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DIRECT MEASUREMENTS OF ELECTRON DENSITY, TEMPERATURE AND ION CO--ETC(U)
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Ionospheric plasma irregularities have been studied on each of two rockets launched into significantly different conditions of equatorial spread-F. In the first operation (into a spread-F decay phase) a number of major depletions ($\Delta N_e/N_e \gtrsim 90\%$) were distributed throughout the F-region from its bottomside gradient centered near 260 km, through the F-peak, to a topside altitude of 500 km. In a second operation (launched into a mid-phase development of spread-F) irregularities were observed only on the bottomside gradient, with no depletions in or above the F-peak.

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20. Abstract (Continued)

In both cases O^+ was the dominant F-region ion down to the very bottom of the F-ledge. At altitudes below the ledge, molecular ions dominated with a scale height approaching infinity. The most significant ion chemical results were collected on the first launch where none of the depletions showed evidence of typical bottomside source ions (NO^+, O_2^+ or meteorics). Instead, the $[N^+]/[O^+]$ ratio proved to be the appropriate signature for the depletion's bottomside source domain. The ion composition results also impact on speculations that neutral atmospheric turbulence is a triggering mechanism for bottomside irregularities. Indeed, the results of the first launch point to a uniform neutral atmospheric profile in the presence of extremely irregular bottomside ion distributions, a result which tends to negate the possible role of atmospheric turbulence.

CONTENTS

DIRECT MEASUREMENTS OF ELECTRON DENSITY, TEMPERATURE AND ION COMPOSITION IN AN EQUATORIAL SPREAD-F IONOSPHERE

I. INTRODUCTION

Accumulated information regarding equatorial spread-F has pointed toward a definite causal relationship between large scale plasma depletions (also referred to as holes, bite-outs or bubbles) and observations of large ionospheric domains with radar backscatter returns from the much smaller (meter size) irregularities called plumes. While there have been a number of rocket efforts[1-3] to examine the exact relationship between radar plumes and ionospheric electron density depletions, only the recently conducted Kwajalein campaign[3] included direct measurements of ion composition...an *important* signature in the growth and transport mechanisms that appear to be active during the occurrence of spread-F.

Before the Kwajalein campaign, knowledge of ion composition within and around depletions had come only from satellite investigations. Typically, satellite mass spectrometric observations[4-6] have shown that the ion composition can be vastly different inside and outside the bite-outs. Fe^+ ions may be enhanced or depleted, with molecular ions usually more abundant inside the bite-out. Brinton et al.[4] and McClure et al.[5] have found O^+ depleted by as much as a factor of 10^3 to

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a concentration below that of NO^+. The molecular ion NO^+ was found to be dominant in the O^+ depleted region, with the bite-outs varying from a few kilometers to tens of kilometers in width. An analysis of the Atmosphere Explorer-C data[6] suggested that a given chemical volume on the bottomside F-layer ($[NO^+]$, $[O_2^+] > [O^+]$) could move upward through a stationary neutral atmosphere and appear at higher altitudes as a bite-out in the local plasma density. As the bottomside F-region plasma cell moved upward, the relative magnitudes of its ionic components would depend on transit time and on altitude through the height distribution of the neutral gases. This model was consistent with the satellite observations as well as the computational work of Scannapieco and Ossakow[7].

To further understand the detailed relationships involving large scale plasma depletions and associated ion-chemical signatures, two rocket payloads instrumented with plasma diagnostics complements (plasma probes, electric field sensors, mass spectrometer and a four-frequency beacon experiment) were launched into the topside F-region ionosphere above Roi-Namur in the Kwajalein Atoll (4.3° N dip latitude). We present here the results of those operations, representing the first coordinated rocket measurements of electron density, temperature and ion composition under conditions of equatorial spread-F.

II SPREAD-F CONDITIONS AND ROCKET RESULTS

Discussion of results and focus on differences in prevailing ionospheric conditions can be achieved by an analysis of the electron density profiles observed in the two operations (PLUMEX I and II). These profiles are presented in Figure 1 with specific features and conditions of observation listed in Table 1.

Spread-F conditions. PLUMEX I was conducted during the late phase in the development and decay of Spread-F. Specifically, the rocket was launched at 0031:30.25 (LT), a full 3 hrs after the occurrence of full range spread and only 30 minutes before its disappearance from ground-based ionograms. Major plume features were relatively stable with respect to vertical drifts, and the most intense regions of radar backscatter were beginning to decay.

The PLUMEX II conditions were substantially different, with the rocket having been launched into the mid-phase of well-developed spread-F, i.e., a ground-based ionosonde showed full-frequency and range spread while the Altair radar maps of meter size irregularity contours displayed backscatter plumes that penetrated to the topside F-layer and continued rising with time. The payload was launched 1½ hours after the onset of full range spread and an estimated two hours before decay.

F-region density profiles. By 2100 hr LT on the night of the PLUMEX I launch, ionograms showed that the nominal bottomside of the F-layer had risen to an altitude of 400 km. At that point, the F-layer began drifting downward with an almost immediate

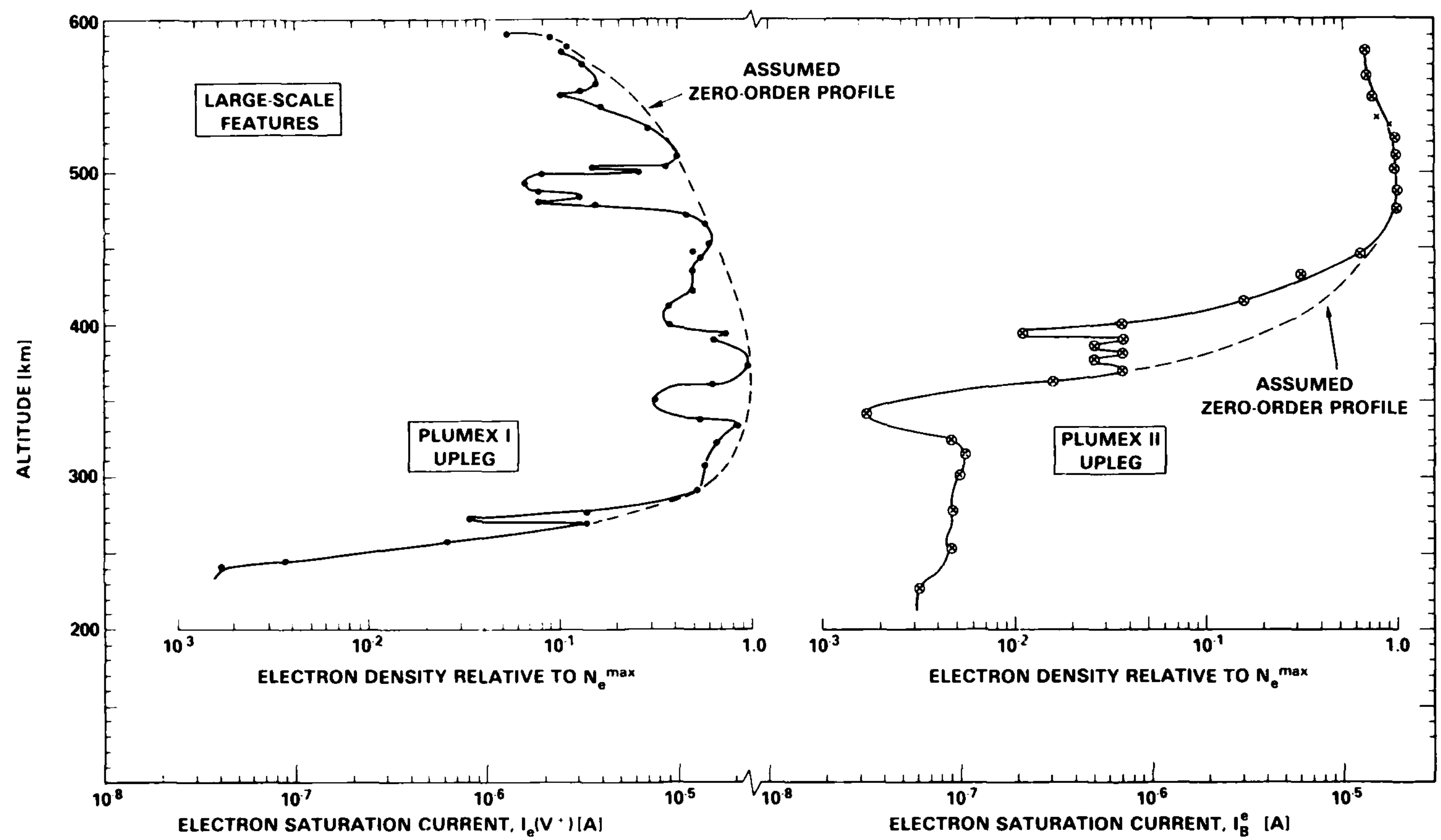

Fig. 1 - Upleg ionospheric electron density profiles measured "in situ" during the PLUMEX I and II operations

TABLE 1

A COMPARISON OF CONDITIONS AND OBSERVATIONS
IN THE DNA/PLUMEX CAMPAIGN

	PLUMEX I	PLUMEX II
Launch Time (LT)	17 July 1979; 0031:30.25	23 July 1979; 2157:30
Spread-*F* Conditions	Late time; topside radar plume in decay phase	Mid-phase of well-developed spread-*F*; plumes penetrating to topside and rising with time
$F_2 h_{max}$	375 Km	510 Km
F-bottom	240 Km	340 Km
N_e^{max}	1.3 (10^6) cm^{-3}	$\approx 6(10^5)$ cm^{-3}
L (Gradient scale length)	4.0 Km	8.6 Km
T_e	1350 (± 250)°K	TBD
Dominant F_2 Ion	0^+	0^+
Number of Depletions $(\Delta N_e/N_e^0 \geqslant .60)$	4	Only Bottomside Spread-*F*
Maximum Depletion $(\Delta N_e/N_e^0)_{max}$	0.90	≈ 0.75 (An estimate of bottomside macroscale structure)
"In Situ" Irregularity Strength	$\pm$80% fluctuations on bottomside gradient	Fluctuation levels are much less intense than PLUMEX I
Ion Signatures in Holes	$N^+/0^+$ ratio	None
Plume Penetration by Rocket	Western "wall" and plume "head"	Eastern "wall"

occurrence of spread-F. The downward drifting continued (as did the spread-F) at an approximate average velocity of 10m/sec with the bottomside F-layer having descended to an altitude near 270 km when the rocket was launched (12:31:30 UT on day 198; 00:31:30, 17 July 1979, LT).

In the PLUMEX I operation, a number of major depletions ($\Delta N_e/N_e^o \lesssim 0.90$) were distributed throughout the F-region with the F-peak (F_2h_{max}) at 375 Km and $N_e^{max} = 1.3\ (10^6)\ cm^{-3}$ ($\pm$ 10%). The very bottom of the F-layer (F-bottom) was at 240 km and the macroscopic gradient scale length $L^{-1} = (N_e^o)^{-1}\ dN_e^o/dz$ of the bottomside ledge was 4.0 Km. (The macroscopic L was calculated from a zero-order fit to the bottomside ledge between 10^{-2} and 10^{-1} N_e^{max}.) The electron energy distribution was characterized by $T_e = 1350\ (\pm 250)^oK$ with no obvious signatures of energy redistribution in and around the depletions.

On the night of the PLUMEX II launch, ionograms showed that by 2000 hr LT the virtual height (h'F) of the F-layer had risen at an average rate of 12 meters/sec to an altitude of 350 km. At that point vertical drifting ceased and shortly thereafter full-range spread-F was observed. The virtual height remained constant until 2130 hr LT, when upward drifting again commenced at an average rate of 18 meters/sec. With full-range spread-F still in effect and with the F-layer still drifting at an upward rate near 18 meters/sec the PLUMEX II rocket was launched (0957:30 UT on day 205; 2157:30, 23 July 1979, LT).

The PLUMEX II data have not yet been amenable to the same level of analysis already applied to the first operation, a result largely due to the complications of uncontrolled payload tumble and ACS jet firings that arose from a subsystem failure to separate the science payload from the second stage rocket motor. However, there are a number of conclusions that can be drawn at this time. In the upleg density profile (Fig. 1) of the PLUMEX II flight, F-region irregularities were observed only on the bottomside gradient, with the F-peak (F_2h_{max}) at 510 km and $N_e^{max} \approx 6(10^5)$ cm^{-3}. In PLUMEX II the bottomside gradient was substantially softer than in PLUMEX I with F-bottom at 340 km and L = 8.6 km.

Ion composition. Figure 2 shows the altitude versus current profiles of the mass spectrometer aperture plate output and the species O^+, N^+, $O_2{}^+$ and NO^+ measured on ascent on PLUMEX I. (Absolute total ion density can be scaled by comparison of aperture plate current with probe current and electron densities in Figure 1. Relative ion densities can be scaled from respective currents through the relation 1.4 I_i (moleculars)/I_i (atomics) = N_i (moleculars)/ N_i (atomics).) The positive spikes on the aperture current below 250 km and the negative spikes at higher altitudes are due to the nitrogen gas emitted during the firings of the attitude control jets. The rocket penetrated a number of "bite-outs" in the F-region, and in no case was there any evidence of enhanced bottomside ions (NO^+, O_2^+ or meteoric ions). The steep F-region ledge was created by O^+ ions which rose by more than three orders of magnitude over a space of less than 20 km.

The strongest ionospheric fluctuations with up to 90% depletion occurred between 265 and 285 km (the bottomside

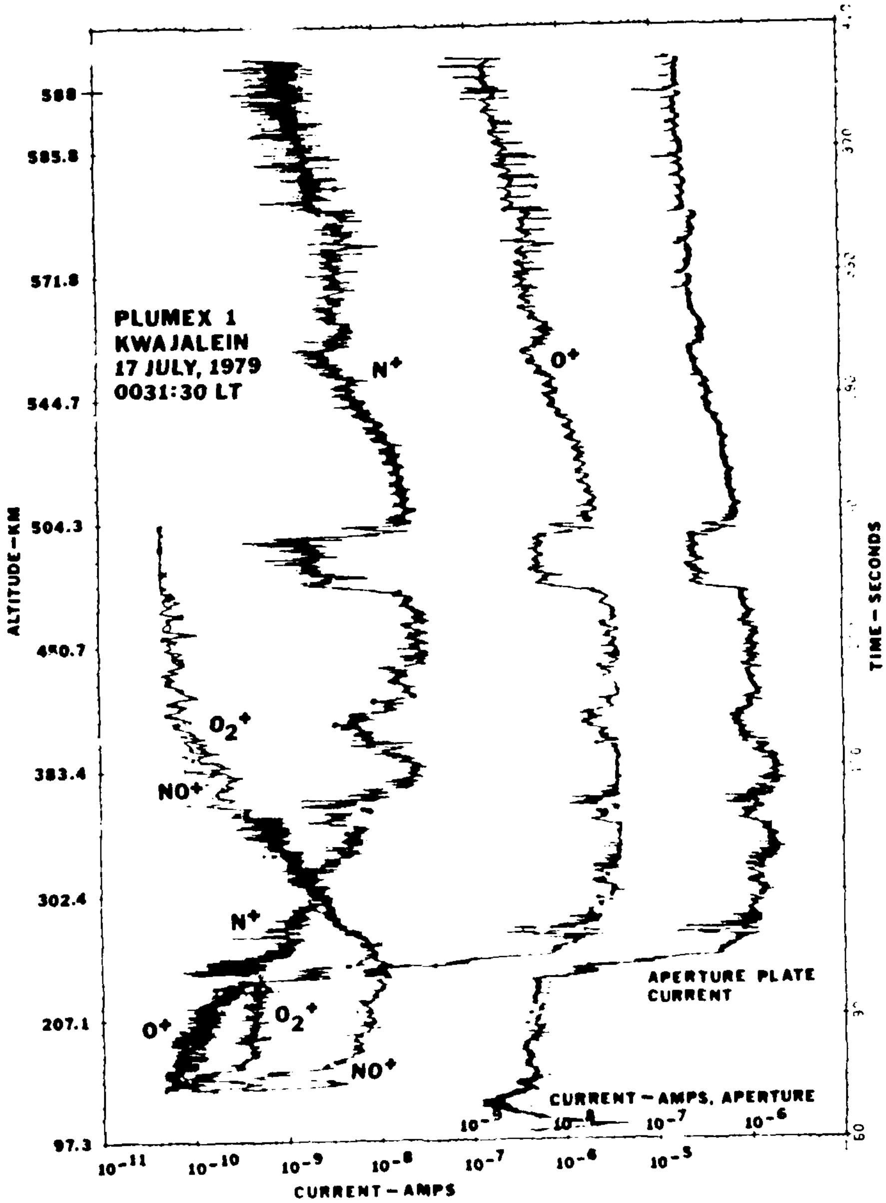

Fig. 2 - Ion mass spectrometer currents in the upleg trajectory of PLUMEX I. The data has not been smoothed to eliminate aspect sensitivities and ACS jet firings (e.g., spikes in data). Absolute densities and macroscale features can be determined by correlation with Figure 1, left panel.

depletion in Figure 1). An expanded pl... of this region is given in Figure 3. Note that the O^+ and N^+ ions generally follow the ionospheric fluctuations as depicted by the aperture plate current while NO^+ and O_2^+ do not. It can be shown that the NO^+ and O_2^+ ions have steady state distributions under the prevailing ionospheric conditions.

Table 2 depicts the NO^+ and O_2^+ chemistry. Since the recombination coefficients (α's) and reaction rates (k's) vary mainly with temperature which is relatively constant over the altitude range 250 to 400 km, the NO^+ and O_2^+ concentrations should be directly proportional to the N_2 and O_2 concentrations respectively, as long as $[O^+] \approx N_e >> [(NO^+) + (O_2^+)]$. The molecular ions can achieve their steady state values in a relatively short time. An estimate of this time may be made by referring to Figure 3. Assuming first a zero-order ionosphere and then the immediate removal of 90% of the plasma (the hole near 273 km) causing a 90% depletion in O^+, NO^+ and O_2^+, the time required for the molecular ions to return to their steady-state values from the chemistry in Table 2 is approximately 8-9 minutes. Note that this time is not necessarily the age of the hole since it could have been in steady state longer nor is this time a lower limit on the hole's age because the hole may not have formed by an abrupt depletion mechanism. However, the NO^+ and O_2^+ distributions do indicate normal, relatively smooth N_2 and O_2 profiles, and this suggests that neutral atmospheric turbulence is not a major source for bottomside ionospheric plasma irregularities.

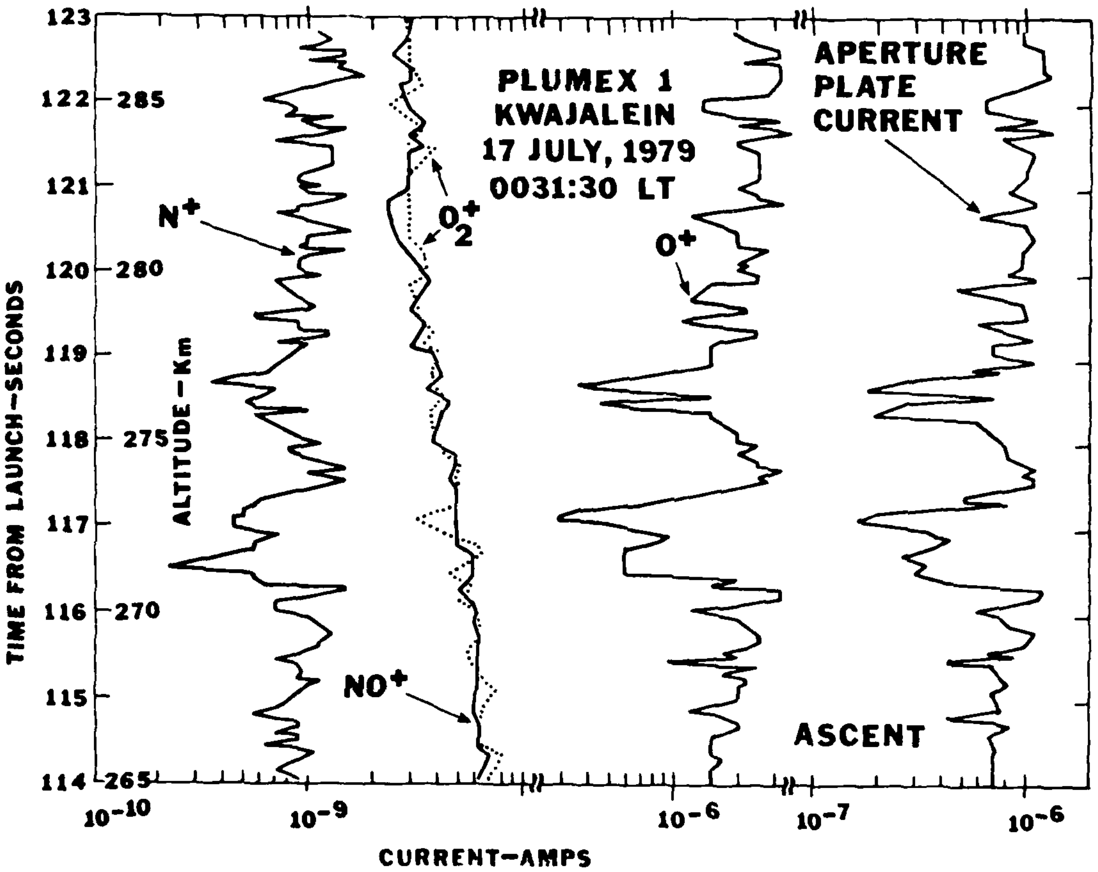

Fig. 3 - An expanded view of ion composition in the highly turbulent domain on the bottomside gradient of PLUMEX I. (This region is shown as a single "bite-out" near 270 km in Figure 1, left panel.)

TABLE II

NO^+ and O_2^+ CHEMISTRY

Production:	$O^+ + N_2 \xrightarrow{k_1} NO^+ + N$	$O^+ + O_2 \xrightarrow{k_2} O_2^+ + O$
Loss:	$NO^+ + e \xrightarrow{\alpha_1} N + O$	$O_2^+ + e \xrightarrow{\alpha_2} O + O$

STEADY STATE and $[O^+] \approx n_e$

$$[NO^+] = \frac{k_1}{\alpha_1}[N_2] \qquad\qquad [O_2^+] = \frac{k_2}{\alpha_2}[O_2]$$

The level of N^+ in this lower F-region domain (Fig. 3) is interesting itself since there are no significant chemical sources of N^+ at night and N^+ is rapidly destroyed in reactions with O_2. One might suspect appreciable downward transport since the lifetimes of N^+ at 250 and 300 km are 1 and 7 minutes, respectively. There was indeed a significant downward ionospheric drift of 10 meters/sec as indicated by simultaneous radar observations. Because both chemistry and ionospheric motions play equally important roles, the N^+ distribution can only be properly calculated with a detailed F-region chemical-transport model. However, considering the short lifetime of N^+ it is perhaps unlikely that the irregularity structure in Figure 3 is more than tens of minutes old.

The N^+ distribution at higher altitudes also presents some interesting features as shown in the N^+/O^+ ratio versus altitude in Figure 4. It is seen that the N^+/O^+ ratio is considerably smaller in the large scale depletions than in the adjacent "zero-order" areas. This fact and the O^+ and N^+ concentrations suggest that the depletions originated at or near the bottomside F-region where $[O^+] \approx [O^+]$ hole. The radar data revealed that the large scale depletion at 475-500 km was at nominal altitude for more than 30 minutes and that its upward rise velocity was essentially zero. Further, the radar measurements indicated that spread-F occurred shortly after ionospheric motion reversal from upward to downward when the F-region ledge was at much higher altitudes. Thus, while it is still correct that the ion composition indicates that the source region of this bubble was at or near the F-region ledge, this

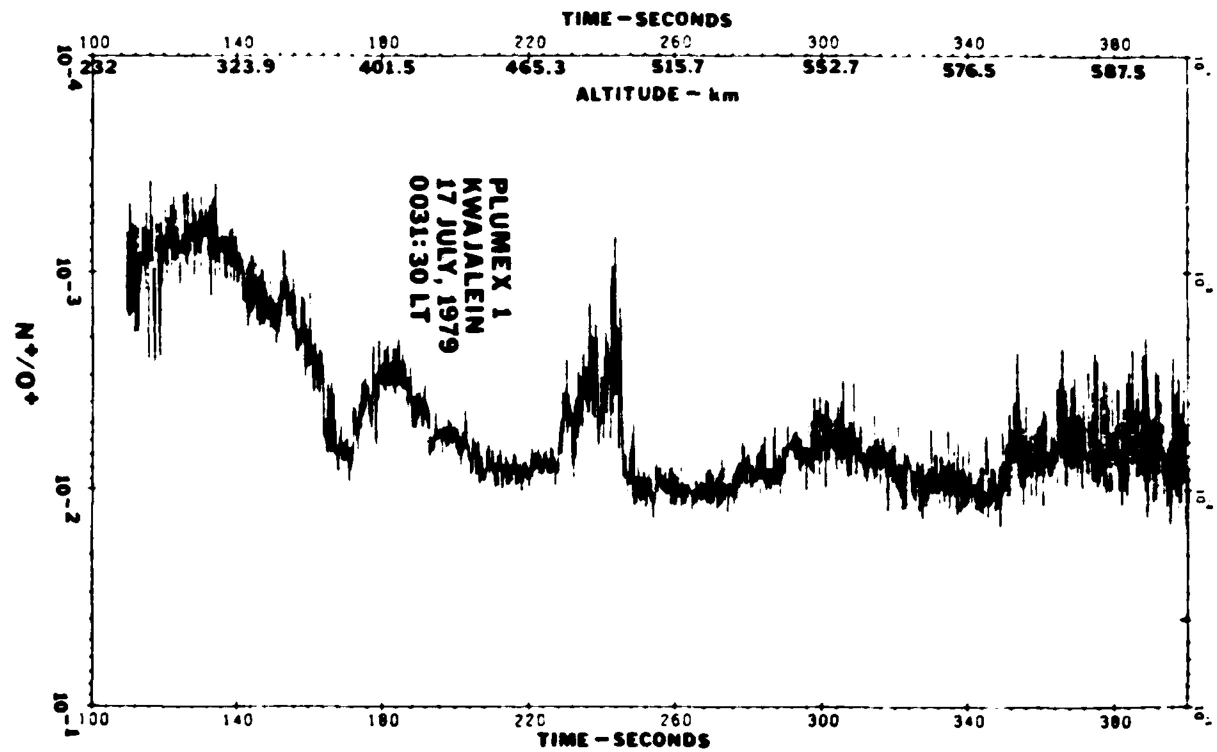

Fig. 4 - The PLUMEX I ratio of N^+/O^+ currents

ledge probably was at much higher altitudes than 250 km when these bubbles formed. The picture seems to be that the bubble was generated at the ledge and then rose while the ledge drifted downward during the night.

If the radar measurements were unavailable and it was presumed that the 475-500 km depletion originated near 262 km where similar concentrations prevailed, one can calculate an upper limit of the bubble vertical drift velocity by utilizing the source region levels of NO^+ and O_2^+. The molecular ion concentrations in the source region are not preserved at higher altitudes because of losses by dissociative recombination and a simultaneous loss in production by ion-atom interchange and charge exchange reactions since $[N_2]$ and $[O_2]$ decrease markedly with altitude. The longer it takes a bottomside depletion to move upward, the more likely the elimination of molecular ion signatures when $[O^+] \approx N_e >> ([NO^+] + [O_2^+])$. In the case of the 475-500 km depletion, a vertical transport time somewhat greater than 360 seconds would account for the molecular ion deficiency. This estimate is based on an instantaneous displacement of the bottomside ion composition to the 475-500 km range and a calculation showing that in about 6 minutes the molecular ion levels would be comparable to the ones in the depletion. This time estimate would then suggest an upper limit of about 600 m/sec for the depletion's average vertical drift velocity. However, the radar measurements showed the bubble was essentially stopped for some time, and considering the short lifetime of N^+ at the lower altitude region near 250 km, it is unlikely that the lower altitude N^+ levels could be maintained if the source region was at this low altitude and the bubble subsequently rising to about 500 km even if the upward drift velocity was 600 m/sec. Further the $[N^+]$ in the higher altitude hole is somewhat larger than in the source region where $[O^+] \approx [O^+]_{hole}$. Although the O^+ in the source region would be preserved during the upward traversal time, N^+ would not and would certainly show a decay. This all indicates that the source region for the 475-500 km hole was indeed at the ledge, but when this ledge was at much higher altitudes where N^+ concentrations could endure. The ledge was probably in the 300-350 km region; the exact altitude being dependent on bubble vertical velocity.

Meteoric species measured on PLUMEX I are shown in Figure 5. Iron and magnesium ions were present up to 180 km with peak concentrations up to about 100 ions/cc. Meteoric ions, mainly Mg^+, were detected at much higher altitudes but only in concentrations of 5-10 ions/cc.

The PLUMEX II payload was launched six days later and about 2½ hours earlier in the evening. Figure 6 shows the altitude versus current ascent measurements of the aperture plate output and the species O^+, N^+, NO^+ and O_2^+. In this flight the payload did not separate from the rocket motor which rendered the attitude control system ineffective. The vehicle's attitude

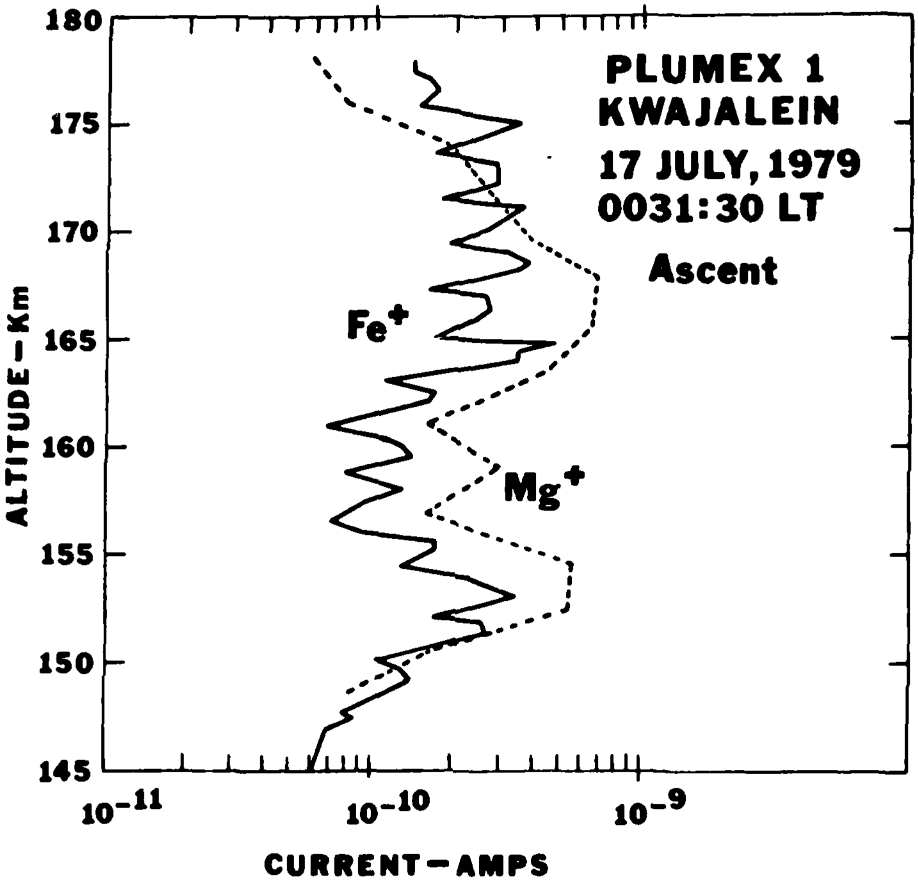

Fig. 5 - Observation of metallic ions on ascent of PLUMEX I

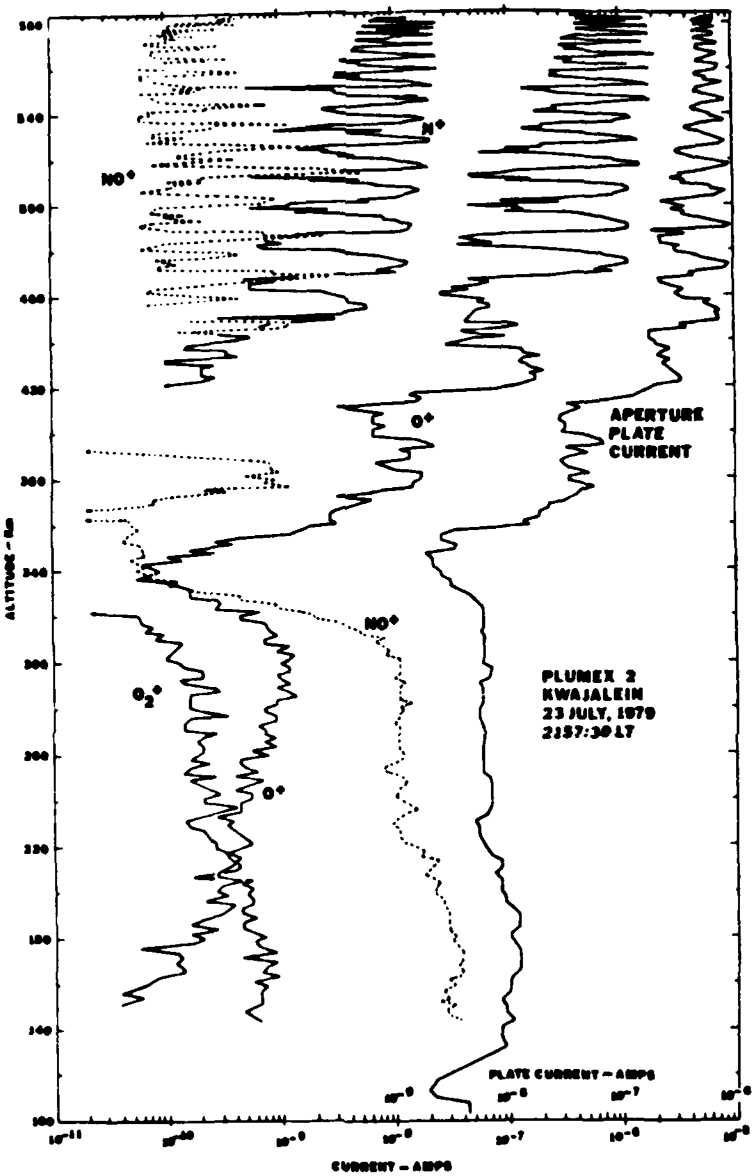

Fig. 6 - Ion mass spectrometer currents in the upleg trajectory of PLUMEX II. The data has not been smoothed to eliminate aspect sensitivities and ACS jet firings (e.g., spikes in data). Absolute densities and macroscale features can be determined by correlation with Figure 1, right panel.

was stable up to 300 km above which the angle of the attack increased and varied throughout the flight, causing the modulations in the data. The smaller scale irregularities between 350 and 420 km cannot be entirely explained by vehicle aspect modulations and are probably real representations of bottomside spread-F. This position is supported by the on-board plasma probes.

The meteoric species measured on PLUMEX II are shown in Figure 7. Significant concentrations of iron and magnesium ions are seen in layers up to 260 km, about 80 kilometers higher than PLUMEX I. These species were perhaps present at higher altitudes due to earlier upward ionospheric drift and before the downward motion brought them to lower altitudes.

III COMMENTS AND CONCLUSIONS

In both PLUMEX operations O^+ was the dominant F-region ion down to the very bottom of the F-ledge (F-bottom). At altitudes below F-bottom, molecular ions dominated with a scale height approaching infinity. The connection of this observation to topside bubbles and instability mechanisms is as follows:

The Rayleigh-Taylor and $\bar{E} \times \bar{B}$ gradient drift instabilities, which have been proposed for bubble formation, require a steep bottomside gradient. However, the PLUMEX results show that the molecular ions are dominant only at altitudes below the bottomside F-region gradient, where scale heights are very large and inhibit the instability process. If the bubble does indeed form on the F-region ledge, and if it

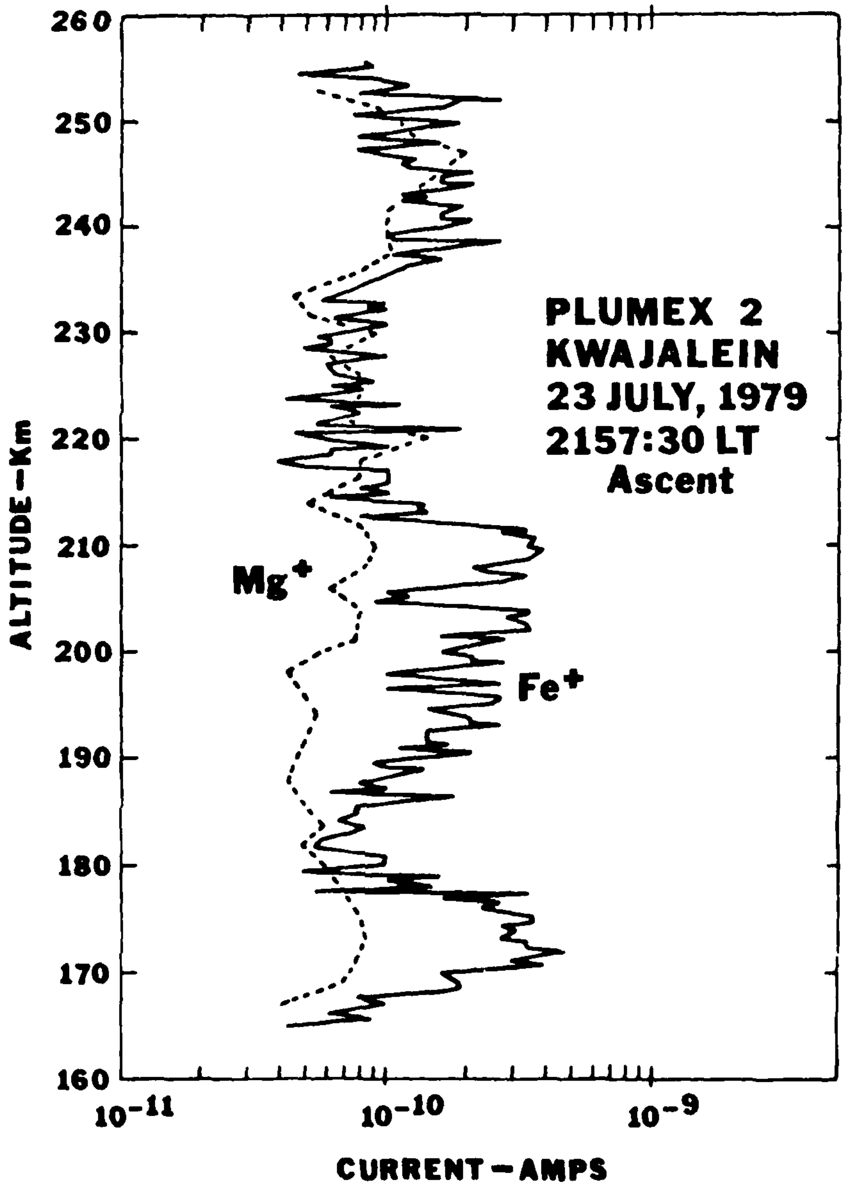

Fig. 7 - Metallic ions measured on ascent of PLUMEX II

transports only local ions to higher altitudes, then molecular ions will never dominate topside depletions. This apparent dichotomy has a number of explanations:

(a) Relatively small depletions (i.e., $\Delta N_e/N_e^o \lesssim 0.9$) originating on the F-ledge with initially small horizontal extent can transport the local ion composition to higher altitudes by the Rayleigh-Taylor process; but molecular ions will not be the dominant positive species. Instead, the $[N^+]/[O^+]$ ratio will indicate the original source domain as suggested by McClure et al.[5] and demonstrated in the PLUMEX I results.

(b) For molecular ions to be dominant in a topside F-region depletion it appears that one of two mechanisms must apply:

(i) An initially small depletion (i.e., $\Delta N_e/N_e^o \lesssim 0.9$) of large horizontal scale size can result in much higher depletion levels (e.g., References 4-6) by fringing fields that drawup the lower densities and molecular ions that populate altitude regimes lower than the site of the initial perturbation. This mechanism has been studied by Zalesak and Ossakow[7] and appears in substantial agreement with observations.

(ii) An alternate mechanism for molecular ion dominance in topside depletions has been proposed by Chiu and Straus[8]. They suggest that plasma bubbles in the nighttime equatorial ionosphere originate as wind driven waves at one of the highly variable density gradients below 200 km, rather than at the bottomside F-region ledge. Once the bubble is formed, with the low densities and molecular ion dominance characterized by the lower altitude, it can propagate into the bottomside F-region and provide the initial perturbation required for the onset of the Rayleigh-Taylor mode[9-11].

Current analyses of PLUMEX ion composition results support conclusion "a" as the operating principle on the nights of "in situ" investigations. This does not negate "b" and associated alternatives as candidates for other conditions, but it does leave open the question for further experimental tests.

Further analyses of "in situ" measurements conducted in the Kwajalein campaign lead to the following comments and conclusions:

The measurements clearly demonstrated that not all holes contain enhanced bottomside molecular and metal ion species, indeed none of the holes had such signatures.

The ion-chemical results demonstrated that the N^+/O^+ ratio can be an important signature in determining a depletion's source region; indeed the N^+/O^+ ratio was used in PLUMEX I to determine the altitude of the bottomside F-region ledge (the source domain) at the time of depletion formation.

Evidence was presented from the molecular ion distributions on the bottomside F-layer gradient that pointed toward a stable neutral atmosphere in the presence of strong ionospheric fluctuations. This result suggests that neutral atmospheric turbulence is not a major source of bottomside plasma irregularities.

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