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LOW-ENERGY PLASMA OBSERVATIONS
AT SYNCHRONOUS ORBIT

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ABSTRACT

The University of California at San Diego Auroral Particles Experiment on the ATS-6 Satellite in synchronous orbit has detected a low-energy plasma population which is separate and distinct from both the ring current and plasma sheet populations. The density and temperature of this low-energy population were highly variable, with temperatures in the range $kT = 1$ to 30 eV and densities ranging from less than 1 cm^{-3} to more than 10 cm^{-3} . The occurrence of a dense low-energy plasma is most likely in the afternoon and dusk local time sectors, whereas $n > 1 \text{ cm}^{-3}$ is seen in the local night sector only during magnetically quiet periods. These observations suggest that this plasma is the outer zone of the plasmasphere. During magnetically active periods, this low energy plasma is often observed flowing sunward. In the dusk sector, enhanced plasma flow is often observed for 1-2 hours prior to the onset of a substorm-associated particle injection.

I. INTRODUCTION

The existence of a bounded region of magnetospheric thermal plasma was first suggested by the "knee whistler" observations of Carpenter (1963). These studies showed that the magnetospheric ionization density decreased smoothly with altitude up to an altitude of several earth radii, but then displayed a sharp decrease, or "knee." The density decrease was 1-2 orders of magnitude or more. Subsequent whistler measurements (Carpenter, 1966; Carpenter, 1970) have shown that the L-value of the density decrease, or "knee," decreases with magnetic activity and that the boundary is not azimuthially symmetric but rather possess a distinct bulge near local dusk. Subsequently, in situ measurements primarily with an ion spectrometer on OGO-5 (see Chappell, 1972 and references therein), has confirmed the essential features of the plasma region and boundaries deduced earlier from the whistler measurements and has provided insight into the formation mechanisms and the response of the plasma to magnetospheric processes. Parenthetically, over the years the plasma region has come to be known as the "plasmasphere" and the anthropomorphic term "knee" has been replaced by the more descriptive but less colorful term "plasma-pause."

The morphology and dynamics of the plasmasphere and plasmopause have been reviewed by Chappell (1972) and the reader is referred to this review and references therein for a more complete discussion of the subject. In brief, the following picture has emerged concerning the plasmasphere:

1. The ultimate source of the thermal plasma is the ionosphere.

2. As the plasma is thermal, gradient and curvature drift are negligible. The motion across magnetic field lines is due essentially entirely to $E \times B$ drift. In other words, the morphology of the plasmasphere is due to electric and magnetic fields within the magnetosphere.

3. The plasmopause is therefore the boundary between magnetic flux tubes that co-rotate with the earth and can act as a reservoir and those which are connected to the magnetopause part of the time and therefore lose their accumulated plasma. This boundary between co-rotating and connecting flux tubes, and therefore the plasmopause, moves inward with the increasing crosstail electric field associated with increasing magnetic activity.

4. The nightside plasmopause boundary location responds most immediately to changes in magnetic activity.

This magnetospheric reservoir of thermal plasma is important because of its response to magnetospheric convection, because of the dependence of certain plasma wave phenomena upon the background plasma density, and because this thermal plasma is a direct link between the ionosphere and the magnetosphere. Furthermore, the outer regions of the plasmasphere interact directly with the energetic ions which constitute the ring current and with energetic particles injected into the magneto-

sphere during magnetic substorms (DeForest and McIlwain, 1971). Finally, there is much practical interest in studying the plasma environment at geosynchronous orbit from the point of view of plasma-spacecraft interactions, in particular the electrostatic charging of spacecraft (DeForest, 1972, Reasoner et. al. 1976). With the foregoing motivations, we have undertaken a study of the low-energy plasma populations (≤ 100 eV) at synchronous orbit using data from the University of California at San Diego Auroral Particles Experiment on board the ATS-6 satellite. This instrument, described in the next section, has the capability of measuring particles with energies down to 1 eV or less. As previous studies of plasmasphere morphology showed that the bulge region should extend out to synchronous orbit, we expected that ATS-6 would be in the plasmasphere for a portion of the orbit at certain times and that the instrument would be able to detect the higher energy components of plasmaspheric thermal particles.

ATS-6 was launched in May, 1974 into synchronous orbit at 94° west longitude with an orbital inclination of 2.5° . The L-value at this location was approximately $L = 7.1$. During the summer of 1975 the satellite was moved to 35° east longitude and was brought back to about 105° west longitude during the summer of 1976. The UCSD instrument was first turned on June 15, 1974, and all the data reported here are from the first 40 days of operation.

2. DESCRIPTION OF THE INSTRUMENTATION

The UCSD Auroral Particles Experiment on ATS-6 consists of five electrostatic analyzers. Each analyzer consists of a set of ovoidal deflection plates which discriminate according to particle energy per unit charge (and charge sign) and focus particles onto a channel electron multiplier for detection. The ATS-6 satellite is inertially stabilized in all three axes with one axis (the local Z axis) always toward the center of the earth. In order to obtain angular information a pair of analyzers, one sensitive to electrons and the other to ions, were placed in each of two mechanically rotating heads. The heads rotate in two orthogonal planes with sweep angles of 220° . One head, the "North-South-Head" rotates approximately in a meridional plane and the other, the "East-West Head," rotates approximately in the plane of the satellite orbit. A fifth analyzer, sensitive to ions only, is fixed to the spacecraft and looks in the local east direction, i.e., in the satellite ram velocity direction. This is called the "Fixed East Detector." Figure 1 is a sketch of the ATS-6 satellite. The large parabolic antenna points toward the earth and the solar cell panel booms lie along a north-south direction. The Environmental Measurements Experiment (EME) with the two UCSD rotating heads is seen on back of ATS-6.

There are 64 energy levels sampled during a 16-second energy scan. Defining an energy step index S , the equation for the sampled energy in units of eV as a function of S is $E = -21 + 16.1 (1.145)^S$. This equation gives $E = -5$ for $S=0$, where the deflection voltage is of reverse polarity for background determination, and $E = 81.5$ keV for $S=63$. The deflection voltage can also be programmed to dwell on a fixed energy for an interval. In typical operation a "scan-dwell" program is commanded whereby energy scans alternate with dwells at varying energies. The dwell durations and steps are commandable.

The angular head sweeping can also be controlled by command. Normally, both heads are sweeping in synchronization requiring 5 minutes to complete a sweep. Additionally, the N-S head can sweep while the E-W head is parked at a desired angle, or both heads can be parked at desired angles. For example, one useful mode was to park the E-W head looking west (i.e. opposite in direction to the fixed east detector) and simultaneously allowing the N-S head to sweep normally.

During laboratory testing of the instrument it was discovered (C.E. McIlwain, personal communication) that following the end of an energy scan the deflection voltage did not immediately return to the level appropriate to the following dwell step but rather there was a "slewing" of the voltage to the proper value. This slewing effect, not well understood but well documented, is described by the equation:

$$E(t) = -21 + 16.1 (1.145)^S + \frac{C_1}{4t + .25}$$

where S is as before, t is measured in seconds and is the time since the last step $S=63$, and C_1 is a temperature dependent factor ranging from 10 to 120 for the N-S head and 30 to 400 (in units of eV) for the E-W head. Because of the $1/t$ dependence, the effect of the C_1 term is most pronounced at the beginning of a low-energy dwell step immediately following a scan, but for high values of C_1 and short dwell periods the effect carries forward into the following scan and can result in corrections in the scan steps of a few volts. Typically, dwell steps are 8 or 16 seconds in length and at the beginning of a scan therefore if C_1 is 100, then the correction is 1.5-3 volts. The effect is of course negligible at energies above 50 volts but is important and must be accounted for when determining the properties of low-energy plasma.

This slewing effect does have a beneficial aspect. Normally the energy range 0-20 eV is covered in only 7 scan steps. However, by setting a dwell step of $S=0$ or $S=1$, the detector will, following step $S=63$, slowly slew through the low energy range with high resolution in the 0-20 eV range if C_1 is sufficiently high. The problem is one of accurate determination of C_1 , since the temperature sensor telemetry word was lost after the first 3 days of operation. However, by comparing low-energy photoelectron counting rates during scans and low-energy dwells, such a C_1 determination can be made

routinely. Although the study reported here was primarily made with the energy scan data, the slewing was used in certain cases to obtain better resolution of the lowest energies.

The lowest counting rate with statistical significance was 12 counts/second corresponding to 3 counts per accumulation interval. Demanding that this minimum counting rate exist for the energy step at peak counting rate and for the two steps on either side of the peak step, and assuming a Maxwellian distribution, Table 1 gives the minimum measurable density as a function of plasma temperature. The minimum resolvable temperature was $kT \approx 1$ eV. However, at times when the C_1 correction term was sufficiently high, plasmas with even lower temperatures could be resolved.

TABLE 1

<u>kT</u> <u>(eV)</u>	<u>N min</u> <u>(#/cm³)</u>
1	7.10
2	2.10
5	0.4
10	0.26
20	.18
50	.10

Table 1: Minimum measureable density as a function of plasma temperature for the UCSD ATS-6 instrument. The basis of the calculation is to require statistically significant counting rates at three contiguous energy scan steps encompassing the peak of the distribution.

3. DATA

a. Illustrative Examples of ATS-6 Data.

Figure 2 shows an example of plasma data from the instrument. For the sake of clarity, only data from the N-S head is shown. The upper panel shows ion detector counting rates, the middle panel electron detector counting rates, and the bottom panel shows the scan energy trace (solid line) and the pitch angle of particles detected by the N-S head (dashed line). In this panel is seen one energy scan preceded and followed by dwells at fixed energies.

It is seen that the ion distribution at this time is composed of two components, one at low energy and one at high energy. The low-energy component can be approximated by a Maxwellian distribution with density $n = 5 \text{ cm}^{-3}$ and thermal energy $kT = 4 \text{ eV}$. This is an example of what we have termed a "weak warm plasma" event, that is the presence of a low-energy ion component with a density n in the range $1.0 < n < 10 \text{ cm}^{-3}$. Similar events with $n > 10 \text{ cm}^{-3}$ have been termed "intense." The high-energy component of the positive ions in this case has a density $n \approx 0.3 \text{ cm}^{-3}$, which is fairly typical, and an average energy of about 30 keV.

The electron components of the plasma populations can be seen in the lower panel of Figure 2. However, the dominant low-energy electron population are spacecraft photoelectrons.

As a complement to the line plot data we have used 12-hour spectrograms of the kind illustrated in Figure 3. The data in Figure 3 are from the East-West detectors only and are taken during the same day (day 176 of 1974) as the line plot data in Figure 2. These spectrograms are basically identical in format to the ATS-5 spectrograms previously discussed by DeForest and McIlwain (1971). For a detailed technical description of this kind of spectrogram as well as a detailed physical interpretation of typical data the reader is referred to the paper by DeForest and McIlwain. Briefly, the upper and lower spectrograms in Figure 3 are intensity-coded plots of the electron and ion counting rates, respectively, as functions of energy (note: zero energy at the top of the ion spectrogram) and universal time $UT \approx LT + 6 \text{ h.}$ The intensity is proportional to the logarithm of the counting rate, as defined by the vertical scales to the right.

On day 176 of 1974 there is a "weak warm plasma" event with $kT \sim 3 - 5 \text{ eV}$ from 00:00 UT to 03:24 UT, interrupted by a few short duration "intense" events (with $kT \sim 3 - 5 \text{ eV}$) between 02:26 and 02:48 UT. After 3:54 UT there is virtually no low-energy ion component on this day until about 23:20 UT. The characteristic sloping band structures in the spectrograms are due to dispersion in time and space of the drifting energetic particles that are being "injected" intermittently at geosynchronous orbit from the magnetotail (DeForest and

McIlwain, 1971). The ion "injection" at 02:30 UT is preceded by a rapid downturn in energy of the horizontal dispersion structure seen at about 2 keV energy (remaining from a previous "injection"). This we interpret as due to a sudden increase of the internal magnetospheric convection, causing a strong westward $\vec{E} \times \vec{B}$ drift at the spacecraft position (~ 20:00 LT). This will be discussed further in a later section.

The high energy electrons associated with substorm injections interact with the spacecraft to produce a negative spacecraft potential. The signature of this negative potential is seen in the ion data between 0700 and 0900. All ion energies are incremented by the spacecraft potential resulting in the characteristic band whose low-energy boundary is the spacecraft potential. This kind of charging has been observed at all local times except for the afternoon sector 12:00 - 18:00 LT. The charging is most frequent in the post-midnight sector 00:00 - 06:00 LT, where it occurred during 50-60% of the total observation time. Further details of the charging events are given elsewhere (Reasoner et. al., 1976). Spacecraft charging at geosynchronous orbit has been discussed previously by DeForest (1972, 1973) in the case of ATS-5.

b. Local-Time Distribution of Low-Energy Ions

To determine typical properties of the low-energy ion component at different local times we have studied the line plot data during forty contiguous days from the period June 15 to July 24, 1974. This period was selected on the grounds of data availability at the time of the study. This data base covered a wide range in magnetic and substorm activity ranging from extremely quiet to very disturbed days, (the daily sum of Kp ranging from 12+ to 51+). Estimates

of the ion density and temperature during a given energy scan of the particle detectors have been obtained directly from the line plots, as described in the Appendix.

Based on phenomenological grounds we have chosen to classify encounters with a well-defined and roughly isotropic low-energy ion component as either a "weak warm plasma event," when the apparent density n of this component is within the interval $1.0 < n < 10 \text{ cm}^{-3}$, or an "intense warm plasma event," when $n > 10 \text{ cm}^{-3}$. The word "warm" here refers to the fact that the temperature is generally several times $10^4 \text{ }^\circ\text{K}$ (cf. Section 3d).

To determine the frequency of occurrence of each type of event as function of local time we have divided the forty 24-h data sets into ten-minute segments. The probability of a certain event in a given ten-minute local-time interval has been calculated as the ratio of the number of days with at least one such event during the interval to the number of days with observations during the interval. Individual events may often have a duration of less than 10 minutes, but the major systematic changes in the density generally occur over more than 10 minutes.

Figure 4 is a circular histogram of the probability of occurrence of "weak warm plasma events," where local time is defined by the angle and the probability is shown on a linear radial scale in percent. The probability peaks at 50-60% during 15:30 - 18:30 LT. Roughly half of the events during 4:00 - 9:00 LT have been observed during spacecraft charging (cf. Section 3a). Since the ion density can be estimated only as a function of ion temperature during charging conditions

(see the Appendix) we have tried to estimate a reasonable upper limit rather than the actual value of the ion density during these conditions. The probability during 04:00 - 09:00 LT may thus be slightly exaggerated. During 18:00 - 01:30 LT the "weak" events and the spacecraft charging events proved to be mutually exclusive, which will be discussed further below.

Figure 5 is a similar histogram for the probability of "intense warm plasma events." Note the expanded percentage scale in this figure. The "intense" events occurred only during 12:20 - 20:50 LT. The probability of "intense" events are roughly uniform during 15:00 - 19:00 LT with a slight tendency to peak at around 15:30 LT.

Figures 4 and 5 are based exclusively on data from the E-W (East-West) and fixed ion detectors. That is, these "weak" and "intense" plasma encounters are with ions at near 90° pitch angle, assumed representative of an isotropic distribution. Superposed on this isotropic component there is often a strongly field-aligned ion component, which may have a widely extended high-energy tail (up to several keV). The flux at pitch angles $\leq 20^\circ$ is sometimes two orders of magnitude larger (or more) than the flux at 90° , but typically the two fluxes differ by less than one order of magnitude. Since the field-aligned component is observed mostly at relatively small pitch angles ($\leq 20^\circ$), the number density of this component is typically smaller than the number density of the isotropic component.

The occurrence of "weak" and "intense" warm plasma events is a function not only of local time but also of magnetic activity, as demonstrated by Figure 6. In this figure the occurrence of at least one "weak" event during each hour of each of the 40 days is plotted as a dot at a vertical position representing the current K_p index. The occurrence of at least one "intense" event is plotted as a star. The K_p index assigned to an event is the concurrent value unless the event occurred during the first hour of the 3-hour K_p interval. In that case, the previous 3-hour K_p value was assigned. This offset is rather arbitrarily chosen to account for an apparent delay in the response of the events to increasing magnetic activity. Earlier observations (cf. Chappell, 1972, and references therein) do indicate that the plasmasphere responds to increasing magnetic activity with different delay times at different local times, but this is disregarded for sake of simplicity in Figure 6. The frequency of occurrence of different K_p - indices during the time period studied is shown by the histogram to the right of the figure. The linear average of the K_p - indices during the period was 3, which is indicated by the horizontal line. The dashed and solid curves are the linear averages of the K_p - indices associated with "weak" and "intense" events, respectively.

As shown by Figure 6 the "weak" events occurred only during relatively low magnetic activity in the local-time sector 21:00 - 06:00. At other local times the "weak" events occurred during virtually any magnetic activity. The "intense" events occurred only in the 12:00 - 21:00 LT sector and showed an increasingly strong positive correlation between frequency of occurrence and magnetic activity from dusk towards noon.

One feature of the occurrence of "weak" and "intense" events which is not explicitly shown in Figure 6, is the negative correlation between the duration of individual events and the overall magnetic activity. The relatively few cases when n was continuously larger than 1 cm^{-3} for several hours all occurred after one or more days of low magnetic activity.

c. Plasma Flow Events.

Earlier when discussing the spectrogram of Figure 3 we pointed out that the injection event at 0230 of that Figure was preceded by an increased rate of change of the energy dispersion trace toward low energies. This we interpret as the effect of an increased cross-tail electric field acting to convect plasma toward the satellite. Figure 7 shows an example of another such rapid dispersion event preceding an injection on day 200 of 1974. Here the time scale is expanded so that the period shown is 0330 to 0500 UT (2130 to 2300 LT). The sawtooth-like trace at the top indicates the angle of the East-West head relative to the spacecraft. At the upper inflection the detector is looking to the east and is looking west at the lower inflection. We see that the low-energy ion fluxes are strongly modulated as a function of

detector angle, in this case being maximum when the detector is looking toward local east, or tailward. Thus, the electric field acts upon the higher energy ions to produce an increased energy dispersion rate at the satellite and at the same time this flow is directly observable in the low-energy ion data as a directional modulation in the flux.

In the case of a Maxwellian distribution of low-energy ions the differential number fluxes in the directions parallel and antiparallel to the drift velocity differ by a factor $\rho(E) = \exp \left[4 \sqrt{D} \sqrt{E/kT} \right]$ (1) where D is the kinetic energy associated with the drift and E is the total kinetic energy. Since the counting rate of the detectors is roughly proportional to $E^2 f(E)$, where $f(E)$ is the particle distribution function, the peak counting rate of the detector facing the flow will thus occur at an energy E_p defined by

$$E_p = \left(\sqrt{D}/2 + \sqrt{2kT + D/4} \right)^2 \quad (2)$$

As long as $D \lesssim kT$ the term $D/4$ may be neglected in comparison with $2kT$, and from (1) we thus get

$$\sqrt{D} \approx \sqrt{(kT/2) \ln \rho(E_p) + 2kT} - \sqrt{2kT} \quad (3)$$

Hence, even if $D \ll kT$ we may expect the drift to show up as a noticeable difference in the peak counting rates of two detectors facing the flow and facing in the opposite direction, respectively.

In Figure 8 the frequency of occurrence of periods when the low-energy ion fluxes from the East and West directions indicated the presence of plasma flow are displayed. The inner histogram shows the frequency of occurrence in each 10-minute local-time interval of "weak warm plasma" events that were observed in the fixed (to the East) detector but not in the E-W detector. That is, while the ion fluxes in the fixed detector indicated a density n in the range $1.0 < n < 10 \text{ cm}^{-3}$ the fluxes in the E-W detector indicated $n < 1 \text{ cm}^{-3}$. The outer histogram shows in an analogous fashion the frequency of occurrence of "weak" events that were observed only in the E-W detector, when this detector was facing westward. The frequency of occurrence is shown on a linear radial scale from 0% to 20% within each of the two concentric zones. These two classes of events are thus indicative of plasma flow (relative to the spacecraft) in the respective directions shown by the two solid arrows at early afternoon LT.

The "flow-events" in Figure 8 were associated with flux ratios $\rho(E_p)$, as defined by Eqs (1) and (2) in the case of a Maxwellian distribution, anywhere in the range $2-10^3$, with $\rho(E_p) = 5$ being a fairly typical value. Inserted in Eq (3) these values of $\rho(E_p)$ give $D \sim 0.1-0.9 \text{ kT}$ with $D \sim 0.25 \text{ kT}$ being a typical value. The thermal energy kT

is generally in the range 1-15 eV (cf. next section), with $kT \sim 5$ eV being typical. Hence, the "flow events" in Figure 8 are generally associated with flow velocities relative to the spacecraft, in the range 1-50 km/sec. and a typical velocity appears to be 8 km/s (corresponding to a typical transverse electric field $E_{\perp} \sim 0.8 - 1.2$ mV/m in the frame of reference of the spacecraft) For comparison, the spacecraft is moving in geosynchronous orbit with a velocity of 3 km/s in a frame of reference fixed with respect to the magnetosphere.

The local-time distribution of the "flow-events" in Figure 8 is biased to some extent by a systematic variation with local time of the angular mode of operation of the E-W detector. The E-W detector was alternately sweeping in angle and parked in different directions according to routines that were different in the three local-time sectors labeled A, B and C in the center of Figure 8. During the period June 15 - July 24, 1974, the different modes of operation were used approximately in the proportions shown in Table 2.

TABLE 2

<u>Mode/LT-sector</u>	<u>A</u>	<u>B</u>	<u>C</u>
Sweeping:	80%	10%	15%
Parked			
Westward:	20%	90%	45%
Eastward:	rarely	rarely	25%
Outward:	rarely	rarely	15%

Table 2: Distribution of angular scan modes for the East-West Detector in the local time segments shown on Figure 8.

In sector B (07:00 - 15:00 LT), where most of the flow from the West was seen, the E-W and fixed detectors were thus looking in opposite directions during more than 90% of the time (including part of the angular sweep), thereby making the detection of any East-West asymmetry particularly easy in this sector. In sectors A and C the E-W and fixed detectors were looking in nearly the same directions during a considerable part of the time (~ 20% and 30%, resp), which means that the frequency of occurrence of flow from the East in these sectors may be larger than shown by this figure.

The sparse occurrence of "flow-events" in the sector 21:00 - 07:00 LT does not necessarily reflect a weak East-West plasma flow here but is rather a consequence of the generally low number densities in this sector, in particular during increased magnetic activity (cf. Figure 6 and next paragraph).

The "flow-events" included in Figure 8 are mostly associated with increased magnetic activity, as seen in Figure 9. In this figure the occurrence of "flow-events" is plotted against current K_p - index. One dot here represents at least one "flow-event" from the East ("weak" event observed only by the fixed detector) during a 1-hour UT-interval of a certain day, and one open triangle represents, in the same fashion, at least one "flow-event" from the West ("weak event

observed only by the E-W detector when facing westward). This figure is otherwise analogous to Figure 6. The dashed curve represents the linear average of K_p associated with dots and triangles. Obviously, the "flow-events" in Figure 8 occurred most frequently during relatively high magnetic activity.

d. Typical Temperatures of the Low-Energy Ions

The temperature of the low-energy ion component has been determined directly from the line plot data by assuming that the peak counting rate of the particle detectors occurs at an energy $E_p \approx 2 kT$, which would be the case with a pure Maxwellian distribution in the absence of plasma flow and spacecraft charging.

Hence,
$$kT = 1/2 E_p \quad (4)$$

where E_p is the energy at the peak counting rate. During spacecraft charging Eq (4) is generally completely misleading (cf. the Appendix), as a result all temperature data have been obtained during non-charge conditions. During strong convective flow the peak counting rate may occur at an energy slightly different from $2 kT$. In the detector facing the flow E_p is given by Eq (2) in the case of a Maxwellian distribution. In all cases of strong flow that have been examined in detail Eq (2) gives $2kT \lesssim E_p \lesssim 4kT$, which is, in fact, within the uncertainty of E_p , at least when $E_p \lesssim 10$ eV (cf. the Appendix).

The thermal energy, as defined by Eq (4), has been determined at least once during each "weak" and "intense warm plasma" event. These samples show a rather wide spread with the different values occurring in the following proportions:

$kT < 3$	15%
$3 < kT < 10$	52%
$10 < kT < 30$	30%
$30 < kT$	3%

This temperature distribution does not represent true time averages, since it favors the frequent short duration plasma encounters. The "weak" and "intense" events of long duration (> 1 hour) usually showed $kT \lesssim 10$ eV. On the average, the "intense" events also appeared cooler than the "weak" events. During individual events the temperature often varied a factor of 2-5. The uncertainty in E_p , as determined from one given line plot, was generally a factor of 2 or less. The temperature did not show an obvious local-time dependence, except for a slight tendency towards lower average temperatures around local dusk.

Apart from the uncertainty in determining E_p , the temperature estimates are subject to an uncertainty in the actual distribution of the low-energy ions. In general the line plots have a less steep negative slope for energies $\gg E_p$ than expected from a pure Maxwellian distribution. Often the transition from the low-energy component to the high-energy component in the line plots is rather diffuse with occasional intermediate peaks. Even

at energies $\lesssim E_p$ the distribution function often deviates considerably from Maxwellian and may sometimes be more closely approximated by $f(E) \sim E^{-3/2}$ up to a break point defined by E_p , while for $E > E_p$ the distribution function has a steeper slope.

4. DISCUSSION

A main feature of the low-energy ion component at geosynchronous orbit and $L \sim 7$ as seen in the frame of reference of the ATS-6 satellite, is a strongly variable density on a short time scale in particular in the local afternoon sector. The density n is sometimes seen to fluctuate two or three orders of magnitude within a few minutes. Such changes are considerably larger than the uncertainty in determining n and appear to be consistent with density fluctuations observed by mass spectrometers in the region between the plasmopause and the magnetopause (Chappell et al., 1971; Harris et al., 1970; Taylor et al., 1970). It may be noted however, that the density fluctuations seen from the ATS-6 occur along the tangential direction, while the latter fluctuations occur primarily along the radial direction, as seen from the spacecrafts. In view of this variability of n at $L \sim 7$ it is hardly meaningful to characterize typical densities to within closer than an order of magnitude, and we have chosen to use the terms "weak" ($1 < n < 10 \text{ cm}^{-3}$) and "intense" ($n > 10 \text{ cm}^{-3}$). The local-time distributions of these types of low-energy plasma events are shown in Figures 4 and 5 and the dependence upon K_p is shown in Figure 6.

From Figures 4, 5, and 6 it is seen that the density of the low-energy ions at $L \sim 7$ is $\leq 1 \text{ cm}^{-3}$ in the 2100 - 0600 local time sector, except during periods of low magnetic activity. In the 0600 - 2100 local time sector the density frequently exceeds 1 cm^{-3} over a wide range of magnetic activity conditions. These observations are in general agreement with the OGO-5 mass spectrometer data (Chappell et al., 1971; Harris et al., 1970; Taylor et al., 1970). However, our measured densities around local noon seem to be systematically lower than the OGO-5 measurements. The latter are based on the current of low-energy ions (with energies $\leq 30 \text{ eV}$) received in the ram direction of the spacecraft, assuming that the most probable ion thermal velocity is much smaller than the spacecraft velocity, which is about 4 km/s at the geocentric distance of interest here (cf. Harris et al., 1967 and 1970). Our temperature measurements indicate that a typical velocity of the low-energy ions is rather 10 times higher than the spacecraft velocity at $L \sim 7$, which implies that the OGO 5 data may overestimate the actual densities by a factor of 3 (or more) according to Fig. 1 in Harris et al., (1970). See also Eq. (1) in Harris et al., (1967). We finally notice that our density measurements seem to be in general agreement with the measurements of the electron plasma frequency by Gurnett and Frank (1974), who state that the total ion density (including both the low and high-energy components) is usually about 1 cm^{-3} or less in the region between the plasmopause and the magnetopause.

Considering now Figure 6 again, the Kp values in this figure is for the three-hour interval which began 1 to 4 hours prior to a given event. However, several authors (c.f. Chappell, et al., 1971, and references therein) have found that the night side sector is the determining region for the plasmopause position. Therefore, we make the following definition: $\langle Kp \rangle$ is the average value of Kp during the last 12 hour interval during which the plasma encountered at a given time would have made a complete traverse of the 1800 - 0600 sector, assuming co-rotation.

Figure 6 shows that warm plasma was observed in the 2100 - 0600 sector only when $Kp < 3$. Furthermore, if the weak warm plasma events in this sector are plotted as a function of $\langle Kp \rangle$ during the preceding local night it was found that events in the 2400 to 0600 sector occurred only if $\langle Kp \rangle < 3$. Therefore the conditions for observing warm plasma in the midnight to dawn sector are especially stringent, requiring a long period (~ 2 days) of magnetic quiet so that the plasmasphere can fill to a density greater than 1 cm^{-3} at synchronous orbit in this sector. Increasing magnetic activity with the associated increases in the dawn-dusk convection electric field then results in a general radial contraction of the plasmasphere in this sector as the plasma is convected sunward.

In contrast to the nightside, weak warm plasma events occurred in the 0600 to 2100 local time sector over a wide range of magnetic activity.

In view of previous observations in this sector (Chappell et al., 1971; Taylor et al., 1970), the weak events here may represent encounters with either the corotating plasmasphere or detached regions from the plasmasphere or simply the plasma that is being filled from the dayside ionosphere (Chappell et al., 1971). Since the frequency of occurrence of "weak" events, as given by Figure 4, peaks in the afternoon sector rather than around local dusk, the dayside filling and "detached" plasma regions may seem to be the major contributors to the "weak" events in at least the 06:00-16:00 LT-sector. The occurrence of "weak" events in the 06:00-21:00 LT-sector shows no obvious correlation with $\langle Kp \rangle$ during the preceding night, except that the events with a duration of several hours occurred only when $\langle Kp \rangle \leq 4^-$ and mostly when $\langle Kp \rangle \leq 2^+$.

As might be expected, the occurrence of "weak" and "intense" events in the 06:00-21:00 LT sector also indicate a sunward plasma flow during increased magnetic activity. Such a flow will have an outward radial component in the dayside sector, which is likely to carry with it detached regions of plasma or "plasma tails" (Chen and Grebowsky, 1974) from the plasmasphere, according to previous observations (Chappell et al., 1971). This is obviously consistent with the occurrence of "intense" events (stars) in Figure 6, since this has a strong positive correlation with increased Kp in the afternoon sector, in particular at early afternoon. It may be noted that the condition $n > 10 \text{ cm}^{-3}$ is equivalent to the condition used by Chappell et al., (1971) to distinguish detached plasma regions outside of the main plasmasphere.

If the occurrence of "intense" events is plotted against K_p instead of K_p there is a similar correlation, although weaker. Some of the "weak" events in the dayside sector are probably also detached regions, in particular during high K_p , including events in the 06:00 - 12:00 LT sector. As indicated by the dashed curve in Fig.6 there is actually a slight tendency towards a higher probability of a "weak" event (during the course of one hour) with increasing K_p in the 06:00 - 16:00 LT-sector. The occurrence of "weak" as well as "intense" events, versus magnetic activity, is thus consistent with a radial outflow of plasma across the dayside part of the geosynchronous orbit during increased K_p .

The only plasma flow in the equatorial plane that is directly measurable by the ATS-6 particle detectors is flow within 20° of the tangent to the orbit. This has already been discussed in some detail in Section 3c in connection with the interpretation of ion-flux asymmetries in the East-West direction. Consider Figure 8. This is the local-time distribution of the "weak" events seen in only one of the two tangential directions and we assume that the asymmetry is due to a large-scale plasma flow with a component tangential to the orbit. This flow is associated with increased magnetic activity, as is evident from Figure 9, where K_p refers to the 3-hour UT-interval during which the respective "flow-events" occurred.

Figure 10 shows a synthesis of our observations of the dominant flow patterns of low-energy plasma at synchronous orbit during magnetically disturbed periods. The absence of low-energy plasma in the nighttime sector when $K_p > 3$ (See Figure 6) reflects a general radial contraction and sunward flow. Similarly, the occurrence of plasma events in the forenoon and afternoon sector is due in part to plasma flowing sunward toward the magnetopause. The observations of flow tangential to the orbit are represented by the tangential arrows. The absence of a tangential flow depiction in the 2100 to 0600 sector is simply a consequence of the fact that there were no low-energy plasma occurrences in that sector during magnetically disturbed times. On the day side, our data indicate that on the average the demarcation between eastward and westward flow tangent to the orbit occurs 1-2 hours past local noon.

Plasma flows at synchronous orbit have previously been reported by Freeman (1968) from an instrument on-board the ATS-1 satellite. These flows were inferred from intense spin modulation of fluxes of $E < 50$ ev ions measured with a retarding potential analyzer. Three events were found in about 50 days of data, and all events were in the noon-to-dusk sector, the flows were toward the sun, and all were associated with intense magnetic storms. These observations are therefore completely consistent with our results, although it seems surprising that the ATS-6 instrument observed many more cases of plasma flow over a similar data base period. (40 days). However, this apparent discrepancy can be explained

by considering the relative sensitivities of the ATS-1 and ATS-6 instruments (J. W. Freeman, Jr., personal communication, 1977).

We conclude this section with a few comments on the observed temperatures of the low-energy ions. The thermal energy kT , as determined from the energy at peak counting rate by Eq (4) was found to vary considerably but to be mostly in the range 1-15 eV. Our measurements thus confirm previous reports of relatively high temperatures of the low-energy ions in the outer plasmasphere and the region beyond the plasmapause. Serbu and Maier (1970) used the OGO 5 retarding potential analyzer to deduce the temperature of ions in the 0-500 eV range. They found, as typical values, $kT_i \gtrsim 1\text{eV}$ in the outer plasmasphere and $kT_i \gtrsim 10\text{ eV}$ beyond the plasma pause. Gurnett and Frank (1974) used data from the plasma wave antenna on Imp 6 to deduce the plasma frequency and, hence, the total ion density, as well as data from the Lepedea instrument on Imp 6 to find

ion intensities in the energy range 52 eV - 38 keV. By fitting a Maxwellian distribution to the low-energy end of the proton spectrum they found $kT_i = 8$ eV in a typical case outside of the plasmasphere. Bezrukikh and Gringauz (1975) compared the currents received by two ion traps oriented in different directions on the Prognoz satellite. They found a hot zone in the outer plasmasphere, adjacent to the plasmapause, with $kT_i \geq 2.5$ eV.

Since the low-energy ions observed at geosynchronous orbit most likely come from the ionosphere, where $kT_i \sim 0.1$ eV, they are obviously heated or, alternatively, they are accumulated from the high-energy tail of the ionospheric ions (cf. Serbu and Maier 1970). We do not want to suggest a specific heating mechanism but merely point out some characteristics of the ions at small pitch angles, as compared to ions at 90° pitch angle. The case illustrated in Figure 11 is very common. That is, the number fluxes of ions with energies ≤ 1 KeV are very often greater along the magnetic field than transverse. Furthermore, the ions at small pitch angles often have a much more pronounced high-energy tail than the ions at 90° pitch angle. Hence, the energy flux is often even more field-aligned than the number flux. This is in contrast with the situations where the ions at 90° pitch angle are either a trapped selection of ions from the high-energy tail of the upflowing ionospheric ions or a gradually heated population of trapped ions. It rather appears as if the ionospheric ions are often energized during transit

to the outer magnetosphere by, for instance, magnetic-field-aligned electric fields. The field-aligned ions seen at pitch angles $\leq 20^\circ$ may well be trapped, since the half angle of the local loss cone is only about 5° , and, hence, originate from field lines far from the position of the ATS-6 at the moment of detection. It is interesting to note that these field aligned fluxes are often seen to increase in connection with "substorm injections" of high-energy particles,

5. SUMMARY.

The low-energy ion component at the geosynchronous orbit at $L \sim 7$ has been studied for the period June 15 - July 24, 1974, by means of data from the UCSD Auroral Particles Experiment on ATS-6. The density and temperature have been determined from the differential ion number fluxes versus energy at large pitch angles to the magnetic field. The main characteristics of the density and temperature at different local times during different magnetic conditions may be summarized as follows:

1. The density n is typically $\leq 1 \text{ cm}^{-3}$ except in the afternoon sector and around local dusk, where $1 \text{ cm}^{-3} < n \leq 10 \text{ cm}^{-3}$ during as much as 50-60% of the time and $n > 10 \text{ cm}^{-3}$ during as much as 10-20% of the time. In the nighttime sector n is often $< 1 \text{ cm}^{-3}$, in particular during enhanced magnetic activity.

2. In the 21:00-06:00 LT-sector $n > 1 \text{ cm}^{-3}$ during a small fraction of the time in connection with low magnetic activity, indicating encounters with the outer fringes of the plasmasphere.

3. In the 0600-1600 LT sector we found that the warm plasma density is between 1 and 10 cm^{-3} during a variety of magnetic activity (c.f. Figure 6). We also observed that long duration warm plasma encounters (greater than one hour) were associated with low magnetic activity. We therefore interpret occurrences in this sector to be regions of detached plasma from the main plasmasphere, regions of dayside filling from the ionosphere, as well as encounters with the stable plasmasphere during periods of low magnetic activity. During enhanced magnetic activity n is more variable and often exceeds 10 cm^{-3} in the afternoon, indicating regions of detached plasma which originated from within the plasmasphere.

4. The thermal energy kT is fairly variable but is mostly in the range 1-30 eV. The temperature does not show a clear local-time dependence, except for a slight tendency towards lower temperatures around local dusk. Lower temperatures also seem to occur more often during low magnetic activity, along with a smoother density distribution.

Our analysis has also given some preliminary characteristics of plasma flow and ion pitch-angle distributions, as follows:

5. The low-energy ion fluxes often have a considerable asymmetry along the direction tangent to the orbit, in particular, during high magnetic activity. From this flux asymmetry a convective flow from the East or West may be inferred as shown in Figure 10. This flow is associated with enhanced magnetic activity. The flow velocities have been estimated to be 5-10 km/s in typical cases and as large as 30-50 km/s in more extreme cases. The radial flow vectors in this figure are consistent with the behavior of the low-energy plasma as functions of time and magnetic activity.

6. The ions at lower energies exhibit some degree of field-alignment during roughly half of the time. This field-alignment is usually limited to energies ≤ 10 keV, but sometimes it extends to the upper energy limit of the particle detectors (~ 80 keV). The energy spectrum of the ions at pitch angles $\leq 20^\circ$ is usually highly variable (on a time scale of 1 minute) and often more widely extended toward higher energies than the energy spectrum of the low-energy ions at 90° pitch angle.

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APPENDIX

Data Reduction Method

In order to obtain the approximate density and temperature of the low-energy ions during a given energy scan, we have compared the actual counting rates with calculated counting rates due to Maxwellian particle distributions with various densities and temperatures. Two calculated samples are shown in Fig. 12 by the solid curves for a density $n = 1 \text{ cm}^{-3}$ and thermal energies $kT = 50 \text{ eV}$ and $kT = 1.5 \text{ keV}$, respectively. The peak counting rate with a given Maxwellian distribution occurs at an energy (approximately) equal to twice the thermal energy. The dashed curves labeled $n = 1$ and $n = 10$ represent the loci of the peak counting rates with Maxwellian distributions with constant densities $n = 1 \text{ cm}^{-3}$ and $n = 10 \text{ cm}^{-3}$ respectively. The dotted contour represents a "typical" plot of actual counting rates versus energy step number for a given detector. Provided the shape of this contour is roughly "Maxwellian" (near the peak counting rate) both the density and temperature of an isotropic distribution may thus be estimated from this kind of nomograph.

Since the energy range 0-10 eV is covered by only five energy steps of the particle detectors and the counting rate at the lowest energies are, in fact, rather fluctuating, it is not possible to make very accurate density and temperature determination of the low-energy particles.

When the low-energy ions have a $kT \approx 1$ eV it is generally not possible to determine the density and temperature to within closer than a factor of 2-3. This inaccuracy is illustrated in Figure 12 by the steep slope at low energies of the dashed curves $n = 1$ and $n = 10$. This is a result of the bias of -21 in the equation for energy as a function of step number (see section 2). Some early attempts at a computerized integration of the particle counts proved to give considerably more variable quantities than the visual method, but averaged over many energy scans (several minutes of data) both methods gave much the same values.

When the spacecraft is negatively charged, as it is during 07:00-09:00 UT in Figure 3, the method illustrated in Figure 12 is not directly applicable. In this case the ions with the lowest energies have been energized to the potential of the spacecraft, causing a narrow spike in the line plot data. During these conditions the energy resolution of the detectors ($\approx 20\%$) generally does not allow the density and temperature to be determined separately. In order to obtain estimates of the ion densities during charging conditions we have therefore used temperature data from non-charge conditions.

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FIGURE CAPTIONS

FIGURE 1

Sketch of the ATS-6 satellite showing the location of the detector package. The large antenna is aimed toward the center of the earth and the solar panel support arms lie along a North-South line. The two rotating detector heads are visible on the sides of the Environmental Measurements Experiment (EME) package.

FIGURE 2

Line plot of counting rates from the North-South detectors for a one minute interval, illustrating the presence of low energy, or "warm" plasma. The top panel is the counting rate due to ions and the middle panel is the counting rate due to electrons. The dashed curve in the bottom panel is the pitch angle, with the scale to the lower right. The solid curve on the bottom panel shows the instantaneous value of the analyzed energy, with the scale (logarithmic) at the lower left. The data are discussed in the text.

FIGURE 3

An intensity-coded display of data for the period 00-12 U.T. on day 176 of 1974 (June 25, 1974). In these displays, or spectrograms, the horizontal axis is time, the vertical axis is the energy scale, and the grey level is related to the logarithm of the detector counting rate. The top spectrogram shows electron data from the E-W detector and the bottom spectrogram shows E-W detector ion data. The traces at the top of the figure show the UCLA magnetometer data in the form total B , field inclination in the meridian plane, and east-west component of B . This spectrogram illustrates many of the features of plasmas at geosynchronous orbit, including weak and intense warm plasma events, changes in the energy dispersion traces due to electric field enhancements, substorm injections of energetic plasmas, and electrostatic charging of the spacecraft. These features are discussed fully in the text.

FIGURE 4

The observed distribution of weak warm plasma events ($1 < n \leq 10 \text{ cm}^{-3}$; $kT=1-30 \text{ eV}$) as a function of local time.

FIGURE 5

The observed distribution of intense warm plasma events ($n > 10 \text{ cm}^{-3}$; $kT=1-30 \text{ eV}$) as a function of local time. Note that the percentage scale differs from that of Figure 4.

FIGURE 6

The occurrence of weak warm plasma events (dots) and intense warm plasma events (stars) in local time-Kp space. The histogram on the right shows the distribution of Kp values during the data base period. The dashed and solid lines are the linear averages of Kp at a given local time for weak and intense events, respectively.

FIGURE 7

A spectrogram illustrating a strong flow of low-energy ions. The time period is 0330 to 0500 UT on day 200 of 1974 (July 19, 1974). The saw-tooth-like curve in the top panel is the angle of the E-W head relative to the spacecraft. The ion flux is strongly intensity-modulated by the detector sweep, being strongest when the detector is viewing to the east. The maximum flow velocity in this case has been estimated to be nearly 20 km/s.

FIGURE 8

Distributions in local time of flows of low-energy ions inferred from view-angle modulations in fluxes observed in the E-W sweeping and the fixed east detector. The outer histogram represents flows from west to east along the orbit (direction of arrow) and the inner histogram represents flows from east to west along the orbit. The sectors labeled "A", "B", and "C" are related to instrument operation modes which bias the data and are discussed in the text.

FIGURE 9

The occurrences of flows from east to west (dots) and flows from west to east (triangles) plotted in local time- Kp space. This figure is analogous to Figure 6. The dashed line is the linear average of Kp associated with both types of events.

FIGURE 10

The average directions of azimuthal and radial flow components at geosynchronous orbit during magnetically active periods ($K_p > 3$). The azimuthal flow arrows are inferred from observations of ion flux asymmetries and represent typical flow velocities of 5-10 km./sec. The radial flow arrows are consistent with changes in the occurrences of warm plasma events with increasing magnetic activity.

FIGURE 11

Line plot data illustrating a strongly field-aligned low energy plasma component. All traces are as in Figure 2, with the addition of ion data from the fixed east detector (dotted trace, upper panel), sampling pitch angles near 90° . The dashed contour is a Maxwellian fit to the fixed east detector data. During the energy scan the sampled pitch angle for the N-S head varied from 10° to 15° .

FIGURE 12

Illustration of a nomograph technique to derive density and temperature from the line plot data. The dashed curves are loci of peak counting rate of a Maxwellian particle distribution which has a given density n and arbitrary temperature. The peak counting rate occurs at $E=2 kT$. The solid curves are Maxwellian distribution contours for $n=1 \text{ cm}^{-3}$ and temperatures as shown. The dotted trace is a sample of line plot data.

**UCSD AURORAL
PARTICLES EXPERIMENT**

Fig. 1

Fig. 2

DBE=2.7 DBP=1.2 DBS= .075 SIPE=3. PSN= 1. NS= 1.0 EVI=360.360.) COM=006073510 SA= -6. LNO=266. MSFC-10/31/76

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10

Fig. 11

Fig. 12

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LOW-ENERGY PLASMA OBSERVATIONS AT SYNCHRONOUS ORBIT

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The University of California at San Diego Auroral Particles Experiment on the ATS-6 Satellite in synchronous orbit has detected a low-energy plasma population which is separate and distinct from both the ring current and plasma sheet populations. The density and temperature of this low-energy population were highly variable, with temperatures in the range $kT = 1$ to 30 eV and densities ranging from less than 1 cm^{-3} to more than 10 cm^{-3} . The occurrence of a dense low-energy plasma is most likely in the afternoon and dusk local time sectors, whereas $n > 1 \text{ cm}^{-3}$ is seen in the local night sector only during magnetically quiet periods. These observations suggest that this plasma is the outer zone of the plasmasphere. During magnetically active periods, this low energy plasma is often observed flowing sunward. In the dusk sector, enhanced plasma flow is often observed for 1-2 hours prior to the onset of a substorm-associated particle injection.

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Key words: Convection, Detached plasma, Field-aligned, Low-energy plasma, Magnetosphere, Plasma flow, Plasmasphere, Plasma trough, Substorm injection, Synchronous orbit, Thermalplasma, Warm plasma