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Contents

2. Composition of the Hot Plasma Near Geosynchronous Altitude

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Abstract

Although there have been no direct measurements of the composition of the hot (keV) plasma at geosynchronous altitudes, the combination of other observations lead to the conclusion that, at least during geomagnetically disturbed periods, there are significant fluxes of ions heavier than protons in this region. Ion composition measurements below 8000 km altitude show upward streaming fluxes of both O^+ and H^+ ions in the L-region of the geosynchronous orbit. These observations are consistent with the conclusion that at least a portion of the total ion fluxes observed at geosynchronous altitude to be highly peaked near the magnetic field lines are heavier than protons and originate in the ionosphere.

1. INTRODUCTION

Quantitative measurements on the ion composition of the hot (keV) plasma near geosynchronous altitude have not yet been performed. Thus, the plasma composition in this region of the magnetosphere must be inferred primarily from composition information obtained at other locations in the magnetosphere. Prior to the work of Shelley et al[1] it was generally believed (or assumed) that the dominant ion species in the hot magnetospheric plasma was always hydrogen (H^+) and that the source of the ions was the solar wind. There is increasing evidence that energetic oxygen (O^+) and helium (He^+) ions of ionospheric origin are frequently significant components in the hot plasma and that during geomagnetically disturbed conditions O^+ ions may be the dominant hot plasma ions in some regions of the magnetosphere. Satellite measurements at low altitudes (near 800 km) during magnetic storms have shown that large fluxes of O^+ ions in the energy range 0.7-12 keV are precipitated along with H^+ ions from the magnetosphere at magnetic L-shells corresponding to the region of geosynchronous altitude.[2, 3, 4] Satellite measurements at intermediate altitudes (near 8000 km) have shown that large fluxes of O^+ and H^+ ions in the kev range are being accelerated out of the ionosphere and injected into the magnetosphere over a wide range of magnetic L-shells.[5, 6, 7] Under certain impulsive magnetospheric conditions which produce velocity dispersion of the trapped ions, measurements at geosynchronous altitude indicate that ions heavier than protons are present in the kilovolt energy range.[8] Thus, it appears likely that significant fluxes of ions other than protons are present near geosynchronous altitude at least for some magnetospheric conditions. In this paper, discussion of the composition of the hot plasma is limited to particle energies less than 50 keV since the dominant plasma density and energy near geosynchronous altitude is produced by particles in this energy range. Composition measurements at higher energies and their importance to magnetospheric processes have recently been reviewed.[9]

The importance of knowing the ion composition of the plasma and the detailed energy and angular distributions of the ion species for modeling the secondary emission effects, current balance, sheath characteristics, etc., during spacecraft charging events is discussed in several other papers in this proceeding and will not be reviewed in this paper. However, for highly anisotropic ion fluxes and certain spacecraft configurations it is possible to have limited regions of a spacecraft acquire a large positive potential with respect to the plasma, in contrast to the large negative potential generally observed and discussed. This possibility of large positive potentials will be discussed in conjunction with the observations of intense ion fluxes aligned nearly parallel with the geomagnetic field direction.

For the purpose of the present discussion, the information presented on the composition of the hot plasma in the magnetosphere will be divided into the three general categories of low, intermediate, and high altitude satellite measurements. The reported observations and plasma composition results in these altitude regions are briefly reviewed and their significance to the geosynchronous altitude environment is discussed.

2. OBSERVATIONS AT LOW ALTITUDES

The most extensive measurements on the composition of the hot magnetospheric plasma have been obtained with an ion mass spectrometer aboard the polar orbiting 1971-089A satellite near 800 km. The satellite was three-axis stabilized with one axis always aligned near the earth's radius vector. The ion mass spectrometer was oriented at 55^{o} to the zenith and thus nearly always sampled ions precipitating from the magnetosphere into the atmosphere. The spectrometer covered the energy range from 0.7 to 12 keV and the mass range from 1 to 32 AMU and the data were acquired primarily during the period from October 1971 to December 1972.

The most prominent ion observed other than H^+ was O^+. The O^+ intensities were largest during principal magnetic storms[4] but significant fluxes were also observed during magnetic substorms.[10] A detailed study of the morphology of the O^+ ions during the rather classic 17-18 December 1971 magnetic storm has been made and reported in the literature.[2,3] Figure 1 from Shelley et al[1] shows H^+ and O^+ data from 6 consecutive satellite traversals of the nightside (0300 LT) high latitude regions during the main phase of the storm. The ordinate is approximately proportional to the integral number flux in the instrument energy range from 0.7 to 12 keV. The principal features of note are: (1) the O^+ fluxes at L-shells (near $L = 6.6$, $\lambda_L = 67^{o}$) corresponding to geosynchronous altitude can be comparable in intensity to the H^+ fluxes, (2) the latitudinal distributions of both species have significant structure and vary from pass to pass, and (3) at a given location the relative composition of the flux changes from pass to pass.

The locations in magnetic latitude of the O^+ and H^+ precipitation regions throughout the time period of the magnetic storm are shown in Figure 2.[10] The integral energy flux of the O^+ and H^+ ions was computed over the latitudinal range $40^{o} < \Lambda_L < 80^{o}$ and the circle for the H^+ ions and the square for the O^+ ions in Figure 2 represents the 50 percent point in the zone integral with the bars representing the 10 percent and 90 percent points in the same integral. From this figure it is seen that significant O^+ precipitation is frequently occurring during the storm at magnetic latitudes (near $\Lambda_L = 67^{o}$) corresponding to the geosynchronous altitude.

The latitudinal dependence of the average precipitation intensity during the entire period of the storm (0532 UT on 17 December to 1146 UT on 18 December) is shown in Figure 3. It is seen that at magnetic latitudes near 67 degrees the O^+ and H^+ fluxes are comparable when averaged over the storm and that the O^+ ion intensities exceed the proton intensities below 65^{o} magnetic latitude.

The energy distributions of the precipitating O^+ and H^+ ions were found to be highly variable at all magnetic latitudes.[1] The average energy for the O^+ ions in the measured energy range during the storm-time period is shown in Figure 4 and

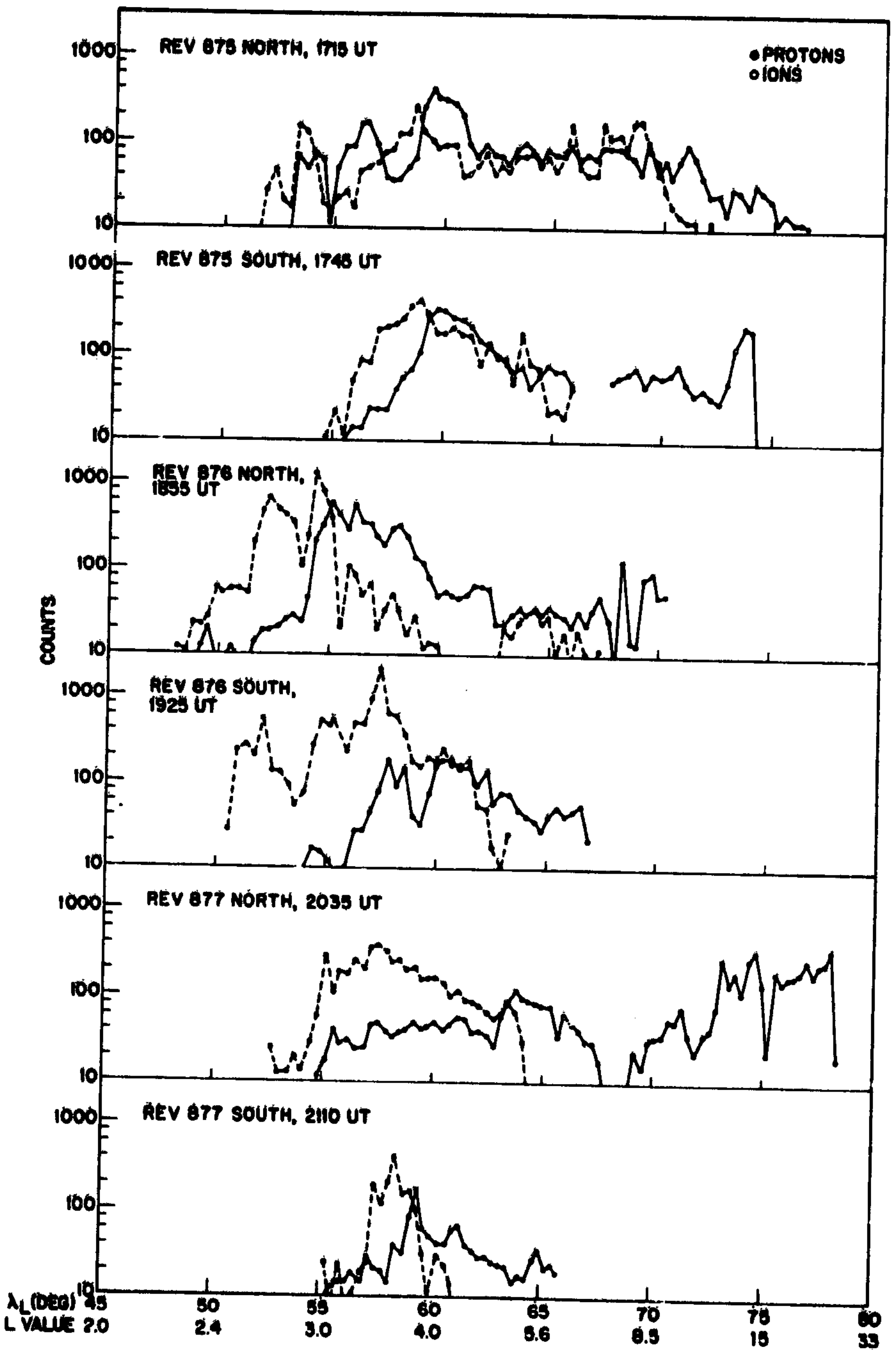


Figure 1. Ion Fluxes During the 17 December 1971 Magnetic Storm (From Shelley et al[1])

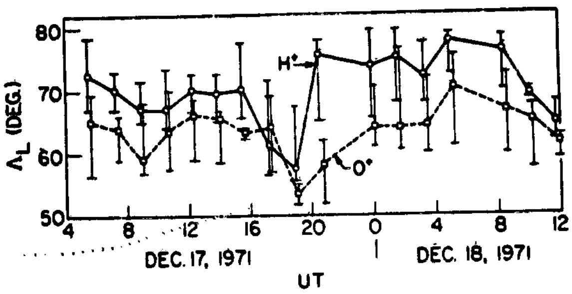
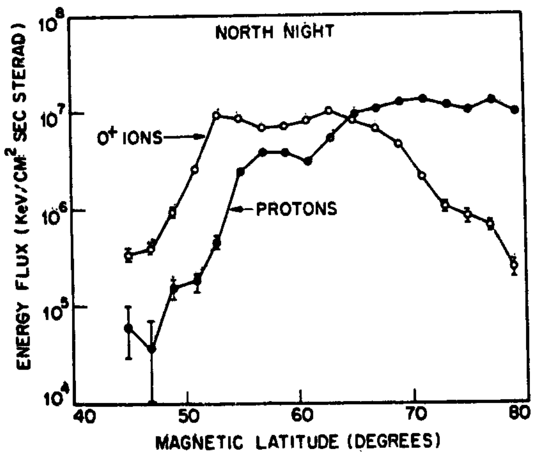


Figure 2. Locations of the Precipitation Zones of O^+ and H^+ Ions During the 17-18 December Magnetic Storm (From Johnson et al[10])

Figure 3. Latitudinal Variation of the Energy Flux of O^+ and H^+ Ions During the Time Period 0532 UT on 17 December to 1146 UT on 18 December 1971 (From Johnson et al[10])



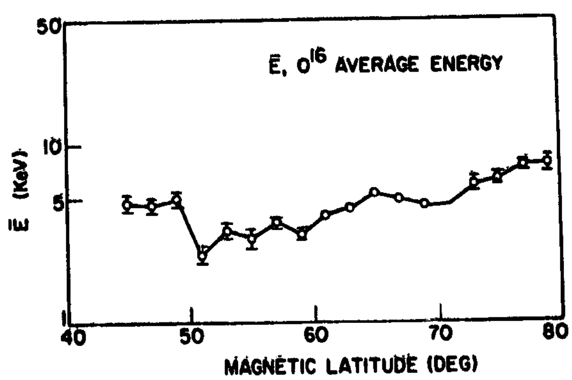


Figure 4. Latitudinal Variation of the Average Energy of O^+ Ions During the Time Period Shown in Figure 2 (From Johnson et al[10])

is seen to be about 5 keV near the magnetic latitudes appropriate to the geosynchronous location.

To assess the local time dependence of the O^+ precipitation during magnetic storms, a synoptic study was made of data from one year's operation of the energetic ion mass spectrometer aboard the 1971-089A satellite.[4] Data were utilized from three orbits in each of eleven principal magnetic storms during the period from December 1971 to November 1972. O^+ ion precipitation was observed during each of the storms. The latitudinal extent and local magnetic time distribution of the O^+ regions are shown in Figure 5 from Shelley et al.[4] The dot indicates the

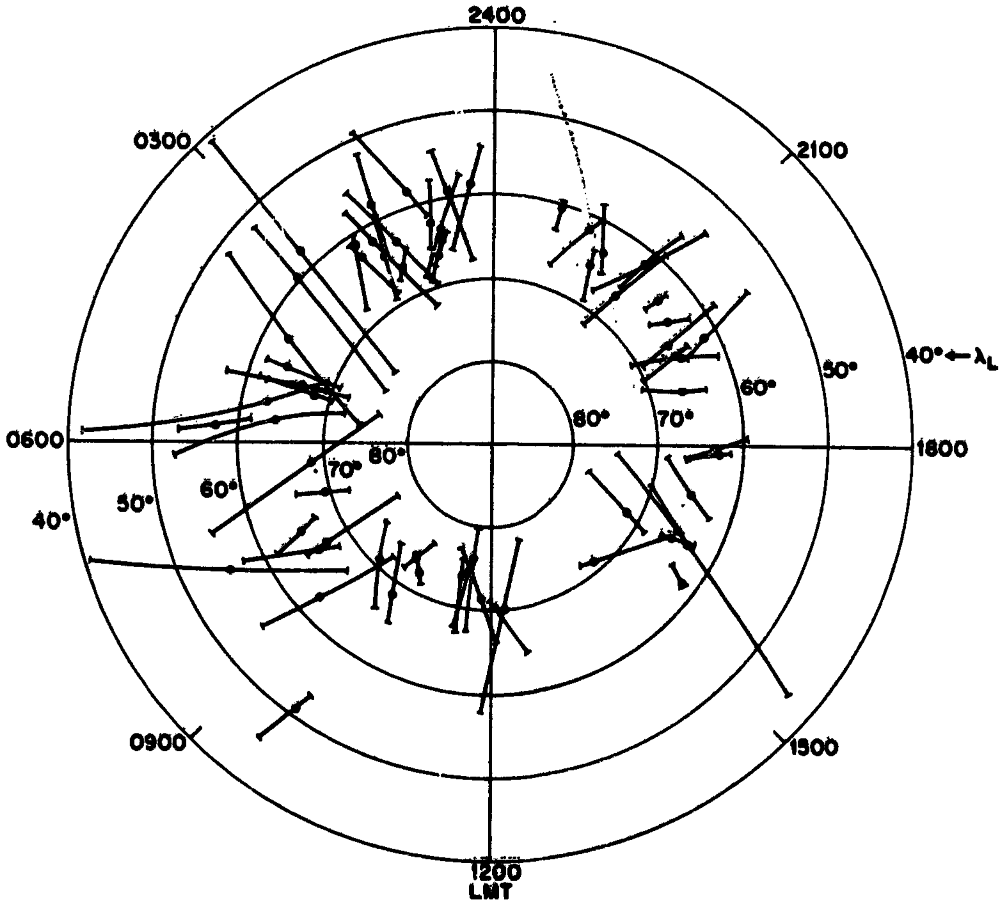


Figure 5. Polar Plot in Invariant Latitude and Magnetic Local Time of the Regions of Observed O^+ Precipitation During 11 Major Storms (From Shelley et al[4])

position of the maximum flux intensity during each pass and the lines indicate the position of the pass during which the flux was above the spectrometer sensitivity threshold of about 2×10^5 ions/cm^2-sec-sr. From these data, it is seen that O^+ fluxes were frequently observed at the geosynchronous L-shells at essentially all local times, except for possibly a few hours near 1200 local magnetic time. The peak fluxes were typically in the range 5×10^5 to 4×10^7/cm^2-sec-sr. The O^+ peak intensities near noon were found to be, on the average, about a factor of ten lower than near the midnight sector.[4]

Precipitating O^+ fluxes have been observed with the same spectrometer in association with magnetic substorms.[10] The peak intensities were in the range of 3×10^5 to 3×10^6 ions/cm^2-sec-sr and were observed at L-shells corresponding to the geosynchronous altitude.

Precipitating fluxes of He^+ and He^{++} were also observed with the 1971-089A satellite on L-shells corresponding to geosynchronous altitude.[11,12] The He^+ and He^{++} fluxes were observed much less frequently than the O^+ fluxes and their intensities were much less than those typically observed for the O^+ ions during magnetic storms. However, based on ion lifetime considerations Tinsley[13] and Lyons and Evans[14] conclude that He^+ is most likely the dominant ion in the late-time ring current.

Rocket measurements with ion mass spectrometers at altitudes below 1000 km have also shown the presence of energetic He^{++} and O^+ ions in the magnetosphere.[15,16] These measurements have been made near Ft. Churchill, Canada and thus have been limited to the high magnetic latitudes near L = 9.

3. OBSERVATIONS AT INTERMEDIATE ALTITUDES

Preliminary results are now available from an energetic ion mass spectrometer experiment aboard the spacecraft 1976-65B which is in an elliptical polar orbit with apogee near 8000 km.[5] The spacecraft is spinning and provides for the first time detailed pitch angle distribution measurements with identifiable mass-per-unit-charge. The experiment covers the energy-per-unit-charge range from 0.5 to 16 keV and the mass range from 1 to 150 AMU.

O^+ and H^+ ions are frequently observed streaming upward along magnetic field lines with intensities of both O^+ and H^+ often found to be near 10^8 ions/cm^2-sec-sr. The upward streaming ions have been observed over all the local magnetic time range thus far examined from 0900 to 2200 hours. The latitude distributions of these ions have not been determined in detail but during magnetic storms upward streaming fluxes in the evening sector are frequently observed in the range of 65°

to 70^{o} magnetic latitude, thus spanning the L-shell regions at geosynchronous altitude. During the 24 August 1976 magnetic storm, upward streaming H^+ and O^+ fluxes were observed continuously over a latitudinal extent of several hundred kilometers. The energy distributions of the ions extended to at least 8.5 keV and the O^+ energy spectrums were frequently harder than the H^+ spectrums.[6] The upward streaming ion fluxes are observed during quiet as well as disturbed magnetic periods.

The angular distributions of the upstreaming ions are often sharply peaked along the magnetic field lines. A typical example of this[5] is shown in Figure 6 for a segment of data acquired in the northern auroral region at a local time of about 21 hours on 13 July 1976. The relative flux intensities of the O^+ and H^+ ions are plotted versus time and can be compared with the look direction of the instrument relative to the magnetic field direction (upper panel) as determined from the on-board magnetometer. The energy-per-unit-charge of the measured ions is also indicated above the O^+ panel. One can readily see the sharply peaked angular distributions of both the O^+ and H^+ ions. The peak upstreaming O^+ flux observed corresponds to about 10^8 ions/cm^{-2}-sec-sr-keV. The lowest panel shows the response of the electron detector which sampled the energy range $0.35 \leq E \leq 1.13$ keV. The deep minima in the electron flux at pitch angles corresponding to the atmospheric loss cones are clearly evident at the same locations as the ion peaks.

The foregoing type of angular distributions for the ions and electrons could lead to a net positive upward streaming flux at angles near the magnetic field direction. If an anistropic flux of this type is incident on a spacecraft with a hole in the outer skin, then a nonconducting surface on a component inside the skin and on the same magnetic field line as the hole, will become positively charged providing the hole subtends an angle from the component surface equal to or less than the pitch angle range over which the positive ion flux is larger than the electron flux. Assuming that the electron flux is higher than the ion flux at the larger pitch angles (which is typical), then a large negative potential could be formed on the component surface adjacent to a large positive potential. This configuration is illustrated schematically in Figure 7, and to simplify this example, the secondary electron emission from the surface is assumed to be negligible. The surface position L on the component lies along the magnetic field line through the hole in the spacecraft skin. Angles 1_1 and 1_2 are taken to be less than the pitch angle range over which the ion flux is greater than the electron flux so that a positive potential will occur at position L. Position N illustrates a surface region at angles between n_1 and n_2 to the magnetic field direction where the electron flux is larger

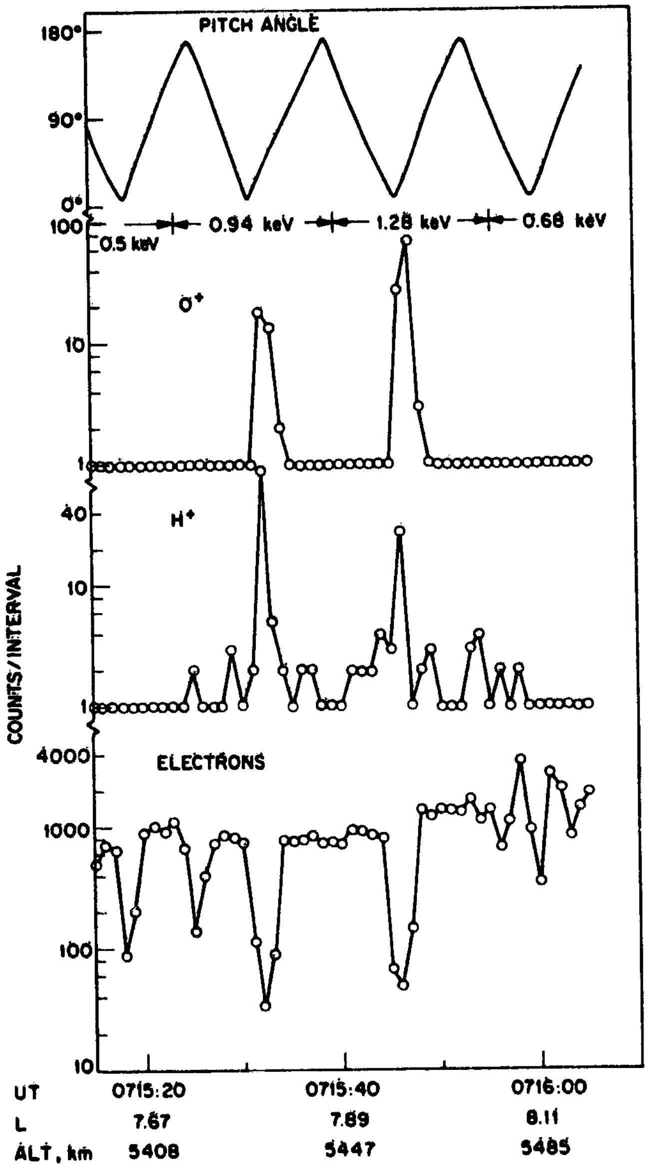


Figure 6. Data From Revolution 35 on July 13, 1976. The upper panel shows the pitch angle of the center of the instrument field of view. The two center panels show data from the mass spectrometer at the indicated energies, and the lower panel shows electron fluxes in the energy range from 0.35 to 1.13 keV. The relative temporal precision of the plots is about one second (from Shelley et al[5])

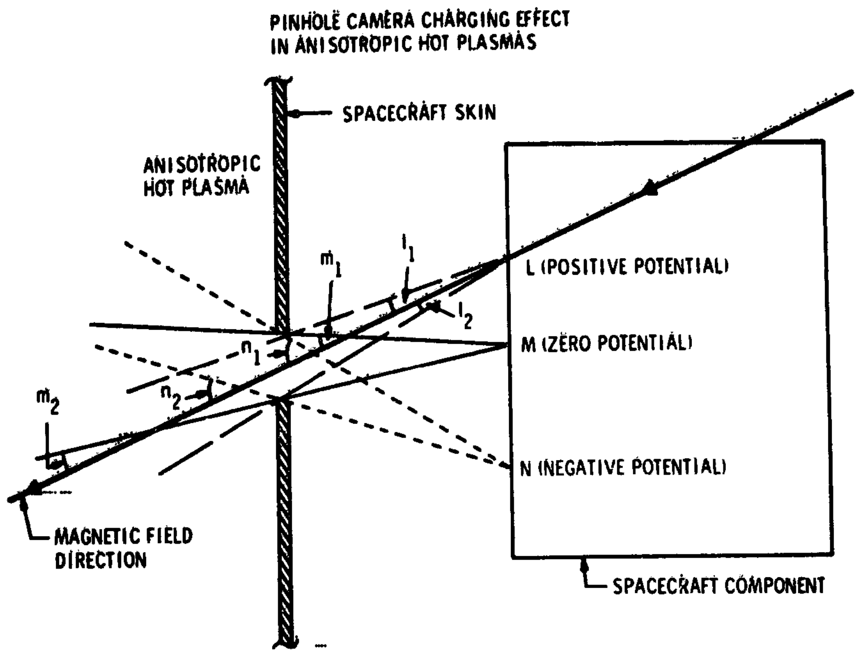


Figure 7. Schematic Drawing Illustrating the Geometry for the Pinhole Camera Charging Effect in Anisotropic Hot Plasmas

than the ion flux. At this position a negative potential will occur. At some position, M, between N and L the electron and ion fluxes will be equal and a zero potential will occur. It can be seen that the surface charging at each position on the surface is related to the pitch angles subtended at the hole in the skin and thus, in analogy to pinhole cameras for electromagnetic radiations, this will be referred to as the "pinhole camera charging effect." Although it has been illustrated for a net positive flux along the field line, an anisotropic electron flux will also produce a potential gradient across the surface in essentially the same way. Another case to consider in relation to the pinhole camera charging effect is the one in which the spacecraft skin is charged highly negative. In this case, the anisotropic ion flux could be produced by the acceleration of the ions along the field line by the spacecraft surface potential, while the electron flux reaching the spacecraft surface at angles near the magnetic field direction is reduced by the negative potential of the surface.

4. OBSERVATIONS AT SYNCHRONOUS ALTITUDE

Extensive measurements on the electron and total ion characteristics of the hot plasma at geosynchronous altitude have been made with instruments aboard the

ATS-5 and ATS-6 satellites.[17, 18] Although the instrumentation could not distinguish the ion species, analysis of bouncing clusters of ions during some types of transient events can provide information on the ion masses. In two cases, McIlwain[8] reports that the data are best fit if He^+ or O^+ ions are assumed for the cluster ions, but quantitative values for the fluxes are not reported.

Angular distribution measurements on the ATS-6 satellite show that the ion fluxes below 10 keV are often enhanced at small pitch angles.[18, 19] An example of this enhancement is shown in Figure 8 from the paper by Mauk and McIlwain.[19] It is seen that the enhancement extends to 6.2 keV and to pitch angles well outside the region of the atmospheric loss cone of about 5°. Enhancement of the ions at small pitch angles at synchronous altitude is consistent with the continued upward flow of the upward streaming ionospheric ions observed at lower altitudes and discussed in the preceding section. Thus, it is reasonable to expect similar ion composition in the peaked ion fluxes at synchronous altitude as is found in the upward flowing ions on the same L-shells at the lower altitudes.

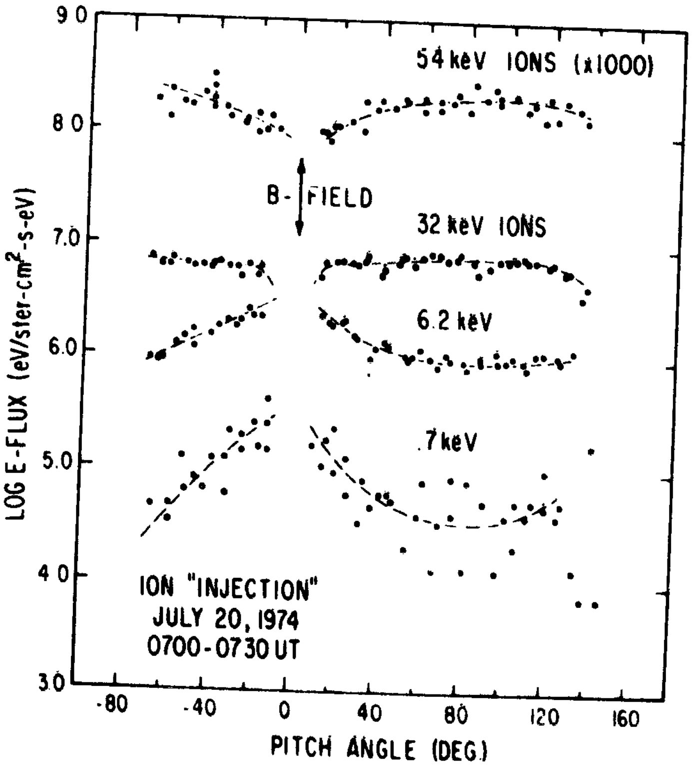


Figure 8. Ion Pitch Angle Distributions as Measured on the ATS-6 Synchronous Satellite During an Ion Injection Event on 20 July 1974 (From Mauk and McIlwain[19])

McIlwain[8] also notes that simultaneous ion and electron field-aligned beams at the higher energies do not seem to occur. Thus, the pinhole camera charging effect discussed in the previous section may be particularly applicable near geosynchronous altitudes.

5. SUMMARY

Plasma composition measurements at low altitudes show that relatively large fluxes of O^+ ions as well as H^+ ions are precipitated from the magnetosphere at magnetic L-shells corresponding to geosynchronous altitude. Upward streaming O^+ and H^+ ions from the ionosphere are also observed on field lines threading the geosynchronous location. Observations at synchronous altitude of ion fluxes highly peaked at small pitch angles are consistent with the ionosphere as the source of the ions. Thus, although there are no definitive measurements of the composition of the hot plasma near geosynchronous altitude, other observations strongly support the conclusion that at least during magnetic storms significant fluxes of ions heavier than protons are also present there.

Acknowledgments

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