RICE UNIVERSITY

HIGH-SPEED TRANSLUNAR MAGNETOTAIL PLASMA FLOWS

by

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ABSTRACT

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Unusual, high-speed flows of plasma away from the Sun in the translunar magnetotail are discovered to occur persistently. Faster, cooler, and less dense than the plasma flows customarily encountered in the translunar magnetotail, these flows suggest that small-scale magnetic merging occurs regularly in the plasma sheet.

Particle and field data from eight and one-half magnetotail crossings are studied, making this the most extensive survey to date. Those crossings are chosen for which there are magnetometer data from Explorer 35 and particle data from the Rice Suprathermal Ion Detector Experiment (SIDE) set up on the Moon by the crew of Apollo 14. This SIDE, like its twins from Apollos 12 and 15, measures plasma energy distributions in the energy/charge range between 10 and 3500 eV/q. Computer reduction of these SIDE data yields plasma bulk speeds, temperatures, and densities.

With the assumption that the plasma is entirely hydrogen, it is found that the plasma flows are characterized by bulk velocity $u = 250$ to $700$ km/s, ion temperature $kT = 50$ to $100$ eV, and ion density $n = 0.001$ to $0.01$ cm$^{-3}$. Most of these flows ("bubble" flows) occur within one or two hours of changes in tail magnetic field strength and direction,
changes suggesting the passage of the Moon near a magnetic bubble. Two or three flows ("lobe" flows) are associated exclusively with $\gtrsim 10 \gamma$ magnetic fields parallel or antiparallel to the Earth-Sun axis. Neither type of flow is directly related to solar or geomagnetic activity.

The transfer of magnetic field energy to mantle plasma in the cislunar magnetotail may cause the bubble flows. Appearances of doubly peaked plasma energy distributions are briefly discussed. The origin of the lobe flows is uncertain. If the field lines associated with them map into a magnetic bubble, the flows are probably bubble flows observed farther than usual from their places of origin. If the field lines map into the polar regions of Earth, then the lobe flows may be ions such as $\text{H}^+$, $\text{He}^+$, $\text{He}^{++}$, and $\text{O}^+$ escaping from the polar ionospheres.
ACKNOWLEDGMENTS

I am pleased to thank Prof. John Freeman, Jr., for suggesting and being the director of this research. I also thank Dr. Kent Hills and Mr. David Nystrom for their knowledge of shortcuts and procedures not contained in the computer manuals, and

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I. INTRODUCTION

The Moon is an excellent space observation platform because its relatively distant and stable circular orbit 60 $R_E$ above Earth's center passes through several environments of magnetospheric interest. For example, at the new and quarter phases the Moon transits portions of interplanetary space ventilated by the solar wind. The plasma constituting this radially outflowing wind has, on the average, bulk speed $u \sim 450$ km/s, number densities $n_i = n_e \sim 5$ cm$^{-3}$, and temperatures $kT_i \sim 8$ eV, $kT_e \sim 13$ eV. The full phase brings the Moon into a completely different region, the magnetospheric tail.

Because of the combined motions of the Earth, Moon, and magnetotail, the Moon's magnetotail passages are not identical. Usually encountered are the magnetosheath, magnetopause, and plasma sheet; excursions into the plasma mantle are less frequent.

Equipment installed on the Moon for Rice University (Final Report 1975) allows these regions to be extensively surveyed. Reduction of data provided by these instruments, called Suprathermal Ion Detector Experiments (SIDEs), indicates that the tail passages from lunation to lunation are roughly similar with 20-minute time resolution. The plasma's antisolar bulk speed $u$ (km/s), ion number density $n$ (cm$^{-3}$), and ion temperature $kT$ (eV) vary characteristically from region to region (Hardy 1976, Hardy et al. 1975, Fenner 1971). For example, in the magnetosheath the ordered
triple of average plasma parameters \((\bar{u}, kT, \bar{n})\) is \((200, 80, 2)\). The magnetosheath passage lasts about one day, after which time the dusk magnetopause is crossed and the plasma sheet, having parameters \((0, \leq 1000, 1)\), is traversed. Mantle plasma, characterized by \((100, 10, 2)\), may appear at any time, but only briefly, and usually close to the flanks of the magnetopause. About four days later the Moon crosses the dawn magnetopause and exits the tail via the magnetosheath.

At 2-minute resolution, a type of plasma flow with parameters \((500, 80, 0.003)\) appears during the tail crossings. A few isolated flows of this distinctive type have been seen and investigated previously and hypothetically identified as polar ionospheric \(H^+, He^+, He^{++}\), and/or \(O^+\) on the basis of associated magnetic field signatures (Hardy, Hills, and Shull 1978). The present work establishes, however, that these flows occur reliably during magnetotail crossings and, additionally, that most of them are associated with tail magnetic field signatures of a completely different type. It is also found that these flows are only indirectly related to solar and geomagnetic activity indicators such as AE, Kp, and the direction of the z-component of the interplanetary magnetic field \(B_z^{IMF}\). In other words, magnetospheric disturbances are not required for the occurrence of the special flows but, rather, create conditions conducive to their increased production and/or detection.
II. EQUIPMENT

Two types of equipment are used in this research, namely, the SIDE and the Explorer 35 Magnetometer (Lindeman 1973). There are three SIDEs on the Moon's earthward face, oriented to detect positive ions coming in within about 30° of the Earth-Moon axis and almost parallel to the ecliptic and lunar orbital planes. Each SIDE actually comprises two devices, the Total Ion Detector (TID) and the Mass Analyzer (MA). In this work, only the TID, which measures the positive ion energy/charge ratio between 10 and 3500 eV/q, is used. The MA is not useful because it analyzes the masses of only the slowest, least energetic (<50 eV) ions. The Explorer 35 magnetometer orbits the Moon and makes vector measurements of the magnetic field.

A. The SIDE in Detail

1. Location and Orientation

The SIDEs are at the landing sites of Apollos 12, 14, and 15 with their "look directions" tilted relative to the local vertical. The ordered quadruples (longitude, latitude; longitudinal tilt, latitudinal tilt) of the SIDEs in selenographic coordinates are (23.4 W, 3.04 S; 15 W, 3 N) for Apollo 12, (17.5 W, 3.65 S; 15 E, 4 N) for Apollo 14, and (3.65 E, 26.2 N; 15 E, 26 S) for Apollo 15. By virtue of its reliable performance and favorable look direction always within 25° of the Earth-Sun line during tail passages, the Apollo 14 SIDE was used in this work. Refer to Figure 1.
Figure 1(a). SIDE locations.
Figure 1(b). SIDE look directions at lunar noon. Short arrows = look directions, long arrows = local verticals.
Figure 1(c). SIDE look directions in the ecliptic plane.
for drawings of SIDE locations and look directions.

2. TID Design

The central feature of the TID is a concentric pair of circularly curved plates, the outer one at a positive potential \( V \) relative to the inner one. Consequently, there is an electric field which accelerates positive ions located between the plates toward the inner plate. An ion of the proper speed, however, can cancel the electrical acceleration with a centrifugal one and thereby escape from between the plates without hitting either. A straightforward calculation of the electrical-centrifugal balance for an ion with mass \( m \), charge \( q \), and speed \( u \) in this device then requires that

\[
\frac{mu^2}{q} = V/\ln(b/a)
\]

for successful passage, where \( a \) and \( b \) are the respective radii of the inner and outer plates.

3. TID Operation

The TID aperture is designed to guide particles squarely into the region between the two curved plates. Those particles which are positive ions satisfying the above relation will pass through the interplate gap without hitting the plates. Upon exit, the ions are accelerated by a \(-3.5\) kV potential relative to the plates into a Bendix 4028 Channeltron electron multiplier for counting.

The voltage between the plates is cycled through twenty steps in order to count ions with energy/charge ratios centered on \( 10, 20, 30, 50, 70, 100, 250, 500, 750, \ldots, 3500 \) eV/q. Because of the nonzero distance \( b-a \) between the
plates, each energy/charge channel actually counts ions that are spread within $\pm 5\%$ of the central energy/charge. Each step in the 24-second-long cycle includes 1.13 s for counting and 0.07 s for data readout and voltage readjustment. The complete TID operating cycle is detailed in Figure 2.

Another voltage stepping cycle, involving the TID aperture, is of minor importance to this work. The TID is grounded to the lunar surface by a spiderlike web of wire, thereby allowing a wire mesh screen guarding the TID aperture to be cycled through 24 steps of 2.56-minute duration between $\pm 27.6$ V relative to the Moon. This permits one to determine the lunar surface potential by examining the effect of the aperture voltage on counting rates of ambient, low-energy, lunar ions. Clearly, the resulting energy variations of order $\pm 10$ eV little effect the high-energy ions being studied here.

**B. The Magnetometer in Detail**

1. Location

The Explorer 35 satellite was launched from Earth on 1967 July 19 and directed to an orbit about the Moon that is approximately in the ecliptic plane. Aposelene and periselene are, respectively, 5.42 and 1.44 $R_M$, while the period is 11.5 hours.

2. Magnetometer Design

The device is a fluxgate magnetometer comprising three
<table>
<thead>
<tr>
<th>SIDE FRAME</th>
<th>TID</th>
<th>MA</th>
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<tr>
<td>0</td>
<td>4*</td>
<td>Mass Spectrum 48.6 eV/q</td>
</tr>
<tr>
<td>1-19</td>
<td>Energy Spectrum</td>
<td>Mass Spectrum 16.2 eV/q</td>
</tr>
<tr>
<td>20</td>
<td>Energy Spectrum</td>
<td>Mass Spectrum 5.4 eV/q</td>
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<tr>
<td>21-39</td>
<td>Energy Spectrum</td>
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<tr>
<td>40</td>
<td>Energy Spectrum</td>
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<tr>
<td>41-59</td>
<td>Energy Spectrum</td>
<td>Mass Spectrum 0.2 eV/q</td>
</tr>
<tr>
<td>60</td>
<td>Energy Spectrum</td>
<td>1*</td>
</tr>
<tr>
<td>61-79</td>
<td>Energy Spectrum</td>
<td>2*</td>
</tr>
<tr>
<td>80</td>
<td>Energy Spectrum</td>
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<td>81-99</td>
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<td>101-119</td>
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<td>120</td>
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<td>1*</td>
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<tr>
<td>126</td>
<td>2*</td>
<td>1*</td>
</tr>
<tr>
<td>127</td>
<td>3*</td>
<td>2*</td>
</tr>
</tbody>
</table>

Figure 2. TID Operating Cycle.
1* Background Reading Taken; Curved Plates Grounded
2* Counting Electronics Calibrated at 137 Hz.
3* Counting Electronics Calibrated at 17.5 kHz.
4* Counting Electronics Calibrated at 560 kHz.
mutually perpendicular magnetic field detectors.

3. Magnetometer Operation

This magnetometer measures the three field components every 6.14 s in each of the three scales 0-20, 0-60, and 0-200 \( \gamma \). Explorer 35 is spin-stabilized, so the data are corrected onboard for the effects of rotation before they are transmitted to Earth. The data used in this work are 81.8-s averages of the field in solar equatorial coordinates, courtesy of Dr. D. S. Colburn.

Unfortunately, several technical problems mar the usefulness of this satellite. The lack of an onboard data recorder results in the loss of data collected while the Moon occults Earth. Additionally, weak batteries drain sooner than planned while the Explorer's solar panels are in shadow, so causing the loss of more telemetry. The data gaps total 7 to 15 hours per day. Also, the satellite has lost its longitude reference, with the result that the reported field vectors are off by an unknown amount in longitude. Fortunately, the error can be corrected to about \( \pm 10^\circ \) by comparing the reported field longitude to the field's actual longitude, which is either \( \sim 0^\circ \) or \( \sim 180^\circ \) in the tail. Finally, the fact that the magnetometer is in orbit while the SIDES are on the Moon means that there may be a difference between the times recorded by Explorer and the SIDES for any given event. The difference can be as large as 2.5 hr for a magnetopause crossing, or as small as 19 s for a 400 km/s flowing plasma event.
III. DATA REDUCTION

The data telemetered to Earth from the SIDEs are counts of positive ions in various energy ranges, or channels, as functions of time. This information is conveniently and graphically arrayed in three-dimensional form with \((x, y, z)\) corresponding to (central energy/charge, start time of cycle, number of counts). An example appears in Figure 3. Notice that a section of this surface sliced parallel to the \(xz\)-plane is an energy spectrum, a fair representation of the ionic energy distribution for a 24-s period. The ordinate of this spectrum is related to the differential flux \(j\). Assuming that the ion species is known, \(j\) is the flux of ions of that species into the TID per unit energy per unit solid angle. The 3x8 mm TID aperture gathers ions from a solid angle roughly \(6^\circ\) square centered on the TID's look direction. Therefore, \(j\) has the dimensions ions \(cm^{-2} s^{-1} sr^{-1} eV^{-1}\). It is a sort of monoenergetic intensity reminiscent of the specific intensity \(I_\nu\) of radiative transfer theory.

A. Theoretical Aspects

1. Introduction

In reality, \(j\) is a step function; \(j(E)\) has twenty discrete values between 10 and 3500 eV/q. For the moment, though, \(j(E)\) is idealized as a continuous function in order to conveniently discuss its utilization. The plan is to transform \(j\) into a three-dimensional distribution function \(f\), whence the plasma parameters \(n, u,\) and \(T\) are readily derived. These parameters may also be obtained by fitting curves to \(j\),
Figure 3. Twenty-minute averages of Apollo 14 SIDB counting spectra. Channel energies in ev are marked along bottom edge. Start time = 1972 3-26 2 UT.
but the cost in time and money is prohibitive for a project of this scale.

2. Derivation of $f$, $n$, $u$, and $T$

One derives $f$ from $j$ by equating equivalent expressions in terms of $f$ and $j$ for the total number of particles $C$ counted by the TID in some time interval $t$. From the definitions of $f$ and $j$

$$ C = \iiint j \, da \, dt \, dw \, dE = \iiint f \, d^3r \, d^3v $$

where $da$, $dt$, $dw$, $dE$, $d^3r$, and $d^3v$ are the respective differentials of area, time, solid angle, energy, coordinate space, and velocity space. Now the integral of $f$ is transformed. The velocity space volume element in spherical coordinates is $d^3v = v^2 \, dv \, dw$. The coordinate space volume element is $d^3r = da \, ds$, where $ds = v \, dt$ is the farthest a particle can be from the TID aperture and still get in before time $dt$ has elapsed. Therefore

$$ \iiint f \, d^3r \, d^3v = \iiint f \, (v \, da \, dt)(v^2 \, dv \, dw) $$

Thus

$$ \iiint j \, da \, dt \, dw \, dE = \iiint v^3 \, f \, da \, dt \, dw \, dv $$

This implies that $j \, dE = v^3 \, f \, dv$. Since $E$ is the kinetic energy $m \, v^2/2$ of the ion, $dE = m \, v \, dv$, and $m \, v \, j \, dv = v^3 f \, dv$. This result may be cast in terms of velocity or energy:

$$ f(v) = \left(\frac{m}{v^2}\right) j(v) \text{ or } f(E) = \left(\frac{m^2}{2E}\right) j(E) $$

With an expression for $f$, one may write the standard statistical mechanical expressions for number density, bulk velocity, and temperature:
The integrations are over all velocity space.

\[ n = \int d^3\vec{v} \]
\[ \bar{u} = n^{-1} \int \vec{v} f d^3\vec{v} \]
\[ kT = (m/3n) \int (\vec{v} - \bar{u})^2 f d^3\vec{v} \]

B. Practical Aspects

1. Introduction

The results of the preceding section must now be revised for practical use. First, a connection is set up between \( j \) and the data transmitted by the SIDEs. Next, modifications are made to accommodate shortcomings in the data, such as their incompleteness, and contamination by the statistical, mechanical, and physical effects described later.

2. Calculation of \( j \) from the Data

The quantity \( C \) telemetered to Earth is the number of ions counted in 1.13 s as a function of energy channel. In the previous section \( C \) was equated to a limited integral of \( j \) over area, time, solid angle, and energy:

\[ C = \iiint j \, da \, dt \, dw \, dE \]

To perform this integration one needs detailed knowledge of \( j \) as a function of \( \vec{r}, \vec{v}, \) and \( t \). In fact, one has no such knowledge, and must consequently be satisfied to approximate the integral with a product, remembering that the TID has a certain efficiency \( \varepsilon \):

\[ C \approx j \Delta a \, \Delta t \, \Delta w \, \Delta E \, \varepsilon \]

Then

\[ j = C/(\Delta a \, \Delta t \, \Delta w \, \Delta E \, \varepsilon) = C/(G \, \Delta t \, \Delta E) \]

where \( G = \Delta a \, \Delta w \, \varepsilon \). Instrument preflight calibrations
revealed that \( G \) and \( \Delta E \) vary with the energy channel. However, good approximations were found to be \( G = 1E-4 \text{ cm}^2\text{sr} \) and \( \Delta E = E/10 \). Of course, \( \Delta t = 1.13 \text{ s} \). Therefore, with \( E \) in eV,

\[
j = (8.85E+4) \frac{C}{E} \text{ ions cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{eV}^{-1}
\]

Lindeman (1973) estimates the uncertainty in \( j \) to be \( \pm 70 \% \).

There is another deficiency in the energy spectra related to their steplike nature. This is that the spectra are incomplete samples of the plasma energy distributions. Each energy channel has a "bandpass" \( \Delta E \) amounting to 10% of its central energy. For all of the channels below 2500 eV, the bandpasses are too small to span the 250 eV gaps between channels. The bandpasses of the higher-energy channels overlap. Figure 4 shows this interchannel spacing graphically.

The net result of this spacing is that, in each spectrum, only 70% of the energy range between 10 and 3500 eV is surveyed. This causes particle number densities to be underestimated. Fortunately, plasma temperatures and bulk speeds, being derived from the shape of the distribution of energy, are only slightly affected.

3. Revision of the Integrals of \( f \)

Given an expression for \( j \), it would seem simple to derive expressions for \( f \) and the plasma parameters. Since the SIDE transmits twenty values of \( C \) for each energy/charge spectrum, one would perform the transformations \( C_i \rightarrow j_i \rightarrow f_i \) for \( i = 1 \) to 20, and replace the integrals of \( f \) by 20-term
Figure 4. The gaps and overlaps of the counting spectrum energy bandpasses. Each bandpass is labelled with its central energy in eV.
summations. One would then be finished. Unfortunately, three circumstances concerning completeness of the data, as well as statistical and physical effects, require the integrals to be modified before they are converted into summations.

Observe first that the integrations giving \( n, \mathbf{u}, \) and \( T \) should be carried out over all velocity space \( v^2 dv \, dw \). In reality, though, \( f \) is known only for the 36 deg\(^2\) solid angle centered on the TID look direction, and for the velocities corresponding to the range between 10 and 3500 eV/q. The condition is relieved in two steps. One starts by assuming that the distribution function has the convecting three-dimensional Maxwellian form \( f = a \exp[-b(\mathbf{v} - \mathbf{u})^2] \).

At this point it is convenient to distinguish two cases, corresponding to \( u = 0 \) and \( u \neq 0 \). When \( u = 0 \), \( f \) is isotropic and one readily has

\[
    n = \int f \, d^3 \mathbf{v} = \iint f \, v^2 \, dv \, dw = 4\pi \int v^2 \, f \, dv = 4\pi [v^2]
\]

\[
    kT = (4\pi m/3n) [v^4]
\]

I introduce the definition

\[
    [v^n] \equiv \int_0^\infty v^n \, f \, dv
\]

When \( u \neq 0 \), \( f \) is anisotropic. Performing the integrations over the limited range of \( d^3 \mathbf{v} \) accessible to the TID leads to pathological results in general; distillation of \( n, \mathbf{u}, \) and \( T \) would prove exceedingly difficult. One may make, however, two simplifying assumptions. The first is that \( \mathbf{u} \) is antiparallel to the TID look direction. This is reasonable because the maximum amount of skewness, about
25°, results in a 10 % error in u. The second assumption is that bulk motion dominates thermal motion, i.e., that 

\[ \frac{u}{(2kT/m)^{1/2}} \geq 5. \]

This means that most of the plasma's velocity vectors lie within the TID's narrow solid angle of acceptance. These assumptions allow the replacement of \( d^3v \) by \( dv \) in the integrals of \( f \), which then yield

\[
\begin{align*}
  n &= \left( \frac{2\pi kT}{m} \right) \frac{[v^0]}{[\frac{v}{v^0}]} \\
  u &= \frac{[v]}{[\frac{v}{v^0}]} \\
  kT &= m \left( \frac{[v^2]}{[\frac{v}{v^0}]} - u^2 \right)
\end{align*}
\]

Now to be recognized is a shortcoming common to both the flowing \((u \neq 0)\) and stagnant \((u = 0)\) cases. In other words, the above integrations over \( dv \) assume limits of 0 and \( \infty \), despite the fact that the measurements correspond to limits of 10 and 3500 eV/q. Statistical and physical considerations shrink the domain of integration even further by raising the lower limit to 50 eV/q.

The distribution function \( f \) is proportional to \( C/E^2 \), the number of counts divided by the square of the energy. There are two sources of error in \( C \). The first is the statistical error which goes as \( C^{1/2} \), while the second is inadequate removal of background noise. Since \( f \) is effectively weighted by the factor \( 1/E^2 \), errors in \( C \) in the low-energy channels can affect seriously the calculated values of \( n, u, \) and \( T \).

The physical sources of error involve the lunar environment, in that the ions collected by the TID have had their velocities perturbed by the Moon in four ways. First,
the lunar dayside potential of about +10 V (Freeman et al. 1973) will cause singly charged ions to lose about 10 eV of energy. Second, the TID aperture grid potential, which varies between ±27.6 V relative to the lunar surface potential, will cause further energy changes between ±27.6 eV. Third and fourth are the effects of the Moon's gravitational potential and orbital motion relative to Earth, which make totally negligible perturbations of 0.03 and 0.005 eV, respectively, to proton energies. Since the combined energy perturbations are on the order of a few tens of eV, one does well to disregard the 10, 20, and 30 eV TID channels.

The integrations are thus confined to an energy domain between 50 and 3500 eV. Fortunately, the region of significant f lies between these bounds most of the time, and the deficiency is therefore acceptable. The final forms of the plasma parameter equations are therefore

\[
n = 4\pi \sum v_i^2 f_i \, dv_i
\]

\[
kT = \frac{(m/3)}{\sum v_i^4 f_i \, dv_i} \sum v_i^2 f_i \, dv_i
\]

for the stagnant case, and

\[
u = \frac{\sum v_i f_i \, dv_i}{\sum f_i \, dv_i}
\]

\[
n = (2\pi kT/m) \sum f_i \, dv_i
\]

\[
kT = m \left( \frac{\sum v_i^2 f_i \, dv_i}{\sum f_i \, dv_i} - u^2 \right)
\]

for the flowing case. In both cases, \( dv_i = \frac{1}{2} (v_{i+1} - v_{i-1}) \)
and the summation index \( i \) runs from 4 to 20.

### C. The Computer Program

The computer program, which is designed for large-scale processing of TID data, consists of three sections which prepare the raw data, calculate the plasma parameters for the flowing and stagnant cases, and select the best set of parameters.

The first section begins by averaging the raw counting data over a length of time chosen by the user. Two minutes represents a good compromise between detail and expense. Three-point averaging is next applied according to the formula

\[
C_{i}^{\text{new}} = \frac{1}{2} \left[ \frac{(C_{i-1} + C_{i})}{2} + \frac{(C_{i} + C_{i+1})}{2} \right]
\]

These two averaging schemes usually reduce sufficiently the statistical jitter of the raw data. Next, the background counts \( B_{i} \) and their standard deviations \( SB_{i} \) are computed from information provided by the TID. The sum \( B_{i} + SB_{i} \) is subtracted from \( C_{i}^{\text{new}} \) to obtain reasonably background-free counting data \( C_{i}^{\text{corr}} \).

The second section calculates the flowing and stagnant plasma parameters from \( C_{i}^{\text{corr}} \) as previously indicated. Also computed are the standard deviations of the differential fluxes \( j_{i} \) for use in the next section.

The third section derives two sets of \( f_{i} \) from the two sets of plasma parameters by substituting the values of \( n, u, \) and \( T \) into the Maxwellian expressions for \( f_{i} \). Two sets of \( j_{i} \) are straightforwardly obtained from the \( f_{i} \) since
\[ j_i = (v_i^2/m) f_i. \] These two sets of \( j_i \) are compared to the original \( j_i \) using a Poisson-weighted \( \chi^2 \) technique (Bevington 1969). The plasma parameters giving the best-matching \( j_i \) are adopted as correct.

IV. RESULTS

The eight and one-half tail crossings selected for analysis are, with one exception, all of those for which SIDE and magnetometer data coexist. The extent of the SIDE and Explorer data is portrayed in Figure 5. Each tail crossing bears the number of the lunation, or synodic month, in which it occurred. Also indicated are the times of magnetopause crossings and midpoint transits. The results of the computer calculations are stored on magnetic tape, computer printout, and graphical CRT hardcopy. Representative portions of printout and hardcopy appear in Figure 6.

A. Survey of the Data

A glance at the hardcopy sample in Figure 6 reveals the typical coarse structure of the magnetotail at 60 \( R_E \). Before 0\(^{th}\) UT on 1972 April 26 is the moderately fast, cool, dense magnetosheath plasma. After 5\(^{th}\) UT on April 26 is the stagnant, hot, dense plasma sheet. The transition between the two regions is moderated by the appearance of mantle plasma.

Instances of the unusual, high-speed plasma flows (hereafter called bursts) constitute fine structure; one burst is marked by an arrow in Figure 6. Four hundred and
Figure 5. Tail Crossings. Upper bars = SIDE data, lower bars = Explorer data, wavy lines ≈ magnetopause crossings, vertical bars = midpoint passages.
Figure 6(a). CRT hardcopy version of plasma parameters.
<p>| | | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
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<th></th>
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<tbody>
<tr>
<td>.265E 03</td>
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<td>.156E 03</td>
<td>.507E 02</td>
<td>.132E 00</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>.302E 01</td>
<td>.436E 01</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>.220E 03 #1</td>
<td>.138E 01 #2</td>
<td>.150E 03 #3</td>
<td>.394E 02 #4</td>
<td>.538E-01 #5 #6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>.232E 01 #7</td>
<td>.341E 01 #8</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>.113E 01</td>
<td>.337E 01</td>
<td>.131E 03</td>
<td>.158E 02</td>
<td>.106E 00</td>
<td></td>
<td></td>
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<tr>
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<tr>
<td>.212E 01</td>
<td>.271E 01</td>
<td>.130E 03</td>
<td>.177E 02</td>
<td>.935E-01</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>.215E 01</td>
<td>.637E 00</td>
<td>.114E 03</td>
<td>.339E 02</td>
<td>.210E 00</td>
<td></td>
<td></td>
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</tr>
<tr>
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<td>.604E 00</td>
<td>.139E 03</td>
<td>.409E 02</td>
<td>.986E 15</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>.196E 01</td>
<td>.529E 33</td>
<td></td>
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<tr>
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<td>.980E 02</td>
<td>.832E-03</td>
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<tr>
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<td></td>
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<tr>
<td>.107E 01</td>
<td>.150E 12</td>
<td>.249E 00</td>
<td>.143E 03</td>
<td>.779E 02</td>
<td>.141E 05</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 6(b). Computer printout version of plasma parameters. A box encloses the parameters for a burst occurring on 1972 117d 5h 43m UT.

Key: Item 1 = kT (eV) for stagnant case
      Item 2 = n (cm⁻³) for stagnant case
      Item 3 = u (km/s) for flowing case
      Item 4 = kT (eV) for flowing case
      Item 5 = n (cm⁻³) for flowing case
      Item 6 = case selected (1 = flowing, 0 = stagnant)
      Item 7 = fitting parameter for stagnant case
      Item 8 = fitting parameter for flowing case
fifty-two bursts are observed in the entire data set; their occurrences in the tail crossings are marked in Figure 7. The bursts have bulk speeds between 250 and 700 km/s, ion temperatures between 50 and 100 eV, and ion densities between 0.001 and 0.01 cm$^{-3}$. The exact plasma parameter distributions are shown by Figure 8. The noticeable clumping in bulk velocity, especially for cold bursts, results from the previously mentioned compartmentalization of a smooth plasma energy distribution into discrete channels.

Bursts typically last only a few minutes. It is probable, though, that certain closely spaced series of bursts are actually parts of continuous events. In other words, when the computed flowing and stagnant fits to the data are equally poor, the computer selection process results in an almost random alternation between stagnant and flowing fits on the hardcopy that resembles a picket fence. In these cases, examination of the printout reveals that the unselected flowing fits which could transform the fence into a wall are actually like the selected flowing fits. The fitting quality parameters $\chi^2$ of the flowing and stagnant Maxwellian fits are listed on the printout.

B. Trends in the Data

A first explanation of bursts should account for their main observed properties. These properties have to do with plasma parameter values and burst occurrence patterns.

Examination of Figure 8 indicates that no systematic internal relations exist among $u$, $T$, and $n$ for bursts. All
Figure 7. Burst Occurrences. Short vertical strokes = bursts (number above a stroke is the number of bursts if greater than 1). Other notation as in Figure 5.
Figure 8(a). Plasma Parameter Distributions. Number density vs. bulk speed.
Figure 8(b). Plasma Parameter Distributions. Number density vs. temperature.
Figure 8(c). Plasma Parameter Distributions. Temperature vs. bulk speed.
that may be said is that their average values are \((500, 80, 0.003)\). However, one should also check for relations between the plasma parameters and external conditions. This will be done in the next section.

Definite observations may be made, however, about burst occurrence. An examination of Figure 7 shows that bursts tend to occur in groups, that the number of bursts per lunation varies markedly, and that bursts tend to occur predominantly on one side or the other of the tail crossing midpoint. Table 1 is a numerical summary of these facts.

<table>
<thead>
<tr>
<th>Lunation</th>
<th># in 1st Half</th>
<th># in 2nd Half</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>28</td>
<td>7</td>
<td>53</td>
<td>60</td>
</tr>
<tr>
<td>29</td>
<td>8</td>
<td>53</td>
<td>61</td>
</tr>
<tr>
<td>30</td>
<td>-</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>31</td>
<td>5</td>
<td>6</td>
<td>11</td>
</tr>
<tr>
<td>32</td>
<td>48</td>
<td>57</td>
<td>115</td>
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<td>36</td>
<td>14</td>
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<td>30</td>
<td>31</td>
</tr>
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<td>40</td>
<td>27</td>
<td>72</td>
<td>99</td>
</tr>
<tr>
<td>42</td>
<td>8</td>
<td>24</td>
<td>32</td>
</tr>
</tbody>
</table>

**Table 1. Burst occurrence statistics**

Explanations for these basic observations are presented in the next section.

**V. ANALYSIS**

This section makes three principal statements about the observed characteristics of bursts. They are, one, that the distribution patterns in Table 1 are consequences of lunar and plasma sheet relative motion, two, that burst occurrences correlate with the encounter of magnetic bubbles in the tail, and three, that the energy released by merging
processes that may transpire between the bubbles is consistent with the kinetic energy of the bursts. Geomagnetic activity is sometimes important, and is discussed in connection with the effects of the relative motion of the Moon and plasma sheet.

A. Effects of Relative Motion

1. Lunar Motion

The relative motion of the Moon and plasma sheet accounts for the variation in the number of bursts observed per tail passage, as well as the asymmetrical distribution of the bursts about the passage midpoint. Basically, the closer the Moon comes to the center of the plasma sheet, the more bursts are seen during that passage. The asymmetry of the distribution depends on the angle between the lunar orbit and the plasma sheet symmetry plane.

Consider the appearance of the lunar orbit and the plasma sheet's cross-section to an Earthbound observer who is fixed in a right-handed geocentric coordinate system with his back to the Sun. Let the +x-axis point to the Sun, and have the +z-axis parallel to the projection of the northern half of Earth's spin axis onto a plane which is perpendicular to the x-axis.

How will the lunar motion appear to this observer? In an inertial heliocentric coordinate system the Earth's spin axis is essentially fixed because the precession period of the axis is 26,500 years. Consequently, the angle between the y-axis and ecliptic plane cycles annually between $\pm 23.5^\circ$. 
The Moon's orbit is inclined about $5^\circ$ to the ecliptic. Because the lunar orbit precesses as well, the inclination of the orbit to the ecliptic varies between $\pm 5^\circ$ as seen by the Earthbound observer. Thus, that portion of the lunar orbit seen by the observer assumes inclinations to the $y$-axis between $\pm 28.5^\circ$. Realize also that the observer will not necessarily see the lunar orbit intersect the $x$-axis. At $x = -60 \, R_E$ the lunar orbit will have a $z$-intercept (defined as the $z$-coordinate when $y = 0$) ranging between $\pm 5 \, R_E$, which is the product (radius of lunar orbit)$x$($\sin(\pm 5^\circ)$). The precise path may be calculated using the ALSEP/SIDE ephemeris.

2. Plasma Sheet Motion

The apparent motion of the plasma sheet is now looked at. The plasma sheet's orientation is the result of two independent motions which are well-described by Bowling (1974). The motion is clearly visualized if the plasma sheet is modelled as a long board that is hinged to the plane of the geomagnetic equator $5 \, R_E$ out in the plane from Earth's center.

The first motion, which Bowling calls pivoting, is a consequence of the magnetic dipole's $11^\circ$ inclination to the spin axis (the dipole is not regarded as decentered). The long board, because it is rigidly attached to Earth, pivots about its long axis with an approximate amplitude of $11^\circ$ as the magnetic axis diurnally rotates. This causes the plasma sheet to assume a cross-section resembling an hourglass or barbell (Hardy 1976, Meng and Mihalov 1972). The plasma
sheet's symmetry plane has the same inclination to the ecliptic as the y-axis.

The second motion, which Bowling terms hinging, is related to the tilting of the spin axis toward or away from the Sun. As the spin axis leans toward the Sun, the hinge rises above the ecliptic, elevating the plasma sheet in such a way as to keep its length parallel to the ecliptic. This occurs in summer. In winter the opposite happens. Now, since the ecliptic contains the x-axis, the plasma sheet will rise and fall relative to the x-axis in an annual motion. The maximum displacements are about \(2 R_E = (5 R_E) \tan 23.5^\circ\), and occur at the solstices; at the equinoxes the displacements are zero. Always present, however, is a random form of this motion with an amplitude of about \(1 R_E\) and a period most often between 10 and 100 minutes.

3. Results of the Combined Motions

The interplay of the lunar and plasma sheet motions for the 8.5 lunations of this study is shown in Figure 9. The motion of the plasma sheet is added to that of the Moon to obtain the lunar motion relative to the plasma sheet. The diurnal motion of the plasma sheet is represented by the hourglass cross-section of the sheet.

Comparison of Figure 9 with Figure 7 explains Table 1. First, the smaller the z-intercept (defined previously) of the Moon's tail trajectory, the more bursts are observed. Figure 10 shows the almost linear relation between the number of bursts N and the intercept B. Observe that lunations
Figure 9. Lunar motion relative to plasma sheet. Orbital motion from right to left.
Figure 10. Relation between the number of observed bursts $N$ and the lunar $z$-intercept $B$. Points are labelled by their lunation numbers. Bar on #30 reflects the uncertainty due to its being a half-crossing ($N = 10$ is the observed lower limit. $N = 20$ is a reasonable upper limit).
32 and 40 do not conform well to the rule. Second, it is plain that during most tail passages, the Moon is deeply immersed in the plasma sheet for only half of a trajectory. Thus it is seen that most bursts are observed in the half of a trajectory that penetrates most deeply into the plasma sheet. Exceptions to this rule are lunations 31, 36, and 42.

4. Role of Geomagnetic Activity

The deviations from the two rules just cited seem to correlate with substorm activity. In Table 2 are the average values of Kp for each half of each lunation.

<table>
<thead>
<tr>
<th>Lunation</th>
<th>1st Half Kp</th>
<th>2nd Half Kp</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>28</td>
<td>3</td>
<td>2-</td>
<td></td>
</tr>
<tr>
<td>29</td>
<td>1</td>
<td>1+</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>-</td>
<td>3+</td>
<td></td>
</tr>
<tr>
<td>31</td>
<td>1</td>
<td>4</td>
<td>Unbalanced</td>
</tr>
<tr>
<td>32</td>
<td>2+</td>
<td>3-</td>
<td>Kp = 3, 4, 5 at midpoint</td>
</tr>
<tr>
<td>36</td>
<td>1-</td>
<td>3-</td>
<td>Unbalanced</td>
</tr>
<tr>
<td>39</td>
<td>2</td>
<td>1-</td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>1+</td>
<td>2-</td>
<td>Kp = 4, 5, 6 near end of 2nd half</td>
</tr>
<tr>
<td>42</td>
<td>2+</td>
<td>6-</td>
<td>Unbalanced</td>
</tr>
</tbody>
</table>

Table 2. Average Kp values

The two halves of each lunation "balance" each other fairly well, except for lunations 31, 36, and 42. In these cases the imbalances are pronounced, with the extra activity occurring in the halves of the lunations which should contain the fewest bursts. Apparently, strong geomagnetic activity can either distend the plasma sheet cross-section, thereby improving the probability of burst detection, or encourage the generation of enough bursts to dominate the effect of the lunar trajectory. Geomagnetic activity can also explain the
surplus bursts in lunations 32 and 40. Strong activity occurs at the midpoint of lunation 32 and in the second half of lunation 40, locations which would clearly have no adverse effect on the correct qualitative distribution of bursts in them, but would raise the observed number of bursts above nominal levels.

There seem to be no other correlations of geomagnetic activity with bursts. Indeed, averages of the values of Kp, AE, and $B_z^{\text{IMF}}$ measured during the times of all the bursts studied indicate only low to moderate levels of activity. Specifically, $\overline{Kp} = 2 + 1.7$, $\overline{AE} = 205\gamma$ with $1\sigma = 220\gamma$, and $\overline{B_z^{\text{IMF}}} = +0.02\gamma$ with $1\sigma = 2.9\gamma$. One concludes that geomagnetic activity is nonessential to the basic burst phenomenon, and plays only passing roles.

B. Translunar Magnetic Field Topology

1. Introduction

The reason for bursts occurring at the times they do involves the configuration of the tail magnetic field near the Moon. Explorer 35 measures this field and reports its direction and strength. As the Moon crosses the tail, the field's coarse structure varies in a regular way. In all but three of the 452 bursts, deviations of particular sorts from this nominal field occur within one or two hours of the bursts detected by the SIDE. These deviations are consistent with lunar passages near magnetic bubbles.

2. Coarse Structure of the Field

The field measurements are made at a mean distance of
about 1 R_E from the Moon's center. Figure 11 shows how the average field quantities change with time during a tail crossing. The field behavior agrees with one's expectations based on the Moon's location in the magnetotail. When the field is strong (≥ 10 γ) and points nearly sunward, the Moon is above the plasma sheet symmetry plane. When the field is strong and antisunward, the Moon is below the symmetry plane. The reversal of the field longitude occurs before or after the crossing midpoint according to whether the Moon penetrates the symmetry plane before or after the midpoint. Field magnitudes averaging 8 γ (the average IMF strength at 1 AU) that are accompanied by violent, simultaneous fluctuations in latitude and longitude mark the lunar passages through the turbulent magnetosheath which precede and follow plasma-sheet traversal.

3. Fine Structure of the Field

Examples of the magnetic fine structure signatures that correlate with bursts are shown in Figure 12. There are four basic types of fine structure signature, and all involve drops in the average field strength to 5 γ or fewer. A Type 1 signature consists of longitude variations between the sunward and antisunward directions while the latitude remains greater than 30° in magnitude. Type 2 signatures involve the simultaneous reversals of longitude (sunward ↔ antisunward) and latitude (north ↔ south). Type 3 signatures involve no significant direction changes at all. A Type 4 signature is marked by variations in latitude between
Figure 11. Changes in the magnetic field during a typical tail crossing. The abscissa is the elapsed time in days. The ordinates are field latitude, longitude, and strength.
Figure 12. The four observed types of magnetic signature. Notice the four periodic recurrences of the Type 3 signature. Times of occurrence of the samples:

Type 1 -- 1972 60$^d$ 11$^h$
Type 2 -- 1972 29$^d$ 21$^h$
Type 3 -- 1972 91$^d$ 9$^h$
Type 4 -- 1972 149$^d$ 2$^h$

All times are UT.
north and south while the longitude remains essentially con-
stant.

In the periods when SIDE and Explorer 35 data coexist, there are 18 signatures of Type 1, 13 of Type 2, 9 of Type 3, and 6 of Type 4. The total number of signatures is thus 46. This number is smaller than the number of bursts be-
cause of the ~50% Explorer 35 data dropout rate, and the fact that most signatures span one to two hours, whereas most bursts last only for minutes. Despite the spottiness of the magnetometer data, one can by eyeball inspection es-
timate that the average time between signatures is six hours or more. Also, whenever Explorer 35 data are available, almost all bursts lie within one or two hours of a signature. This leads to the conclusion that bursts and signatures are related. The relation is particularly striking in lunations 28, 30, and 31, and very clear in lunations 29 and 36.

4. Magnetic Bubbles

Magnetic bubbles are loop- or ring-like patterns of magnetic field lines (Schindler and Ness 1972), and are il-
ustrated in Figure 13. Bubbles in the plasma sheet may be caused by localized, brief (3-6 hr), and random increases or decreases in the crosstail sheet current. Bowling (1974) discusses the nature and origin of bubbles, or loops as he calls them, and calculates that they can reach 1 or 2 RE in size within a few hours. Given the evanescent nature of these bubbles (Coroniti et al. 1978) and the random 10 to
Figure 13. Magnetic Bubble Schematic. Black arrows = magnetic field direction, filled black circles = current emerging perpendicularly from plane of page.
100 minute oscillations of the plasma sheet, it is not unreasonable to expect the lunar trajectory to oscillate a few times along some of the four types of path illustrated in Figure 14 during a tail crossing. Oscillations along the paths labelled 1 to 4 result in the magnetic signatures of Types 1 to 4, respectively, illustrated in Figure 12. Thus, the observed magnetic signatures associated with bursts are consistent with lunar encounters of magnetic bubbles (Haerendel et al. 1978). Because there is only one satellite measuring the field, though, this magnetic bubble hypothesis cannot be proved.

C. Burst Energization

1. Introduction

The final question to settle on the subject of bursts concerns the values of their plasma parameters. Why, on the average, are they (500, 80, 0.003)? Since plasma sheet plasma is stagnant, and the adjacent mantle plasma has an average bulk speed of 100 km/s, which equals the speed at which it \( \mathbf{E} \times \mathbf{B} \) drifts into the quiettime plasma sheet from above and below (Freeman et al. 1977, Hardy et al. 1975), it is clear that an acceleration mechanism is required. The fact that mantle plasma has a mean temperature of \( \sim 10 \) eV which is below the mean burst temperature suggests that the plasma source for the bursts is the mantle plasma, and that the acceleration is accomplished by magnetic merging between magnetic bubbles in the plasma sheet.
Figure 14. Possible lunar paths through magnetic bubbles. Numbered black bars = possible paths, black arrows = magnetic field direction, filled black circles = current emerging perpendicularly from plane of page.
2. Magnetic Merging

Magnetic merging is a process that transfers energy from magnetic fields to plasma. There is much difference of opinion on the details of the process (Hill 1975, Vasyliunas 1975), but laboratory and theoretical research has established the basic properties of the phenomenon. Basically, any plasma entering a region possessing the magnetic topology illustrated in Figure 15 will be drawn into the central diffusion region, energized, and squirted out sideways, most of it parallel to the field lines. The energization process in the diffusion region is still the subject of wide debate (Haerendel 1978), but it seems to have minimal effect on the plasma temperature. Rather, most of the magnetic energy seems to be transformed into plasma bulk motion. The plasma exit speed is roughly the Alfvén speed \( u_A = B_0 (4\pi \rho)^{-\frac{1}{2}} \), where \( \rho \) is the plasma density, and \( B_0 \) is the strength of the magnetic field encountered by the plasma as it approaches the diffusion zone. The Alfvén speed is the result of equating the emergent plasma energy density \( \frac{1}{2} \rho u^2 \) to the magnetic field energy density \( B^2 / 8\pi \).

3. Relation of Merging to Bursts

The region between two magnetic bubbles (Figure 13) is like that in a merging zone (Figure 15). I hypothesize that when such a pair of bubbles forms in the plasma sheet, mantle plasma \( \vec{E} \times \vec{B} \) drifts into the merging zone and is energized. Plasma shooting out along field lines that map to the Moon is detected by the SIDEs. SIDEs on the far side
Figure 15. Merging Schematic. White arrows = plasma flow, black arrows = magnetic field direction.
of the Moon might detect bursts heading toward the Sun because bursts, presumably, would counterstream around a bubble. At this point, it is additionally surmised that geomagnetic activity stimulates merging by increasing the supply of mantle plasma, and/or causing more inhomogeneities in the crosstail current system.

I do not associate bursts with fireball or large-scale merging phenomena. Bursts from fireballs (Frank et al. 1976) are ruled out because fireballs are associated with substorms, occur near the magnetotail flanks, and emit particles with the parameters (100-500, 1E4, 1). There is also doubt about the reality of merging in fireballs (Hones 1978).

Large-scale merging is unsatisfactory for similar reasons. Large-scale merging results from an imbalance between tail lobe pressure (mostly magnetic pressure) and plasma sheet pressure (primarily particle pressure). The plasma sheet collapses, and allows the antiparallel field lines above and below the sheet to reconnect. Large-scale merging is therefore strongly associated with substorms, and is also disqualified.

4. Energy Transfer Calculations

Calculations confirm that the average energy density of the bursts detected by the SIDE roughly equals the average energy density of the magnetic fields associated with the flows. The burst energy density is given by the expression \( E_{\text{kin}} = (8.35E-14) n u^2 \) in erg cm\(^{-3}\), assuming that the plasma is hydrogen, that \( n \) is in units of 0.001 cm\(^{-3}\), and
that \( u \) is in units of 100 km/s. For \( n = 3E-3 \) cm\(^{-3} \) and 
\( u = 500 \) km/s, one obtains \( E_{\text{kin}} = 6E-12 \) erg cm\(^{-3} \). The mag-
netic energy density is written \( E_{\text{mag}} = (3.98E-12) B^2 \) erg
\( \text{cm}^{-3} \) for \( B \) in \( \gamma \). Since the mean field strength of the mag-
netic signatures is \( 2.7 \gamma \), \( E_{\text{mag}} = 3E-11 \) erg cm\(^{-3} \). In Table
3 are tabulated the means and standard deviations of the
field strengths of the four types of magnetic signature as-
bond with bursts.

<table>
<thead>
<tr>
<th>Type</th>
<th>Number of Signatures</th>
<th>Mean</th>
<th>Std. Dev.</th>
</tr>
</thead>
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<td>2.0</td>
<td>1.0</td>
</tr>
<tr>
<td>2</td>
<td>13</td>
<td>1.6</td>
<td>1.0</td>
</tr>
<tr>
<td>3</td>
<td>9</td>
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<tr>
<td>4</td>
<td>6</td>
<td>3.3</td>
<td>1.7</td>
</tr>
</tbody>
</table>

Table 3. Magnetic signature mean field strengths (\( \gamma \))

When one compares the total ranges of \( E_{\text{kin}} \) and \( E_{\text{mag}} \), there
is considerable overlap, as shown in Figure 16. The overlap
shows that merging processes near magnetic bubbles may ener-
gize bursts. The range of \( E_{\text{mag}} \) is given by \( 1 \leq B \leq 5 \) with \( B 
\) in \( \gamma \), while the range of \( E_{\text{kin}} \) is given by \( (0.001, 250) \leq (n, u) \leq (0.05, 700) \) for \( n \) in cm\(^{-3} \) and \( u \) in km/s.

D. Lobe Flows

Two or three of the observed bursts occur when the mag-
netic field configuration is that of the tail lobe region.
For example, the burst that occurs on 1972 September 23 be-
tween 17\(^{h}\)55\(^{m}\) and 17\(^{h}\)59\(^{m}\) UT is located in a 15 to 20 \( \gamma \) sun-
ward magnetic field above the plasma sheet. The Kp index is
3. Possibly, those field lines map to a more than usually
distant magnetic bubble. Alternatively, the burst might
have originated in the polar ionosphere if the field lines
Figure 16. Overlap in the ranges of $E_{\text{kin}}$ and $E_{\text{mag}}$. Average values are indicated by filled circles.
map to Earth's polar cap. The polar ionospheres are widely regarded as prime sources of singly charged heavy ions, most notably $\text{O}^+$ (Schopke and Paschmann 1978, Frank et al. 1977, Shelley et al. 1976, Johnson et al. 1974). Hardy et al. (1978, 1977) discuss the plausibility of such an interpretation.

E. Doubly Peaked Spectra

An examination of the count spectra of the 452 bursts reveals that 196 of the spectra are doubly peaked. That is, the spectra resemble the superposition of two Maxwellians of varying temperature, the primary peak being at lower energies, and the cold secondary peak being at higher energies. Sample spectra are shown in Figure 17. To facilitate high-energy ion study, the computer data reduction program computes the plasma parameters of only the high-energy peak, thereby attributing those parameters to burst phenomena. Visual inspection of the Explorer 35 data and study of the plasma parameter printouts shows that the double peaks are related to neither the magnetic field of the tail, nor the Moon's position, nor to $u$, $T$, and $n$. Since the abundance by number of helium to hydrogen is about 1% near the plasmasphere (Chappell et al. 1970), further research might reveal that a few percent of the bursts are helium. At the present time, however, the identities and significance of the dual peaks are unclear. The twin peaks might represent the simultaneous detection by the SIDE of bursts and another variety of magnetotail plasma. Alternatively, the peaks
Figure 17. Doubly peaked counting spectra for the bursts of 1972 January 30. Times are UT. Twenty SIDE frames span one counting spectrum.
might result from the interstreaming of hydrogen with heavier ions not necessarily of the same speed.

VI. SUMMARY

This research involves the detection and analysis of unusual, high-speed plasma flows in the vicinity of the plasma sheet. Computer reduction of the data indicates that these flows, called bursts, have bulk speeds between 250 and 700 km/s, ion temperatures between 50 and 100 eV, and ion densities between 0.001 and 0.01 cm$^{-3}$, assuming a 100% hydrogen composition. About 450 bursts are studied.

Bursts occur during every one of the 8.5 tail crossings studied. The number and location of bursts detected during a given tail passage depends on the lunar trajectory relative to the plasma sheet. The closer the Moon passes to the plasma sheet center, the more bursts will be seen. The Moon usually enters the plasma sheet obliquely, causing more bursts to be observed during one half of the tail crossing than the other. Burst phenomena are therefore probably concentrated near the plasma sheet symmetry plane. More bursts are found when there is strong geomagnetic activity. Possibly the activity increases the number of bursts occurring; perhaps the activity merely improves the conditions for burst observation.

Correlation of bursts with magnetic field direction in the tail, and the equality of burst and magnetic field bubble energy densities suggests that bursts are the result of
small-scale, omnipresent, but random magnetic merging in the plasma sheet. The exact merging sites could be the regions between adjacent magnetic bubbles, bubbles which form around inhomogeneities in the plasma sheet's crosstail current system.

Two or three of the bursts do not occur with the magnetic field properly configured. Possibly the bursts are bona fide, and merely unusual. If not, they could be heavy-ion phenomena. Double peaks occur in 40% of the bursts' energy spectra. It is not clear whether they result from the simultaneous detection of two different hydrogen plasma populations, or from the detection of hydrogen and another plasma species.
REFERENCES


King, J.H., 1977. *Interplanetary Medium Data Book - Appendix*, National Space Science Data Center, Greenbelt, MD.


