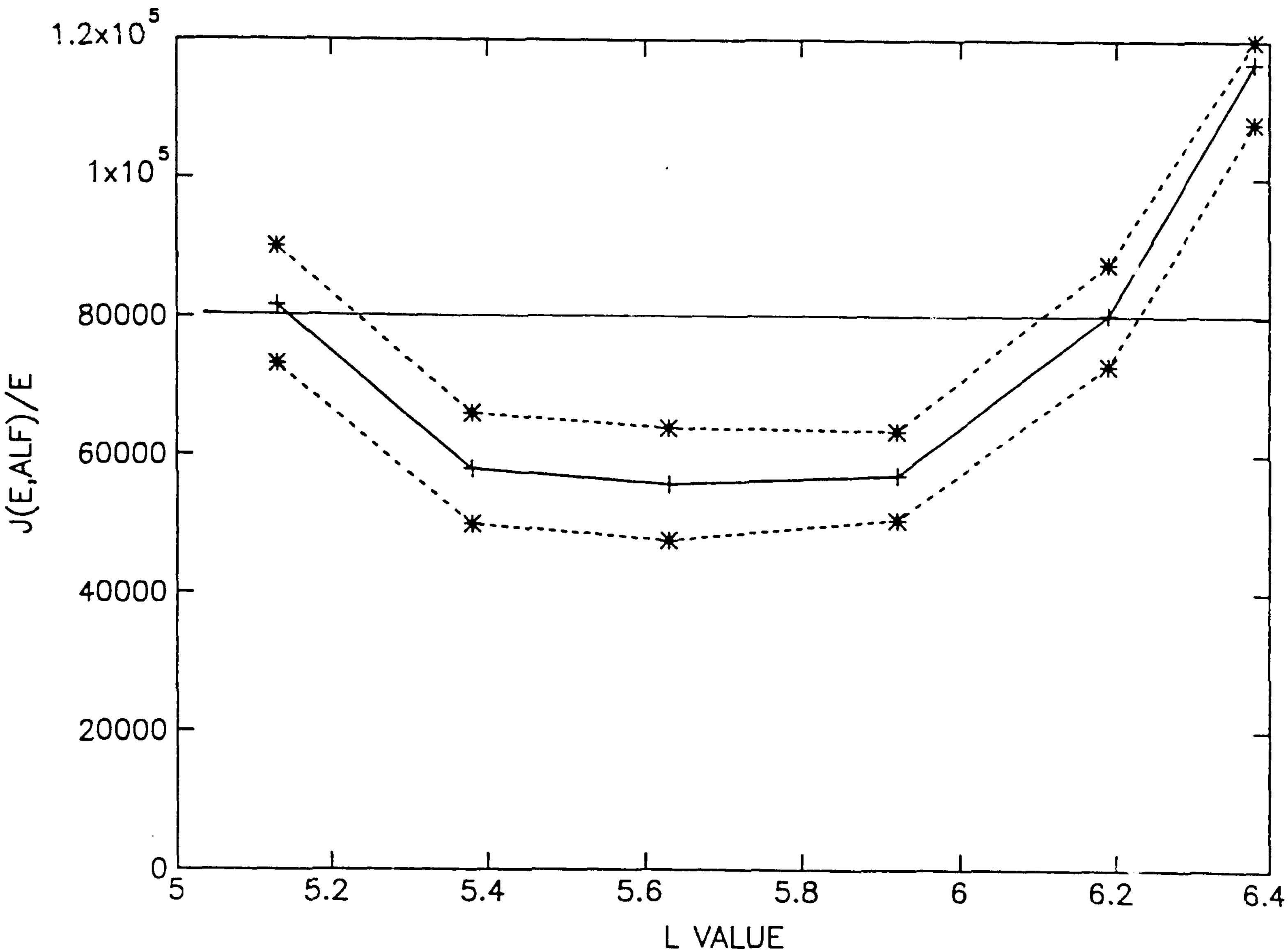

Figure 10. Ratio of 90°-directional flux of 2.5 keV ions divided by ion energy $E = 2.5B/B_0$ versus L (see text). (Orbit number = 0458A)

electric field toward lower L values.

3.3.2 Induced Electric Field

During the magnetic storm of August 26, 1990, measurements on Orbit 77 were made of unusual low-energy ion pitch-angle distributions in which the flux increased steadily as the pitch-angle increased from near 0° to near 180°. Moreover, such pitch-angle distributions persisted for several hours. Measurements of this type had never been reported before. Our analysis of this event is reported in in Section 3.3.2.3.3 (A New Loss Mechanism) of our First Annual Report, [Collin et al., 1991]. As reported there the dipole tilt angle was large - about 20.5° at that time - and the magnetic field component along the solar-magnetospheric Z_{GSM}-axis was increasing in time during the entire period of the observed "clipped-wing butterfly" pitch-angle distributions. On Orbit 77 apogee was near 06 hr LT so, owing to the large tilt angle, the projection in the X_{GSM},Y_{GSM} plane of the area enclosed by a local field line was large. Hence, since the magnetic field was increasing through the loops of the the undisturbed field lines, we suggested that the unusual pitch-angle distributions were due to an induced electric field that accelerated ions all along the local field lines from the northern ionosphere to the southern ionosphere.

The induced potential Ψ along the field-line loop can be estimated by computing the time rate of change of magnetic flux through the area enclosed by the field line projected on the X_{GSM}, Y_{GSM} plane. Assuming the field line to be dipolar, its enclosed area is $\frac{3}{16}\pi r_0^2$; and since apogee was near $Y_{GSM} = 0$, the projection of this area in the X_{GSM}, Y_{GSM} plane is $(\frac{3}{16}\pi r_0^2) sin\theta_{tilt}$, where θ_{tilt} is the tilt angle. Hence,

$$\Psi = (\frac{3}{16}\pi r_0^2 sin\theta_{tilt})\frac{dB_{Z_{GSM}}}{dt}$$

During the event observed on Orbit 77, the average measured value of $dB_{Z_{GSM}}/dt$ was about 7.6×10^{-3} nT/s and $r_0 \approx 7$. Substitution of these values in the above equation, assuming the measured quantity $dB_{Z_{GSM}}/dt$ to be uniform over a volume extending along the Z_{GSM} axis within the field line loop, gives $\Psi \approx 3$ kV. Actually, the magnitude of the magnetic field and the ion fluxes fluctuated in harmony, but on the average, the observations were consistent with a potential of about 1 kV. — During a similar compression of the magnetosphere on the preceeding orbit, the tilt angle was nearly equal to zero and "clipped-wing butterfly" distributions were not observed.

A survey of the ion spectrograms obtained while apogee of the CRRES orbit was on the dusk side of the magnetosphere reveals that "clipped-wing butterfly"pitch-angle distributions occur quite often during disturbed periods, but most are of short duration. However, two such events were found recently that persisted for many hours. The data were obtained during the magnetic storms of June 5 1991 and July 13 1991 on Orbits 766 and 856, when apogee was near dusk. During both of these events, the dipole-tilt angle was high.

During orbit 856 a series of regular fluctuations of the magnetic strength and direction began at 10:50UT. During this time the magnetosphere was compressed with **B** being enhanced by about 50nT above the modeled field. CRRES was at $6.0 < L < 7.5$ near dusk in the local time range of 15 to 19 hours. The period of the fluctuations was about one hour and they persisted until about 16:00UT. Each fluctuation consisted of an increase in **B** of about 25nT together with an antisunward turning of at least 20° followed a corresponding decrease and sunward turning consistent with compression and expansion of the magnetosphere. During each expansion phase the ions with energies between 1keV and 300keV, measured by IMS-LO and IMS-HI, were essentially isotropic and increased in intensity by at least an order of magnitude above their intensities during the compression. Electrons with energies between 1keV and 300keV, measured by IMS-LO and SEP, were also isotropic and behaved in the same way as the energetic ions. The high energy electron spectra were essentially identical during each of these intensifications suggesting that the fluctuating magnetosphere was repeatedly moving the same flux tubes past CRRES. The electrons at energies between 300eV and 1.7keV included an isotropic component which varied in step with the high energy electrons and ions but also included a counterstreaming field aligned component. The IMS-LO ion survey plot for this orbit is shown in Figure 11. The changes in direction of **B** are reflected in the changes in the range of pitch-angles scanned which is dependent on the angle between **B** and CRRES's spin axis. The H^+ shows a very complex behaviour at energies below 1keV with variable asymetric pitch-angle distributions. At times the peak H^+ flux appears to be systematically changing in pitch-angle, e.g. 11:00-11:40UT. At energies below 1keV an intense field aligned flow of O^+ towards the equator can be seen, at 0°, but without any comparable O^+ flow downward towards the ionosphere. Although the pitch-angle coverage does not extend as close to 180° as to 0°, the equatorward flow is wide enough that a similar flow in the opposite direction would have been clearly detected. This O^+ distribution is similar to the O^+

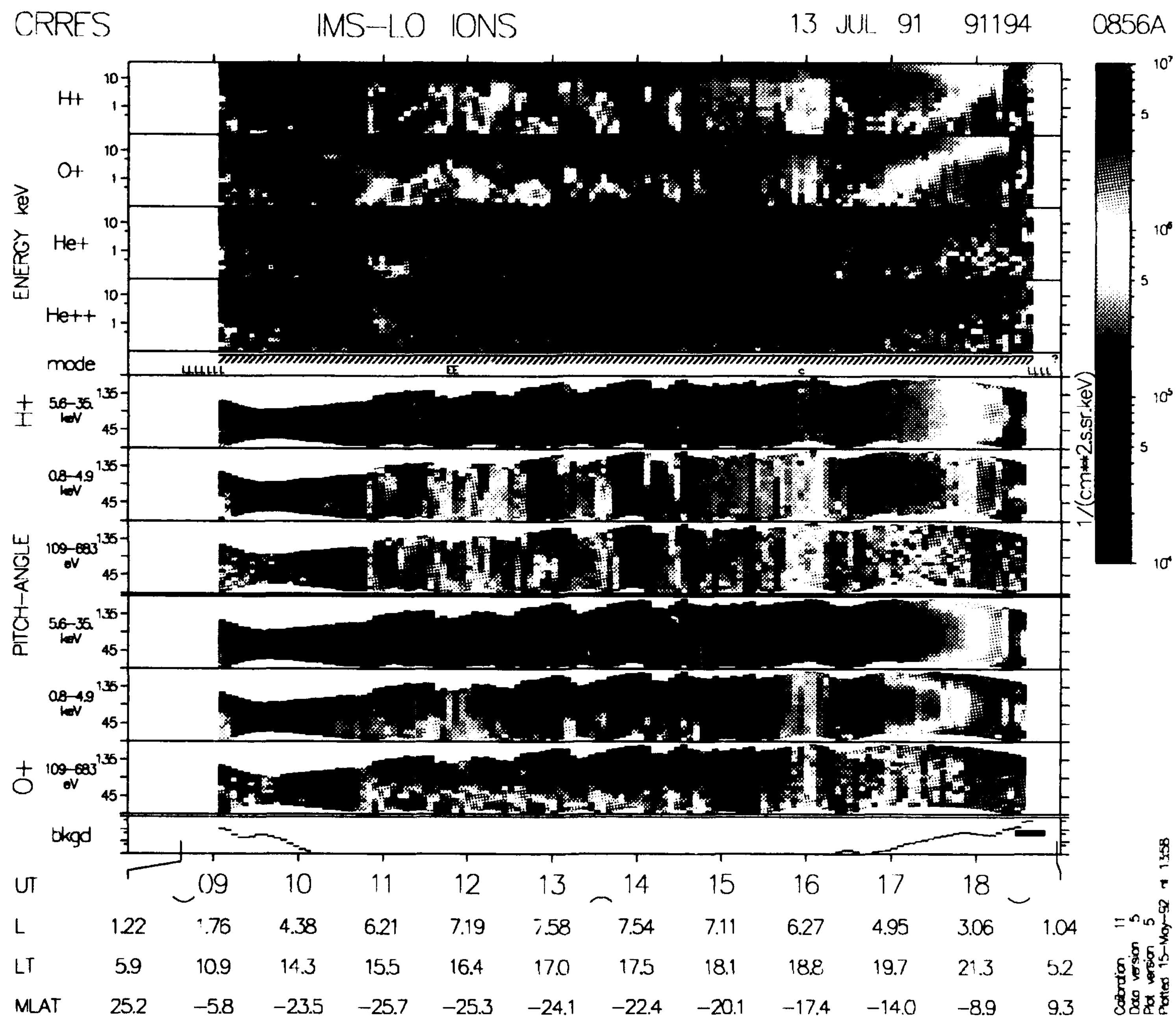

Figure 11. A survey plot of ion energy spectra and pitch-angle distributions measured on orbit 856.

"clipped-wing butterfly" distribution seen in similar circumstances during the 26 August 1990 storm [Collin et al., 1991].

Note that the pitch angle distributions of the O^+ ions, especially those in the energy ranges 109 - 683 eV and 0.8 - 4.9 keV, appear to increase steadily as the pitch angle decreases from its highest to its lowest values. Although the distributions vary in time, this general feature persists from about 11 to 14.8 hr UT. The magnetic field measurements made during the event revealed that the magnitude of the magnetic field was generally increasing with time relative to the model field from 11 to about 14.5 hr UT, but it was also fluctuating slowly. The fluctuations appear to be well correlated with the changes of the ion fluxes and pitch-angle distributions. The average value of $dB_{Z_{GSM}}/dt$ from 11 to 14.5 hr UT was about 5.55×10^{-3} nT/s; the tilt angle was 29.6° and $r_0 \approx 7.5$. These values indicate that the average induced potential along the local field lines was about 3.5 kV. This potential seems to be consistent with the ion data. Note that, here, the sense of the electric field is such that it accelerates ions along the local field lines from the southern to the northern hemispheres. Therefore, the sense of this electric field is opposite to that of the August 26, 1990, event. Nevertheless, both electric fields are appropriately directed to explain the pitch-angle distributions.

The event on Orbit 766 was found only recently and magnetic field data for that event have not yet been received. However, it is a better example than the one measured on Orbit 856 in that the ions were measured over a wider pitch-angle interval and the clipped-wing features were more pronounced.

3.3.3 Magnetic Storm Selection

The magnetic storm of February 1, 1991, was selected for special studies of dynamic processes. It was a moderate, single-injection storm, yet the ion distributions displayed the full dynamical behavior of stormtime ions. The Kp index was high, between 5− and 6-, for about 6 hours prior to the ion injection; it then steadily diminished to 2- during the following 9 hours and remained low, between 1- and 2, for the next 40 hours. About two hours after the injection, the Dst index decreased to a minimum of -76 nT, near 24 hr UT, and recovered during the following 3 days. Since these indices were modest, the magnetic and electric field variations were probably not so severe as to restrict the applicability of particle-tracing analyses. Fortuitously, the CRRES satellite was also in the right place and time to detect the injection of O^+ ions, which probably occurred during the expansion phase of the storm.

The ion spectrograms obtained on Orbit 465 are shown in Figure 12. Note that although high fluxes of field aligned O^+ and H^+ ions were present at local times earlier than 23.5 hours (22 hr UT), an intense injection of fairly isotropic O^+ ions of energies 0.8 - 4.9 keV occurred from 22 to 24 hr UT (23.5 - 0.6 hr LT) while the satellite was near apogee. The characteristics of these ions are quite similar to those expected of ions that are transported from the dayside cleft/cusp ionosphere to the nightside magnetosphere during times of enhanced convection [Cladis and Francis, 1992]. The unexpected feature of the observed ions is their high degree of isotropy. Cladis and Francis [1992] predicted butterfly distributions in which the directional flux at pitch angles of 30° and 150° is higher than the 90° flux by about a factor of 3. Electric-field data provided by John Wygant reveal that large electric-field fluctuations, with amplitudes of 2 mV/m and higher and frequencies near the O^+ gyrofrequency, were present from 22 hr UT on February 1 to 03 hr UT on February 2. These waves would be very effective in increasing the injected-ion flux near 90° by heating the ions perpendicular to the magnetic field. Such waves would similarly heat the field-aligned ions that presumably originate in the ionosphere at local times prior to 23.5 hr on February 1 and after 0.6 hr on February 2.

At the times of Orbits 466 and 467, the Kp index was low, and the injected ions appear to decay principally by charge-exchange collisions. The ion transport code will be used to test this loss process. However, a strong source of ions, especially O^+, from the ionosphere was also present. The field-aligned ion flux is very high at all L values higher than about 3.5 R_E. These ions could be accelerated from the ionosphere by electric potential differences along the magnetic field or by wave-ion interactions. The latter appear more promising since the wave field is often high in plasma-depletion regions. In this stage of the magnetic storm, the plasmasphere is still highly contracted. If good wave-field data appropriate for the regions of the magnetosphere during the recovery phase of magnetic storms is available, the acceleration process can also be modeled in our ion-transport codes.

4 Future plans

Agency tape processing, the generation of the high resolution database, the survey plot library, and the summary database will be continued and are expected to be completed within the next year.

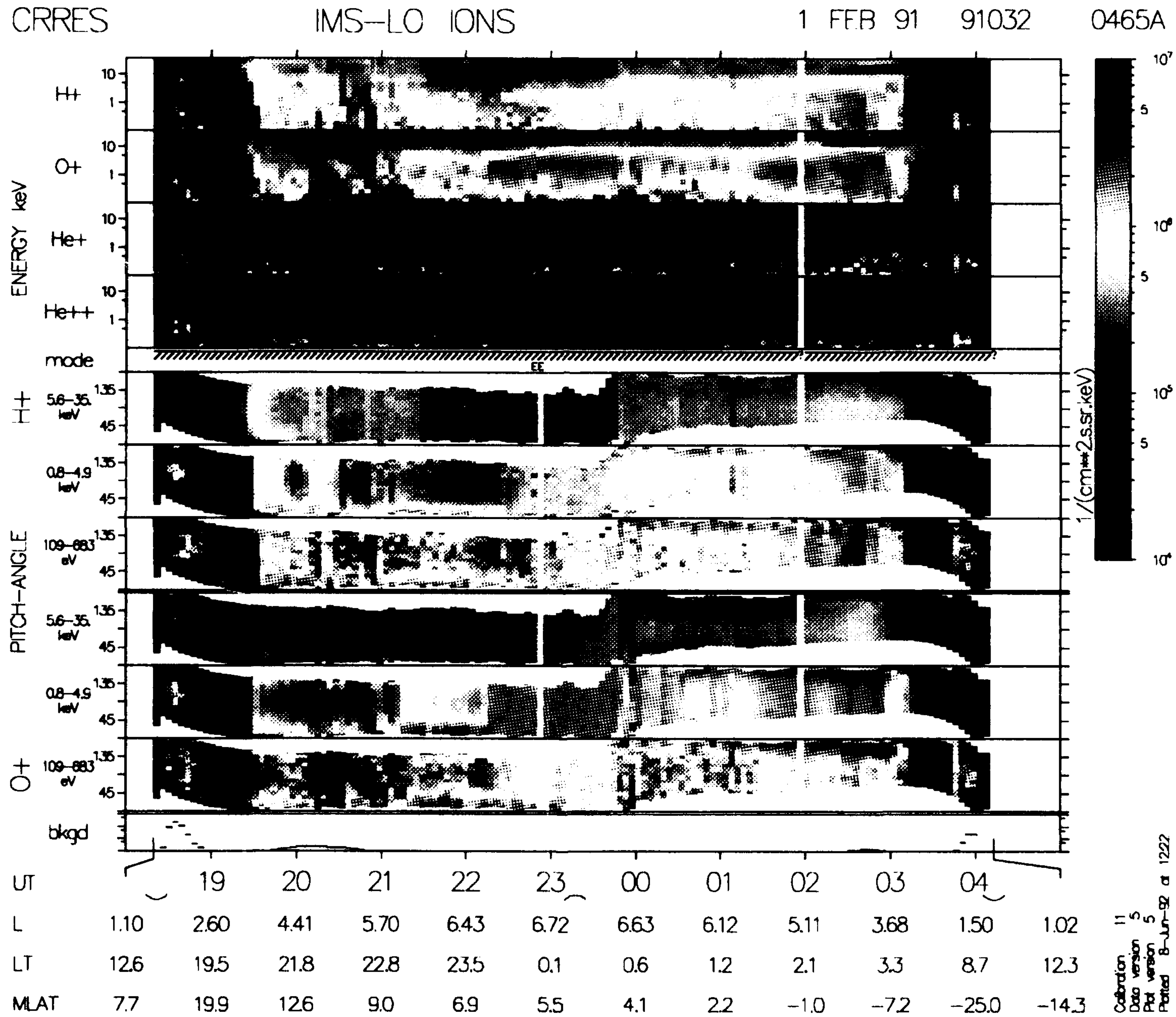

Figure 12. A survey plot of ion energy spectra and pitch-angle distributions measured on orbit 465.

Cross calibration of IMS-LO with LEPA will address their response to O^+ and attempts to understand the source of the missmatch will be continued. We will also attempt to cross calibrate with MICS since there is sufficient overlap between the energy ranges of IMS-LO and MICS.

The static version of the empirical model of ring current ion composition will be completed and a preliminary dynamic version will be constructed.

Under Task 3 the effort on estimating electric fields using the Liouville's Theorem method will be continued, but this effort will require the availability of the IMS-HI fluxes. Also the study of induced electric fields along magnetic field lines and their effects on ions and the investigation of the dynamics of the February 1 storm as implied by the behavior of the low-energy (IMS-LO) ions will be continued.

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Appendix 1

Abstracts of Papers Presented

A Preliminary Statistical Model of Low Energy (110eV-35keV) Ring Current Ions

H L Collin J M Quinn and J B Cladis (Lockheed Palo Alto Research Laboratory, 3251 Hanover St., Palo Alto, CA 94304)

The statistical model of low energy ring current ions is constructed from data acquired by the Lockheed IMS-LO ion mass spectrometer on CRRES. This satellite has a highly elliptical orbit with apogee of about 7 R_E and an inclination of 18° and samples a substantial portion of the ring current region. The mass spectrometer acquires measurements of ions in the energy range 110 eV to 35 keV with good pitch-angle coverage. The statistical model consists of a set of average equatorial energy/pitch-angle distributions of H^+ and O^+ for a number of magnetic longitude and L ranges. In the absense of parallel electric fields and wave-particle interactions, these distributions can be used to determine the ion distributions at non-equatorial magnetic latitudes by adiabatic mapping. Average equatorial distributions are constructed by accumulating and averaging equatorial distributions from many orbits. The ion data are mapped adiabatically from the satellite location to the equatorial plane, which is taken to be the minimum B surface. There the data are binned by their equatorial pitch angle and sorted into ranges of L and magnetic longitude. A preliminary version of the statistical model will be presented.

CRRES Energetic Particles and Ion Composition Measurements During the March 1991 Storm

R M Robinson, H L Collin, H D Voss, R R Vondrak, R W Nightingale and W L Imhof, (Lockheed Palo Alto Research Laboratory, 3251 Hanover St., Palo Alto, CA 94304)

The ONR 307 experiment package on the Combined Release and Radiation Effects Satellite (CRRES) consists of three different types of instruments that measure particle fluxes and ion composition with good temporal and angular resolution. The Spectrometer for Electrons and Protons (SEP) measures electrons with energies from 40 keV to 5 MeV and protons with energies between [illegible] keV and 40 MeV. The low energy ion mass spectrometer (IMS-LO) measures electrons and major ions between 110 eV and 35 keV. The medium energy ion mass spectrometer (IMS-HI) measures the composition of ions at ring current energies. The development of the March 1991 storm over the energy ranges and particle types sampled by the ONR 307 instruments will be described. The SEP instrument monitored the dramatic increases in energetic electrons and protons associated with the storm including the onset of the solar proton event at 1100 UT on 23 March and the second proton belt beginning at 0400 UT on 24 March. The IMS-LO data show persistent dispersive signatures in the ion fluxes that are suggestive of multiple injection events. Dynamic variations in the low energy plasma fluxes were observed near apogee in association with the storm. The IMS-HI measurements provide information about the behavior of the ring current. The data from these three experiments are intercompared to study the relative responses of electrons and ions over a broad energy range throughout the storm period.

Observations of a quiet magnetosphere and polar cap by CRRES, DE-1, and DMSP.

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W K Peterson, H.L. Collin, and R.M. Robinson, (Lockheed Palo Alto Research Laboratory),
H J Singer, K Kerns, D A Hardy, W F Denig, and N C Maynard, Phillips Laboratory, Hanscom AFB, Mass.
J R Wygant, University of California, Berkeley,
J A Slavin, NASA, Goddard Space Flight Center,
C J Pollock and T E Moore, NASA, Marshall Space Flight Center.

On February 18, 1991, from 0730 to 0900 UT the DE-1, CRRES, and DMSP-F8, F-9, and F-10 spacecraft obtained a comprehensive set of plasma particle and field measurements. The DE- spacecraft traversed the nightside auroral zone and entered the polar cap at an altitude of 20,000 km; the CRRES satellite apogee was in the near magnetotail in the vicinity of magnetic field lines sampled by the DE-1 spacecraft. The DMSP satellites sampled the polar cap and auroral zones sunward of the DE-1 orbit track.

The magnetosphere was quiet at this time and had been quiet ($Kp < 1_+$) for more than 24 hours. The data assembled provide an unusual opportunity to characterize the quiet auroral zone and polar cap plasmas. We will present summary data from many of the particle and field instruments on the five spacecraft and examine in more detail the multipoint ion composition data obtained on magnetic field lines in the nightside auroral region.