Observation and Modeling of Energetic Particles at Synchronous Orbit on July 29, 1977


In the 12 hours following a worldwide storm sudden commencement at 0027 UT on July 29 there was a series of at least four magnetospheric substorms, the last and largest of which exhibited an expansion phase onset at 1200 UT. Data from six spacecraft in three general local time groupings (0300, 0700, and 1300 LT) were examined, and vector magnetic field data and energetic electron and ion data from ~15 keV to >2 MeV were employed. Four primary types of studies were carried out: (1) timing and morphology of energetic particle injections; (2) variation of particle phase space densities f(E = p^2/(2mB)), using local magnetic field and particle flux data; (3) measurement of boundary motions, using high-energy ion gradient anisotropies; and (4) adiabatic modeling, which included injection, large-scale convection, corotation, and gradient drifts. For the 1200 UT substorm it is concluded that there was a substantial flux dropout in a broad sector near local midnight because of a large-scale boundary motion, followed by a recovery to a predropout configuration. There were then several subsequent injection events with distinct onsets (extending as far eastward as 0300 LT), for which ion anisotropy information suggests an inward motion of particles from outside of geostationary orbit. Particle drift information reveals that these particles drifted azimuthally completely around the Earth. It is also concluded from the phase space density studies that 'fresh' particles with magnetic moments of up to at least several hundred MeV/gauss were injected near geostationary orbit. The present adiabatic convection model can explain the observed injection of large magnetic moment particles from the plasma sheet into synchronous orbit, although physical elements of the normal model must be altered somewhat.

INTRODUCTION

During the past two decades, space physics has progressed from missions whose goal was a rudimentary exploration of the near-earth magnetosphere to the present stage in which rather detailed modeling and understanding of magnetospheric plasma processes has emerged. Nonetheless, because of the vast scale distances involved within the magnetosphere, it has been a very difficult problem to probe the system concurrently at enough different points to truly understand the complex relationships between its different parts.

Understanding just the 'quiet' or 'equilibrium' state of the magnetosphere has been a challenge. Even more difficult has been the problem of understanding the dynamic behavior of the magnetosphere. This dynamic aspect of the magnetosphere may be effectively discussed in terms of energy input from the solar wind into the magnetosphere. Such excess added energy causes the magnetospheric system to move out of its equilibrium state into a more energetic state. In some cases this gives rise to a very large scale disturbance (the geomagnetic storm), which in turn causes worldwide effects. Much more frequently, however, disturbances within the magnetosphere tend to be somewhat more localized involving the regions connected to nightside auroral field lines: such a disturbance is termed the magnetospheric substorm. (See the paper by McPherron [1973], and papers thereafter, for a discussion of a phenomenological model of substorms.)

In order to understand better the nonequilibrium behavior of the magnetosphere, a period (July 28-30, 1977) was chosen for intensive study. This period was characterized by the development of a large geomagnetic storm and also by the occurrence of several magnetospheric substorms [Manka et al., this issue]. In addition, this period offered the advantage of a total of 11 earth-orbiting spacecraft positioned at widely separated points immediately upstream and throughout the magnetosphere, and these satellites provided data coverage of plasma and field changes associated with the geomagnetic storm and substorms.

In order to exploit fully the information provided by such a wide array of spacecraft probes, an effort was made, under the aegis of the International Magnetospheric Study (IMS), to assemble researchers who had data from satellites for the July 28-30, 1977, time period. In May of 1979, approximately 10 scientists with interest in, and data on, the high-energy plasmas of the magnetosphere met at the National Space Science Data Center (NSSDC) located at the NASA Goddard Space Flight Center in Greenbelt, Maryland. In a workshop setting called CDAW 2.0 (Coordinated Data Analysis Workshop—2), the researchers studied data that they had provided earlier to a central computer facility. This central computer allowed data from any sensor on any satellite to be directly compared with concurrently acquired data from any other sensor on the same or any other satellite. Thus unlike most prior space research situations, experimenters, modelers, and theorists had at their immediate command the data required to address many questions about magnetospheric dynamics. Variations of plasma con-
There are two distinct facets of, or reasons for studying, energetic particles within the earth's magnetosphere. The first of these facets reflects the intrinsically interesting question of where and how these particles are actually produced, say, during magnetospheric substorms. The second facet of energetic particle studies is a very practical and pragmatic one: Given that such particles exist (i.e., that they can be observed), how can these particles be used as tracers or probes of large-scale magnetospheric processes? The CDAW-2 subgroup 6 research team attempted to explore each of these avenues associated with energetic particles.

The types of studies carried out by subgroup 6 were basically four in number: (1) timing and morphology of particle injections; (2) variation of particle phase space densities; (3) measurement of boundary motions, using ion (proton) gradient anisotropies; and (4) adiabatic modeling (with increased particle flux (i.e., injection), convection, corotation, and drifts).

In the following, we will discuss our findings derived from each of the above lines of inquiry. Our initial research efforts were concentrated on the 1200 UT substorm of July 29. This was the last and largest (AE ~ 1200 γ) of a series of substorms that occurred on July 29, following a worldwide SSC (storm sudden commencement) that occurred at 0027 UT [King et al., 1982; Wilken et al., this issue]. We concentrate here on measurements made at geostationary orbit (6.6 Re), where a total of six spacecraft made extensive observations of the energetic particle behavior.

**Observations**

Figure 1 is a geocentric solar ecliptic projection of the positions of the six primary, near-geostationary satellites used in the present study. The ATS 6 and 1977-007 spacecraft were located very near one another at 0300 LT. ATS 6 had NOAA, Aerospace, and TRW energetic particle, UCLA magnetometer, and UNH plasma experiments on board, while 77-007 had Los Alamos energetic particle sensors on board. The Los Alamos-instrumented spacecraft 1976-059 at 0700 LT was bracketed by the GOES 1 and 2 satellites, which carried NOAA energetic particle and magnetometer instruments. Finally, the European Space Agency satellite GEOS 1 (1.3 ≤ r ≤ 8 Re) carried a complete complement of plasma and field measurement instruments and was located near apogee at ~1300 LT.

General geomagnetic activity for July 29-30, 1979, is shown in Figure 2 [see also Manka et al., this issue]. The upper panel shows selected high-latitude magnetometer station records, while the second panel from the top shows H-component magnetograms from five standard auroral zone stations. The third panel of Figure 2 shows mid-latitude stations from several geographic longitude sectors. The bottom panel summarizes auroral electrojet activity in the form of the AE(5) index, i.e., the index derived from the five auroral zone stations shown in panel 2.

Particularly evident in Figure 2 are the storm sudden commencements caused by an interplanetary shock wave hitting the earth at 0027 UT on July 29 [cf. King et al., this issue, and Wilken et al., this issue] and the rapid storm main phase development thereafter. These features are seen clearly in the mid-latitude magnetograms of panel 3. Also quite evident, especially in the plot of AE, are the generally disturbed auroral zone conditions on July 29 and the large substorm (AL > 1000 γ) at ~1200 UT. As previously mentioned, it is the 1200 UT substorm upon which we concentrate in this paper.

**Energetic Particle Behavior at 0300 LT**

Figure 3 shows energetic electron fluxes measured by instruments on the 1977-007 spacecraft. The five energy
channels shown are a representative sample of the ~20 electron channels ($E > 10$ keV) available from 77-007 and/or ATS 6. All electron channels at ~0300 LT exhibit roughly the same sequence of events with a pronounced flux decrease, or 'dropout,' commencing at ~1135 UT [see Fennell et al., 1982]. The fluxes eventually diminish from ~1 to 3 orders of magnitude (depending on energy), but as is especially clear in the 30 keV channel, the measured intensities remain nonzero throughout the dropout. Hence it is concluded that the geostationary spacecraft at 0300 LT entered a region of much reduced electron flux, but they did not emerge into the extremely low intensity region of the high tail lobes. The most likely explanation is, therefore, that 77-007 and ATS entered the high-latitude plasma sheet between ~1140 and 1155. In the northern 'horn' of the plasma sheet it would be expected that energetic particle fluxes (prior to substorm onset) were lower than in the outer trapping zone but higher than in the tail lobes.

After the flux dropout, the electron intensities appeared to recover simultaneously at all energy levels to slightly more than the predropout values. At 1200 UT there was a large increase of electron flux, and this injection corresponded closely to the sharp negative bay onset seen at College (cf. Figure 2). Note that lack of energy dispersion between the several energy channels suggests that the electron 'injection front' extended as far east as 0300 LT.

At 1205 UT, another substantial flux increase or injection took place. This was largest and most evident in the higher ($E > 100$ keV) energy channels. This injection spike was also simultaneous in all energy ranges (i.e., without energy dispersion) and this again allows the conclusion that the injection region extended as far eastward as 0300 LT.

A third flux injection event (with some evidence of energy dispersion) occurred at ~1208 UT. Note further that after ~1225 UT the drifting high-energy electron population apparently moved azimuthally around the earth and once again passed over the spacecraft.

Given this observed electron behavior, we now turn to the energetic proton flux variations. In Figure 4, several representative low- and mid-energy proton (ion) channels from ATS 6 are shown. The 18–20-keV channel is from the University of New Hampshire plasma experiment while the other four channels (33–150 keV) are from the NOAA energetic particle experiment.

Prior to 1200 UT, the energetic protons in the range 15–150 keV exhibited behavior very similar to that of the energetic electrons seen in Figure 3. A pronounced flux dropout was seen after ~1135 UT, but at least for particle energies up to many tens of kiloelectron volts the flux dropout was not total. This further suggests passage of the spacecraft into a region of reduced, but nonzero, flux. This again argues that the spacecraft entered the high-latitude...
One of the most striking aspects of the data in the lower panel of Figure 5 is the appearance of the very regular, periodic, proton drift-echo pulses [cf. Belian et al., 1978, and Baker et al., 1979]. As has been well documented in the literature, these high-energy proton pulses are injected into the outer radiation zone at substorm onset and maintain their discrete identity sufficiently long to drift azimuthally around the earth many times. In this case it is seen in the 0.8–1.0-MeV channel, for example, that at least four 'echo' pulses were recorded. In a more detailed analysis section below we will return to the information provided by the drift echo data.

**ENERGETIC PARTICLE BEHAVIOR AT 0700 LT**

Figure 6 is the 0700 LT counterpart to Figure 3, i.e., it shows representative energetic electron channel measurements for the 1130–1300 UT period on July 29. Note that, except for the lowest-energy channel, there was a gradual flux decline between 1130 and ~1200 UT. There was, however, no evidence for the major flux dropout seen in the midnight sector (as revealed by 77-007/ATS observations).

After ~1205 UT there were substantial flux increases in all electron energy channels. These increases were gradual in character with apparent energy dispersion effects [Arnoldy and Chan, 1969]. These observations are consistent with the electrons being injected over a broad front near local midnight (actually extending as far east as ~0300 LT) and subsequently drifting eastward to the 76-059/GOES location.

Energetic proton data from spacecraft 1976-059 (0700 LT) corresponding to those shown in Figure 5 are presented in Figure 7. In that figure the upper panel summarizes the 145–340-keV flux variations, while the lower panel summarizes the variations of the very energetic component (E > 0.4 MeV).

As was seen in Figure 6 for the electrons, the proton fluxes shown in Figure 7 also exhibited a gradual flux decline prior to 1200 UT but showed no major flux dropout. The behavior of the proton fluxes at 0700 LT after ~1200 UT was highly energy dependent. Up to ~250 keV the proton fluxes appeared to recover gradually and indistinctly with some possible energy dispersion. By contrast, the >0.4-MeV proton population exhibited a very clear onset with considerable energy dispersion. As is evident from the lower panel of Figure 7, the high-energy proton behavior was of the clear drift-echo character. Careful comparison of the details of...
shape and timing of the pulses in Figure 7 with those of Figure 5 shows two things: (1) The pulse shapes at 03 and 07 LT were remarkably similar in width and amplitude for any given energy channel. (2) An identifiable drift-echo pulse in any given channel at 07 LT appeared slightly before the same pulse appeared at 03 LT.

It is concluded that essentially all of the proton results seen at the 76-059/GOES location can be accounted for by an injection of protons near midnight with a subsequent westward drift completely around the earth to the 07 LT position. The complex recovery behavior of 150-250-keV proton fluxes prior to ~1225 UT appears to have been primarily adiabatic and will be discussed further below. The width of the proton injection regions around local midnight are progressively broader at lower and lower energies.

Energetic Particle Behavior at 1300 LT

Figures 8 and 9 show the electron and proton fluxes, respectively, measured at the location of GEOS 1. The data are shown in the form of stacked energy spectra in each instance. In the case of both particle species, the lowest-energy channels show a gradual flux decrease between ~1130 and 1200 UT followed by a gradual recovery. Only in the higher-energy channels \( E \approx 80 \) keV was the recovery very sharp or dramatic. The flux recoveries in both particle species showed very clear energy dispersion, with the recovery occurring first in the higher-energy channels. This feature is consistent with substorm injection of energetic particles (broadly) near midnight, with subsequent drift of the particles to the 1300 LT position.

Phase Space Density Variations

In the foregoing section we have discussed pronounced flux increases in terms of injections. That is, we have presumed that the flux enhancements actually corresponded to new or ‘fresh’ particles transported to or accelerated in the vicinity of geostationary orbit. In order to confirm this supposition we have evaluated the particle distribution func-
The phase space density, or distribution function, of a particle population can be defined in terms of adiabatic invariants and time:

\[ f(\mu, J, t) = j p^2 \]  

(1)

Here, \( \mu \) is the first adiabatic invariant (magnetic moment), \( J \) is the second invariant, \( t \) is time, \( j \) is the directional differential particle flux, and \( p \) is the relativistic momentum. Taking \( j \) to be the equatorial perpendicular flux and \( J = 0 \), the phase space density at constant first invariant is given by

\[ f(\mu, t) = j/2m_0\mu B \]  

(2)

where \( m_0 \) is the particle rest mass, and \( B \) is the total equatorial magnetic field strength.
As is evident from (2), the advantage of studying the phase density at constant $\mu$ is that adiabatic (magnetic field) variations are removed. Thus true particle density increases or decreases are revealed, and sources or sinks of particles can be identified. In particular this analysis can reveal whether or not new particles were injected in the 1200 UT substorm on July 29. Figure 10 shows exemplary spectra which were obtained at various times for this event period. The panels on the left show spectra for the 03 LT spacecraft grouping, while the panels on the right show similar data for the 07 LT grouping. The upper panel in either case shows $j$ for electrons, while the lower panels show $j$ for protons.

As is evident from Figure 10, the data are distributed relatively accurately according to a simple exponential spectrum. This is particularly true below $\sim 300$ keV. The dashed line accompanying each set of data is the least squares fit to the observed particle distribution, where the fit is given by

$$ j = K e^{-E/E_0} $$

and has units of particles ($cm^2 s sr keV)^{-1}$. Except in the highest proton energy ranges after $\sim 1220$ UT (where drift-echo effects are dominant), the spectral fits provide an excellent analytical representation of the observed spectra. Our procedure in the present analysis, therefore, has been to
fit (for each 1-min flux average) the observed energy spectrum to obtain $K(t)$ and $E_\theta(t)$. Given these fits, we thus have $j(E, t)$ to be used in (2).

The other required information for phase density calculation is the total magnetic field strength. In Figure 11 we show the values of $|B|$ for the 0300 and 0700 LT spacecraft locations. The largest variability, as might have been expected, was seen in the nighttime sector at the ATS 6 location. Because one component (Y) of the ATS 6 magnetometer [McPherron et al., 1975] was inoperative at the time of these measurements, the inferred field line direction from electron anisotropy data at 77-007 was used to complement ATS field data. In a CDAW 2 algorithm procedure the two measured ATS 6 field components (X and Z) and the field line direction from 77-007 were sufficient to provide the total field vector $B$ at ~0300 LT.

Combining the magnetic field data of Figure 11 with energy spectral data for each minute between ~1130 and 1300 UT gave us the desired phase space densities at constant $\mu$. The ranges of $\mu$ values selected for investigation were chosen as follows. The minimum and maximum kinetic energies of electron and protons measured on any of the six observing spacecraft were $E_{\text{min}} \sim 10$ keV and $E_{\text{max}} \sim 1.0$ MeV. The measured range of $B$ similarly considered was $B_{\text{min}} \sim 100$ G and $B_{\text{max}} \sim 250$ G. Thus the $\mu$ range was

$$\frac{E_{\text{min}}}{B_{\text{max}}} \leq \mu \leq \frac{E_{\text{max}}}{B_{\text{min}}}$$

and with some spectral extrapolations a useful range of $\mu$ values in this case was $\sim 1-1000$ MeV/gauss.

Figure 12 shows examples of the phase space densities for electrons at $\mu = 1$, 10, and 100 MeV/G. The most evident features in the upper panel (77-007/ATS grouping) were the following: (1) Even with removal of adiabatic effects, the flux dropout persists. (2) The phase space densities at constant $\mu$ were identical before the dropout (~1130 UT) and after the dropout (~1155 UT). (3) True phase space density increases were observed for all magnetic moments (energies) after 1200 UT.

The points above, therefore, demonstrate that in a broad sector near local midnight there was a large-scale boundary motion that took the observing spacecraft into a low-density region (i.e., across a spatial discontinuity). This thining-like event clearly preceded the substorm onset. Prior to the substorm onset the midnight sector spacecraft also returned to a predropout density configuration for several minutes (1155-1200 UT); this, therefore, clearly was not an injection event. At ~1200 UT a clear injection of new or 'fresh' particles occurred for all magnetic moments.

The lower panel of Figure 12 shows the electron density variations at 07 LT. Comparison of these results with Figure 6 shows that at this location essentially all flux variations before ~1205 UT were adiabatic. Viewing the phase space densities in this region of the magnetosphere shows essentially flat profiles prior to 1205, a density dip at ~1205, and energy-dispersed density increases after ~1206 UT, consistent with injection and drift from the west.

Proton phase space density variations are shown in Figure 13 for $\mu = 1$, 50, and 300 MeV/G. Compared to the electron data of Figure 12, much more variability was seen in the proton density profiles. This in part represents statistical variations in the measured fluxes, which translate into variations of $K(t)$ and $E_\theta(t)$ in (3). Nonetheless, the following features seem to be established by the data:

1. At 03 LT, there appeared to be a phase space density increase for very low $\mu$ values between ~1135 and 1150 UT, while at higher $\mu$ values a clear dropout was seen.
2. Substantial injections of new particles were seen at 03 LT for $\mu \geq 10$ MeV/G, but little clear evidence exists for injection of new protons with low $\mu$ values.
3. At 07 LT, there may have been some significant dips and peaks before ~1210 UT, particularly at high $\mu$ values, but the most substantial effects occurred after ~1210 UT as protons azimuthally drifted westward from midnight to the 76-059/GOES location.

**Gradient Anisotropy Information**

By examining flux and phase space density variations (particularly at the 03 LT position), it is established that new particles (up to several hundred MeV/G) appeared at synchronous orbit between ~1200 and 1210 UT on July 29. A remaining question about these particles is where the particles came from.

The best available tool for examining the question of the general source region for the injected hot plasma and energetic particles is provided by ion gradient measurements. Because of their large gyroradii, 10-100 keV protons can provide good information about density gradients that exist within a region of strong radial intensity variations or within an injected cloud of plasma and energetic particles [Fritz and Williams, 1979; Williams et al., 1979; Palmer et al., 1976; Walker et al., 1976].

The spacecraft 77-007 and 76-059 are particularly well suited for examining ion gradient anisotropies. The reason for this is that these spacecraft spin about an axis that points south sense. Given the fact that 100–200 keV protons have
typical gyroradii of several hundred kilometers (∼0.1 $R_E$) at synchronous orbit, one can probe regions far removed from the spacecraft by the gradient anisotropy technique.

The gradient parameters are computed as follows:

$$A_{EW} = \frac{(E - W)}{(E + W)}$$

where $E$ is the proton flux ($E_p > 145$ keV) measured in the sector with the detector looking eastward, and $W$ is the proton flux measured looking westward. Similarly,

$$A_{NS} = \frac{(N - S)}{(N + S)}$$

where $N$ is the north-looking measured flux, and $S$ is the south-looking measured flux. Given the direction of the magnetic field in the vicinity of the satellites, and using the sense of gyration of protons, $A_{EW} > 0$ generally implies a higher density (flux) inside the spacecraft, whereas $A_{EW} < 0$ implies a higher density outside the spacecraft. For a stretched (taillike) magnetic field orientation (as distinguished from a completely dipolar field), one also obtains some secondary information from $A_{EW}$. Similarly, the primary information from $A_{NS}$ concerns higher flux above ($A_{NS} > 0$) or below ($A_{NS} < 0$) the spacecraft. The implications of various kinds of gradient anisotropies are summarized in Table 1.

We only present $A_{EW}$ and $A_{NS}$ for the 03 LT position here since this was the primary region into which the direct particle injection was observed. In order to give a sense of the magnetic field orientation at that location, Figure 14 shows the magnetic field line meridional tilt $\theta_B$. The dashed line, for reference, is the field tilt at 0700 LT, while the solid
line is the value of $\theta_B$ at 0300 LT. Note that in a dipole magnetic field $\theta_B$ would be the magnetic dip angle ($\theta_B = \tan^{-1}(2 \tan \lambda)$). For the 76-059/GOES spacecraft this means the dipolar value would be $\approx 25^\circ$, while for 77-007/ATS the dipolar value would be $\approx 10^\circ$. An extreme tail-like (nondipolar) magnetic configuration with the field lines lying nearly parallel to the magnetic equatorial plane is seen at 03 LT during the flux dropout. This again seems to reinforce our interpretation that a large-scale boundary motion took place during the dropout period. It also strongly suggests that the spacecraft entered the high-latitude plasma sheet, where a very tail-like field would be expected. We note that the appearance of this taillike field topology is a common precursor to substorm onset [McPherron, 1970; Baker et al., 1978] and apparently indicates an extreme stressing of the outer magnetosphere prior to the substorm energy release at 1200 UT.

Figure 15 shows the $A_{EW}$ (upper panel) and $A_{NS}$ (lower panel) values calculated from the 77-007 energetic proton data ($E > 145$ keV). Looking at $A_{EW}$ and $A_{NS}$ together, the following sequence of events is seen. Between 1155 and 1200, i.e., during the recovery from the flux dropout, $A_{EW}$ was strongly positive. This suggests that the higher particle density was inside the spacecraft; $A_{NS}$ during this same period was, for the most part, strongly negative, suggesting a high particle flux below the spacecraft. Since Figure 14 showed the field to be very taillike during this period, our contention of a boundary motion during the dropout, with the high flux region moving earthward and equatorward, is fully borne out. As the fluxes recover, the spacecraft were enveloped from inside and from below.

At 1200 UT, $A_{EW}$ went strongly negative. This period corresponded precisely to the first energetic particle and hot plasma injection into synchronous orbit. The character of $A_{EW}$ showed that the injected particles came from outside the spacecraft location. For this same period, $A_{NS}$ was strongly positive, showing that the particles also generally arrived from above the spacecraft. The conclusion is therefore unambiguous in this case, viz., the injected particles arrive at 6.6 $R_E$ from the outside and from above. This very likely means that these particles filled the high-latitude plasma sheet and that these filled field lines then collapsed inward over the spacecraft.

After the leading edge of the particle injection passed over the spacecraft, $A_{EW}$ went strongly positive, and $A_{NS}$ was weakly negative (1202-1205 UT). This indicates that the highest particle density, after the injection, was generally inside 6.6 $R_E$.

A second particle injection occurred (cf. Figures 3 and 5).

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<td>$A_{NS}$</td>
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![Graph showing proton phase space density variations for the 1200 UT substorm period. Densities at constant first invariant values (\(\mu\), as labeled) are plotted.](image)
Fig. 14. Field line dipolar tilt angle $\theta_B$ inferred (as described in text) from the energetic electron anisotropy symmetry axis. A very taillike field ($\theta_B \approx 60^\circ$) is observed at $\sim0300$ LT.

at $\sim1205$ UT. Figure 15 shows again that these particles came from outside $6.6 R_E$ since $A_{EW}$ was strongly negative. Note in Figure 14 that $B$ was more nearly dipolar by $1205$ UT. Therefore, in this case $A_{NS}$ became only weakly positive during the injection. It is concluded with considerable certainty that the $1205$ UT injection of energetic particles and hot plasma, as was also true for the $1200$ UT case, came from outside of synchronous orbit.

The apparent $1208$ UT injection of particles (see Figures 3 and 5) seemed to show energy dispersion effects consistent with the interpretation that the injection front did not directly extend as far eastward as $0300$ LT. Indeed, a substantial gradient anisotropy signature of this injection is not seen in Figure 15.

A composite plot of the $>145$-keV proton flux and the computed value of $A_{EW}$ is shown in Figure 16. The recovery sequence between $1155$ and $1200$ UT, the flux injection at $1200$ UT, and the flux injection beginning at $1205$ UT are all particularly evident in that figure. Minor (but statistically significant) changes in $A_{EW}$ between $1212$ and $1225$ UT are also evident as subsequent small pulses of protons drift past the spacecraft, approaching from the east ($A_{EW} > 0$) and receding to the west ($A_{EW} < 0$).

**Drift-Echo Timing Information**

Proton drift-echo events such as shown above in Figures 5 and 7 can be used to infer times and locations of the 'centroids' of particle injections [Belián et al., 1978]. As illustrated by the detailed 10-s flux averages in Figure 17, the pulses of drifting protons show evidence of basically a triple structure in each pulse. These more detailed (10-s) flux values have been used to carefully determine the time of the 'peak 1', 'peak 2', and 'peak 3' relative flux maxima for the $0.4-0.5, 0.5-0.6, 0.6-0.8$, and $0.8-1.0$ MeV channels at the $0700$ and $0300$ LT positions. The local time of the observed peak pulses (modulo $360^\circ$) was then considered versus the universal time of each peak pulse. Two drift-echo pulses could be clearly discerned in each of the two lower-energy ranges, while three pulse echoes were seen at the two higher energies.

Table 2 summarizes the LT and UT data points inferred from the high-resolution drift-echo data. It should be noted that discerning the individual relative 'peaks' was uncertain when the pulses overlap. On the other hand, some of the peak times, as might even be evident from the 1-min averages of Figures 5 and 7, are quite distinct and obvious. Other of the peak times had to be judged from relatively subtle inflections in the flux profiles. Overall, the data points
in Table 2 have associated UT uncertainties of approximately ± 1 min.

Results for the several selected 76-059 and 77-007 energy channels are plotted in Figure 18. In each panel we separately plot data for each of the peak 1 through peak 3 pulses. The parameter \( \phi \) is equivalent to LT (in degrees), except that it runs clockwise from midnight (in the same sense as proton drifts) rather than counterclockwise. For each energy channel a least-squares fit through the data points is shown.

As seen by Figure 18, it is possible to arrive at an internally consistent interpretation of all of the high-energy proton data, at both 0700 LT and 0300 LT. This interpretation is that there were three high-energy proton injections centered in the post-midnight region and that these injections each exhibited several echoes that were individually seen at both the 0700 and 0300 local times. The universal times of the injections inferred from Figure 18 are: peak 1 events, ~1200 UT; peak 2 events, ~1205 UT; and peak 3 events, ~1208 UT.

**ADIABATIC MODELING RESULTS**

A major underlying theme of our analysis has been that substorm energetic particles are injected in the nightside magnetosphere and that these particles subsequently are trapped and drift to positions removed from the injection site. Much of the foregoing analysis has been carried out within this framework and generally supports such an interpretation. However, in order to model the injection and drift more quantitatively the time-dependent convection model of Smith et al. [1979] was used.

This model follows the motions of charged particles under the influence of the geomagnetic and electric fields. A Volland-Stern type of convection electric field \( E = -V \Phi \) and \( \Phi = AR^2 \sin \phi \) and a dipole magnetic field are assumed. Here \( \Phi \) is the electric potential, \( \phi \) is a local time parameter measured from local midnight, and \( R \) is geocentric radial distance. As shown by Smith et al. [1979], the time variation in the electric field may be characterized by the geomagnetic index \( Kp \), which is then introduced via the parameter \( A \).

Although this large-scale convection model has been quite successful in predicting the behavior of low-energy charged particles during storms [cf. Smith et al., 1979], a goal of the CDAW 2 effort was to test the model for higher-energy particle injections. Figure 19 illustrates several of the results for 'high-energy' trajectory simulations. In each case, protons with \( \mu = 1.0 \text{ keV}/\gamma \) (100 MeV/G) and pitch angle = 90° were injected at a boundary of 10 \( R_E \). For \( \mu = 100\text{MeV/G} \) the kinetic energy of the protons at \( L = 6.6 \) would be about 100
keV. In Figure 19, 1-hour increments of the trajectories between 1200 and 1600 UT on December 29 are displayed. In each instance the GEOS-1 orbit is shown for reference.

Case A shows the nominal model calculations for assumed proton injections at 2300 LT through 0300 LT. As is evident from the figure, the normal convection model described in the preceding paragraph gives rise to untrapped particle drift trajectories which typically encounter the dayside boundary near local noon. In Figure 19b, the Volland-Stern convection field was decreased to one-fourth strength in the radial range 6–10 Re and 1000–1400 LT. This change causes the particles to be 'pulled' back on the dayside, and the relatively high-energy protons injected at 0200–0300 LT are thereby trapped. (Note, however, that the boundary between the decreased field and the normal model field in case B is nonphysical).

Magnetic field observations in the outer magnetosphere during the substorm period under investigation indicated a gradient (ΔB/B) value much less than the normal, nonstorm value. In case C of Figure 19, ΔB/B was reduced to one-half its normal value to be more consistent with observations. This feature increased the trapping efficiency somewhat, but most trajectories from the midnight sector still remained untrapped.

Finally, in case D the field gradient was maintained as in case C but the convection electric field was increased by a factor of 2 in the radial range 7–10 Re and between 2000 LT and 0400 LT. This change drove particles more deeply into magnetosphere initially and thereby increased the trapping. (Again, the boundary between the increased and normal field is unphysical.)

In summary, the time-dependent convection model can produce trapped drift trajectories for the higher-energy proton component (≥100 keV). The changes to the normal model in order to accomplish a large trapping ratio (such as changing the magnetic field gradient) appear quite consistent with observation and, thus, seem to provide reasonable physical improvements to the model. In most cases, it is seen that only high-energy protons injected near 0200–0300 LT are durably trapped. It is interesting that our proton drift-echo analyses also tend to show injection positions near 0200 LT for the observed proton pulses in this substorm case (cf. Figure 18).

**DISCUSSION AND SUMMARY**

In this paper we have used energetic particle and magnetic field data from six satellites near geostationary orbit to study...
Fig. 19. Several time-dependent convection model trajectory plots (as described in the text) for high-energy protons on July 29, 1977.
an intense substorm period on July 29, 1977. Using these several spacecraft well-distributed in local time has given us a perspective on global substorm phenomenology not previously available. Several different analysis techniques (of which some are unique to energetic particles) were applied to the data sets, and a self-consistent picture of the event period has emerged.

The following list summarizes our observational results for the 1200 UT substorm at the three local times samples:

**Observations at 0300 LT**

Taillike magnetic field topology was seen prior to substorm onset.

Large-scale boundary motion occurred as indicated by the flux dropout.

Dropout boundary motion was to the inside and below observing spacecraft.

Observing satellites remained in a finite flux region (high-latitude plasma sheet).

In recovery from the dropout, the spacecraft were enveloped from below and inside.

Two clear particle injections occurred (1200 and 1205 UT), with injection fronts extending as far east as 0300 UT.

Injected particles clearly came from outside and above the spacecraft.

High-energy proton drift echoes were seen (injected at ~0100–0200 LT).

**Observations at 0700 LT**

Weak flux decline was observed.

Only mildly taillike magnetic field stretching was seen.

Energy-dispersed injected electron population was observed: 1205–1220 UT.

Initial proton injection spikes were only weakly manifested.

Proton drift-echo peaks were clearly seen (injected ~0100–0200 LT).

**Observations at 1300 LT**

Energy-dispersed injected protons and electrons (E ≥ 50 keV) were observed: 1205–1220 UT.

Most low-energy (E ≤ 50 keV) particle effects (1130–1300 UT) were adiabatic.

Based on the results presented here, some very firm conclusions about substorm phenomenology can be stated, and these results can be extrapolated slightly to speculate on the missing pieces. First, there seems to be considerable evidence that the magnetosphere went through a period of substantial energy storage prior to the sudden energy release at ~1200 UT [McPherron, 1970; Baker et al., 1978]. An attractive and consistent interpretation is that this energy storage manifested itself as a taillike change of the magnetic topology at 6.6 Re before the substorm, which in turn caused the observed flux dropout. The developing magnetic stress seemed to relax slightly (1155–1200 UT), and then at 1200 UT it was suddenly relieved in the midnight sector simultaneously with the injection of the first pulse of hot plasma and energetic particles.

Our results also show that the injected substorm particles came from outside (and above) the spacecraft at ~0300 LT. With the present information we are unable to tell from how far outside 6.6 Re the particles originated. Given the very stretched magnetic field topology that existed during the injection process, it is quite possible that the field lines carrying the injected particles actually extended deep into the plasma sheet (i.e., beyond 10 Re). One point that is clear is that there was only a very low level of energetic protons with E > 0.3 MeV in the outer radiation zone before the substorm onset, and yet a large flux of such particles clearly appeared at geostationary orbit at substorm onset. Adiabatic modeling shows that trapping can be simulated by convection of high-energy particles from beyond 10 Re.

Several recent papers have discussed the outer zone plasma injection process in terms of convection electric fields [cf. Kaye and Kivelson, 1979, and references therein]. These papers show that inward convection of plasma sheet particles associated with large-scale substorm electric fields can lead to substantial particle acceleration (as indeed was the case in the modeling represented in Figure 19). In this regard, however, Kivelson [1980] has shown, for the 1200 UT event discussed in this paper, that acceleration of particles up to ~1 MeV cannot be done with the usual solar-wind-imposed convection electric field.

Kivelson [1980] has argued that the substorm induction electric field may play an important role in the energization of the high-energy particles seen in this event. Using (see Figure 11)

\[
(\Delta B/\Delta t) \sim 100 \gamma/5 \text{min}
\]

Kivelson estimates (using \( \nabla \times E = -(\partial B/\partial t) \)) that

\[
\Delta \phi = l^2 \Delta B/\Delta t
\]

where \( \Delta \phi \) is the change of electric potential, and \( l \) is the scale of the region in which \( B \) was collapsing. Assuming \( \Delta \phi \) is of the order of 1 MV and \( \Delta B/\Delta t \sim 20 \gamma/\text{min} \) gives \( l \sim 9 \text{Re} \). Such a scale size for the region of near-tail collapse associated with the substorm seems reasonable and thus suggests that induction fields could account for the observed particles at geostationary orbit.

Based on large numbers of other high-energy proton events observed at synchronous orbit and in the plasma sheet, Baker et al. [1979] argued in favor of the importance of induction electric fields. They showed from the timing and duration of energetic proton events that particles with energies of ~1 MeV cannot be produced by a small inward radial convection, say from 8–10 Re; large impulsive acceleration must be responsible for their production [e.g., Pellinen and Heikila, 1978]. The high-energy proton results shown for this event are, therefore, consistent with the plasma sheet energization model presented by Baker et al. [1979].

In summary, it seems evident that the multiple-spacecraft observational approach used here is powerful. Since the geostationary satellites that we have used in this paper have acquired literally years of concurrent data, we look forward to many future joint studies of the effects of geomagnetic storms and substorms on magnetospheric energetic particle populations.

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