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REPLY

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Frank et al. (1986a) interpret their findings of transient decreases in the earth's ultraviolet dayglow intensities over areas ~ 2,000 km^2 in terms of an influx of small comets into the upper atmosphere. Hanson (1986) finds that this comet influx is inconsistent with his measurements of ionospheric plasmas with several spacecraft. His conclusion is based upon the assumption that the interaction of the water cloud with the ionosphere can be described in terms of single-particle mechanisms, e.g., charge-exchange and ion diffusion. On the basis of this assumption Hanson develops a model for the perturbation of ion densities in the ionosphere along the path of the cometary water cloud. Because this anticipated signature is not found in the in situ ionospheric plasma observations it follows that there is no influx of small comets into the earth's upper atmosphere or that another interaction mechanism prevails (Hanson, 1986). Our approach to identification of the mechanisms participating in the interaction of the cometary water cloud with the ionosphere is more direct. We first examine the images of the earth's ultraviolet dayglow as viewed from high altitudes with Dynamics Explorer 1 for a crossing of a transient decrease, or atmospheric hole, with its low-altitude sister spacecraft, Dynamics Explorer 2. Our next step is to verify that the ionospheric signature identified with this crossing is observed at other times in the quiet ionosphere. This signature is then interpreted in terms of laboratory plasma experiments, plasma theory, and previous plasma observations in the wake of a large object in transit through the ionosphere. Thus we find a possible signature of the passage of the cometary water cloud through the ionosphere and are able to indicate a likely mode for this interaction.

In order to identify the interception of an atmospheric hole by the Dynamics Explorer-2 spacecraft as it moves through the ionosphere at low altitudes, its trajectory as a function of time is overlaid on the images taken from high altitudes with Dynamics Explorer 1. The orbital inclinations of these two spacecraft are 90°. A possible interception satisfies one of two criteria: (1) the low-altitude spacecraft is within ± 0.75° in longitude and ± 10° in latitude of the position of an atmospheric hole, and at the time of the atmospheric hole sighting, in an image from Dynamics Explorer 1 or (2), with the assumption of atmospheric corotation of the impact position of the water cloud with the ionosphere, the low-altitude spacecraft intercepts this impact position within 45 minutes of its orbital motion. Condition (1) above requires that the low-altitude spacecraft intercepts an atmospheric hole within ~ 2 minutes of its sighting with Dynamics Explorer 1 and condition (2) allows the identification of ionospheric effects associated with this phenomenon for elapsed times < 45 minutes after sighting of the atmospheric hole.

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The probability of near-simultaneous sighting of an atmospheric hole with Dynamics Explorer 1 and encounter with the position of the atmospheric hole in the ionosphere with Dynamics Explorer 2 is expected to be extremely small. Of approximately 26,900 individual sightings of atmospheric holes, only 334 survive either of the two criteria as defined above. Because simultaneous observations with Dynamics Explorer 2 are required to search for the ionospheric signature, only 124 of the above cases are usable, the remainder are excluded for various reasons, e.g., no telemetry available. Further, the atmospheric holes are projected against the screen of ultraviolet dayglow emissions for the estimated 1,000 to 3,000 km length of their observable trajectories (cf. Frank et al., 1986b). Thus most of the corresponding water clouds are viewed above the low-altitude spacecraft position and impact the ionosphere elsewhere. In other words, only a small fraction are impacting the ionosphere near or at the position of the spacecraft. This fraction is of the order of the ratio of the required miss distance, ~ 100 km, to the entire observable track, ~ 2,000 km, or ~ 1/20. Thus approximately 6 out of the 124 surviving candidates are expected to yield an ionospheric signature. In addition the events must occur in the quiet ionosphere for positive identification, i.e., to exclude sightings in or near the auroral zones and in the early morning sector with its fossils of F-region bubbles. These criteria further reduce the anticipated number of simultaneous events to about 2 or 3 out of the original 26,900 sightings of atmospheric holes. Fortunately one example of simultaneous atmospheric hole sighting and ionospheric disturbance is found.

The ionospheric perturbations due to the passage of the cometary water cloud are identified by examining the ion density fluctuations at the anticipated impact positions determined from images of the dayglow. These ion density fluctuations are detected with a retarding potential analyzer (Hanson et al., 1981). W. B. Hanson gives us permission to examine these measurements as presented in the unverified data summary files for Dynamics Explorer 2, but informs us that he has not examined these data to establish their validity. The ion density fluctuations occurring at the position of an atmospheric hole are shown in the upper left-hand corner of Figure 1. The density fluctuations, $\Delta N/N$ in units of percent, are shown as a function of time for the frequency range 32 to 86 Hz. Intercept of these fluctuations is centered at 0235:40 UT on 8 February 1983. The width of the region is ~ 123 km, and the peak density fluctuation is ~ 0.1%. The open circles represent the threshold for the determination of density fluctuations. The obser-

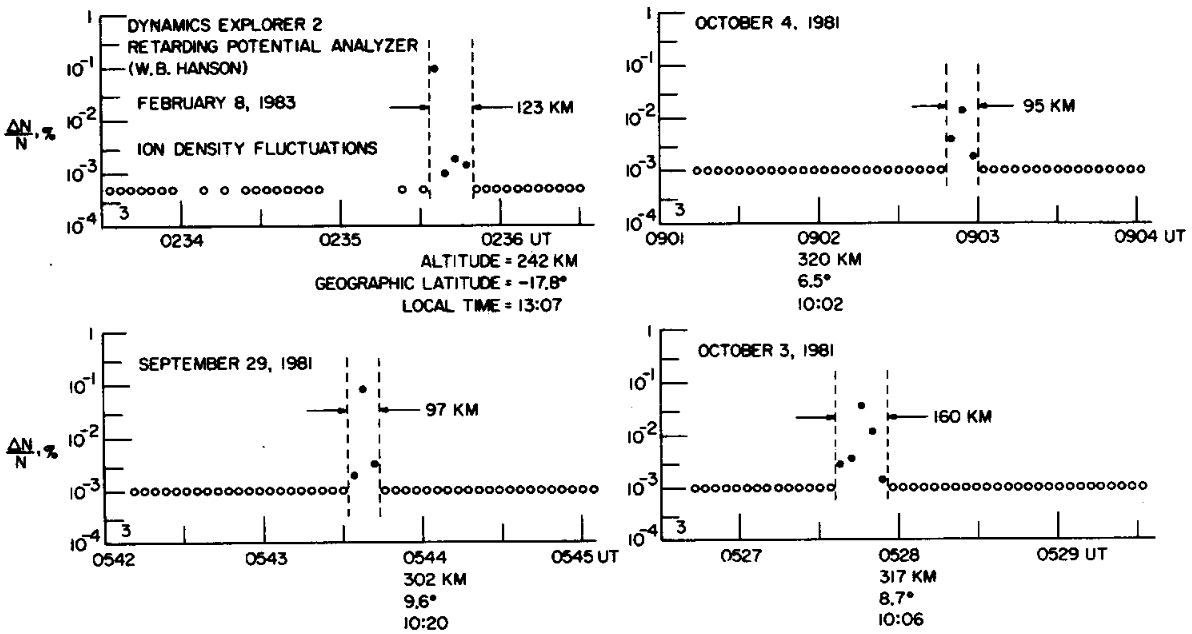

Fig. 1. Several examples of spatially well-defined plasma turbulence as observed in the sunlit ionosphere at low latitudes.

vation of the atmospheric hole with high altitude imaging occurs at 0235:00 UT and at a position ~ 75 km from that of the density fluctuations. The ion density fluctuations are observed in an otherwise quiet ionosphere during early afternoon (13:07) at low latitude (-17.8°) and at an altitude of 242 km.

The identification of a signature of the passage of the cometary water vapor cloud through the ionosphere with the above simultaneous observations allows a search through further thermal ion observations for the presence of similar signatures in the quiet ionosphere. Accordingly we examine a limited part of the available data, ~ 755 minutes at magnetic invariant latitudes within 40° of the equator, and find three such events. These three events are shown in Figure 1. Note that the widths of all four events are roughly similar and that the region of turbulence is well defined. The amplitudes of the events vary, presumably a feature dependent on the time of arrival and approach geometry of the spacecraft relative to the trajectory of the water vapor cloud. On the basis of our findings that no examples of correlated atmospheric holes and ionospheric turbulent regions are found for the longer search interval extending to ~ 45 minutes, i.e., condition (2) above, we conclude that the duration of the turbulence is of the order of minutes. Because four such events are observed in 755 minutes and the lifetime is ~ minutes, the frequency of occurrence can be estimated. The flux of small comets, F, then becomes $F \simeq R/VD\tau$, where R is the observed rate of turbulent regions in units of events/sec, V is the orbital speed of Dynamics Explorer 2 in cm/sec, D is the characteristic diameter of these regions in cm, and τ is the effective lifetime of these turbulent regions in seconds. The flux F, comets/cm^2-sec, is then ~ $8(\pm 4) \times 10^{-20}$/cm^2-sec where $R \simeq 10^{-4}$ events/sec, $V \simeq 8 \times 10^5$ cm/sec, $D \simeq 1.2 \times 10^7$ cm and τ ~ 120 seconds (rough estimate). This flux compares favorably with that given independently by the imaging of the earth's dayglow, a global average of ~ 6×10^{-20} comets/cm^2-sec (Frank et al., 1986a,c).

The diameter and the frequency of occurrence of the spatially well-defined turbulent regions in the quiet ionosphere are shown above to be similar to those anticipated for the influx of small comets. The signature of the comet interaction with the ionosphere, i.e., the plasma turbulence, allows further interpretation of this phenomenon. Hanson (1986) shows that this interaction probably cannot be described in terms of simple kinetic theory. Our findings support his conclusion. In fact the plasma turbulence is similar to that measured directly for the ionospheric plasma flow around a large body, e.g., the space shuttle. The dimensions of the shuttle exceed those of the thermal electron gyroradius and the Debye length but are comparable to the gyroradius for an ionosphere O^+ ion at 1,000 °K, ~ 6×10^2 cm. The plasma flow is sub-Alfvénic, i.e., $V_A \simeq 1.7 \times 10^7$ cm/sec for an O^+ density of 10^6/cm^3. The near-wake of the orbiter in the ionosphere is characterized by plasma turbulence with $\Delta N/N \simeq 1$ to 3% in the frequency range 6 to 40 Hz (Murphy et al., 1986). Such turbulence is similar to, but of greater magnitude than, that in the more distant wakes of the comets in the ionosphere as reported here. We interpret then the comet interaction with the ionosphere in terms of ionospheric plasma flow around a large object, i.e., the plasmas within the cometary water cloud.

The results of extensive laboratory plasma experiments that find the transport of plasma beams across strong magnetic fields are available in the literature (Schmidt, 1960; Baker and Hammel, 1965; Barney and Sprott, 1969). This plasma transport is induced by polarization electric fields as the plasma beam passes across the magnetic field. The magnitude of the polarization electric field in the beam is such that the $\vec{E} \times \vec{B}$ drift velocity is equal to and in the same direction as the beam velocity. The plasma is collisionless and diamagnetic effects are small.

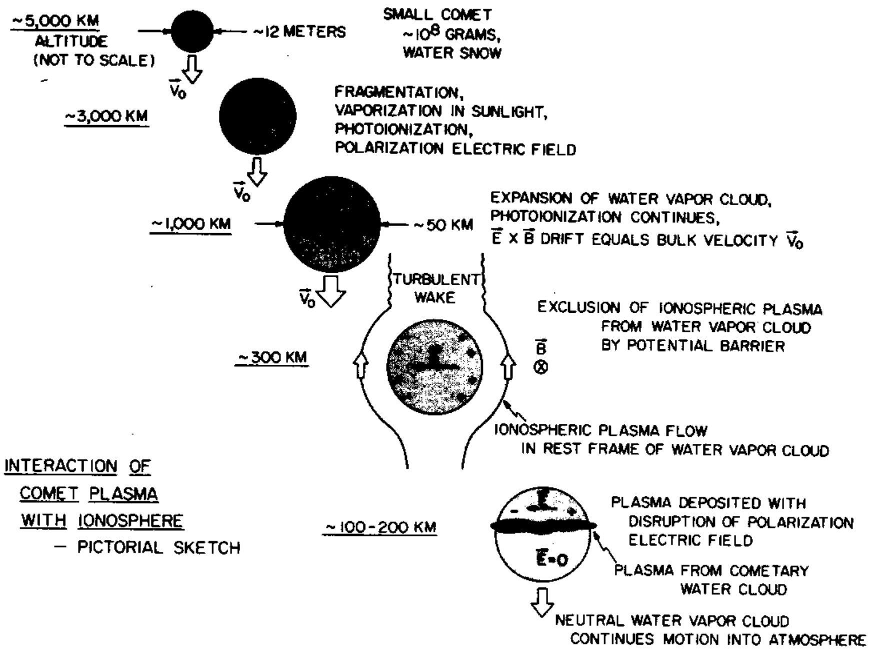

Fig. 2. Transport of the low-β plasma in a cometary water cloud through the ionosphere.

The internal magnetic field within the beam is that of the external magnetic field, i.e., the beam is a low-β plasma. General conditions for achieving this plasma transport are that $r_g/L \ll 1$, where r_g are the gyroradii and L is of the order of the scale size of the injected plasma region, and that the electric drift velocity $V_E \ll L/\tau_g$ where τ_g is the ion gyroperiod (cf. Poukey, 1967). In addition the collision frequency with neutrals or ions must be less than the gyrofrequency. If the polarization charge is dissipated by current closure in the walls of the plasma chamber or by high collision frequencies, the plasma motion across the magnetic field is stopped and the plasma becomes trapped in the magnetic field. Normally there is little application of this physical situation in space plasma physics because a spatially well-defined body of plasma is required. However in the case of the small comet, such a plasma entity is created.

The principal factors to consider for the motion of the comet through the ionosphere are summarized in Figure 2. The water snow in the small comet is fragmented at altitudes roughly estimated to be ~ 3,000 km and rapidly vaporized by solar insolation (cf. Frank et al., 1986a,d). Photoionization of H_2O by solar ultraviolet radiation produces a plasma within the expanding water cloud. When the cloud is initially small in diameter ion collisions with the neutral water molecules will dominate over the $\vec{E} \times \vec{B}$ drift due to polarization charge. For example at a diameter of 1 km for a fully vaporized small comet with mass 10^8 gm the H_2O^+ ion gyroradius is ~ 270 cm for a temperature of 200°K but the mean free path for collisions with neutral H_2O is only ~ 0.03 cm. Thus collisions carry the plasma with the neutral water cloud. As the cloud expands to a diameter of ~ 50 km the mean free path increases to ~ 3.9 × 10^3 cm and polarization electric fields are created such that the electric drift velocity $c\vec{E} \times \vec{B}/B^2$ is parallel and equal to the bulk velocity of the cometary water cloud, $\vec{V}_0$. The magnetic field is directed perpendicular to and into the plane of Figure 2. For $V_0 = 20$ km/sec and $B = 0.3$ gauss the electric field strength within the water cloud is ~ 6 mv/cm, or a potential drop of ~ 3 × 10^4 volts across the horizontal diameter. The water cloud and its plasma traverses the ionosphere at sub-Alfvénic speed with ionospheric plasma flow around this object and a subsequent trail of plasma turbulence. The diameter of the wake can be expected to be somewhat larger than that of the water cloud. This plasma turbulence is observed with Dynamics Explorer 2. Because the ionospheric plasmas flow around the cometary water cloud, neither charge exchange of H_2O with ionospheric O^+ ions or enhanced plasma densities due to Alfvén critical ionization velocity effects for these species are expected. At some altitude the polarization electric field is disrupted. A likely mechanism for the dissipation of the polarization charge is found by noting that the atmospheric neutral density is rapidly increasing with the rapid descent of the water cloud. Eventually the water cloud will reach sufficiently low altitudes that the water cloud is compressed due to increasing atmospheric pressure. The mean free path for ion collisions with neutral water molecules then rapidly decreases and the polarization charge is shunted by a Pedersen current. Other mechanisms such as external discharge of the polarization charge by the Alfven waves propagating away from the water cloud can be also usefully examined. The plasma is deposited perhaps in a layer and the neutral water cloud continues its motion toward the mesosphere. Crude estimates for the altitude range of plasma deposition are given on the basis that the gas dynamic flow of atmospheric neutral molecules around the water cloud becomes subsonic at altitudes ~ 100 km (cf. Frank et al., 1986e). At such altitudes the water cloud may be expected to be compressed significantly by the external atmospheric pressure.

It is of value to briefly examine the expected ion production within the water cloud in order to ascertain that the plasma densities are sufficient to maintain the polarization charge. If we take the photoionization lifetime for H_2O at 1 A.U., 2.3×10^6 seconds, as given by Wyckoff and Wehinger (1976) the ionization rate R for the 50-km diameter cloud of water is $\sim 2 \times 10^4$ H_2O^+ ions/cm^3-sec. Because the water cloud is optically thick the rate R is overestimated in its interior. The rate coefficient α for the recombination $H_2O^+ + e^- \rightarrow H_2O$ is 3.0×10^{-7} cm^3/sec (Mendillo and Forbes, 1978). Thus the equilibrium plasma density N is approximately given by $R \simeq \alpha N^2$, or $N \simeq 3 \times 10^5$ ions/cm^3. If we obtain an estimate of the surface charge density σ that provides an electric field of 6 mv/cm within the cometary water cloud by assuming that it is crudely represented by a conducting sphere, this estimate becomes $\sigma = (3/4\pi)E \cos\Theta$ (Gaussian units) $\simeq 10^4 \cos\Theta$ electrons/cm^2. Ion production in the water cloud is thus sufficient to maintain the polarization charge.

The deposition of the plasmas within the cometary water cloud with disruption of the polarization electric field may contribute to the plasmas associated with sporadic E. A review of the observations and theoretical interpretations of sporadic E is given by Whitehead (1970). Contributors to the ionization in the E-region include auroral precipitation and plasma instabilities. Wind shears in the neutral atmosphere can drift these plasmas into thin horizontal sheets by means of the Lorentz force. The variety of the ionization sources and the complexity of the observational facts concerning sporadic E do not allow us to find a specific type of ionogram event that is clearly identifiable with the deposition of plasma from a cometary water cloud. This identification is rendered more difficult by the low occurrence rate for the small comets, e.g., about once every 40 hours for a 100×100 km^2 area in the sunlit atmosphere. A discussion of the association of sporadic E with meteors at temperate latitudes is given by Ellyett and Goldsbrough (1976). However, the findings from a literature survey of diurnal variations, spatial scales, plasma densities, and metallic ion content, for examples, do not preclude the possibility of the deposition of cometary plasma in the E-region as noted above.

A low-altitude spacecraft such as Dynamics Explorer 2 is expected to be directly impacted by a cometary water cloud over the sunlit hemisphere of the earth approximately once every 7.5×10^5 seconds, or ~ 200 hours. This direct impact is not catastrophic. With the assumption of elastic collisions of the water molecules with the spacecraft and a similar assumption for the ambient atmospheric oxygen atoms at 300 km, the specific linear momentum change of the spacecraft from the collision with the water cloud, ~ 30 gm/cm-sec, is similar to that for atmospheric drag along a 10,000-km track of the orbit, i.e., ~ 25% of a single orbit. The densities of water molecules in the cloud are similar to those in the ambient atmosphere at altitudes ~ 150 km. Further, the energy influx to the surface of the spacecraft during collision is $\sim 7 \times 10^6$ ergs/cm^2-sec, or a factor of ~ 5 greater than the solar energy flux, for a period of $\lesssim 3$ seconds. Thus a collision of the cometary water cloud with the spacecraft is mechanically benign. Of greater interest is the sophisticated complement of aeronomy, plasma and fields instrumentation on board Dynamics Explorer 2. The direct collision of a cometary water cloud with this spacecraft is expected to occur in a latitude zone ± 40° of the sunlit equator about once every 600 orbits. Identification of this brief encounter, $\lesssim 3$ seconds, requires a laborious search, but the anticipated results would seem to merit the effort.

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