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**Effects of Rocket Exhaust Products
in the Thermosphere and Ionosphere**

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EFFECTS OF ROCKET EXHAUST PRODUCTS IN THE THERMOSPHERE AND IONOSPHERE

by

John Zinn and C. Dexter Sutherland

ABSTRACT

This paper reviews the current state of our understanding of the problem of ionospheric F-layer depletions produced by chemical effects of the exhaust gases from large rockets, with particular emphasis on the "Heavy Lift Launch Vehicles" (HLLV) proposed for use in the construction of solar power satellites. The currently planned HLLV flight profile calls for main second-stage propulsion confined to altitudes below 124 km, and a brief orbit circularization maneuver at apogee. The second stage engines deposit 9×10^{31} H_2O and H_2 molecules between 74 and 124 km. Model computations show that they diffuse gradually into the ionospheric F region, where they lead to weak but widespread and persistent depletions of ionization and continuous production of H atoms. The orbit circularization burn deposits 9×10^{29} exhaust molecules at about 480-km altitude. These react rapidly with the F2 region O^+ ions, leading to a substantial (factor-of-three) reduction in plasma density, which extends over a 1000- by 2000-km region and persists for four to five hours.

For purposes of computer model verification, we include a computation representing the Skylab I launch, for which observational data exist. The computations and data are compared, and the computer model is described.

I. INTRODUCTION

Present understanding of ionospheric F-layer depletions caused by exhaust products from large rockets began with the observations by M. Mendillo et al.¹ of an abrupt decrease in vertical electron column density along the trajectory of the launch of Skylab I, May 14, 1973. The effect was attributed¹⁻⁴ to the chemical reaction of rocket exhaust molecules, primarily H_2O and H_2 , with O^+ , the dominant F2-layer ion. These reactions produce molecular ions H_2O^+ and OH^+ , which recombine rapidly with electrons, causing a reduction in electron-ion concentrations.

Practical interest in these ionospheric depletions ("holes") has increased with the advent of proposals to build large space structures in earth orbit, such as the solar power satellite (SPS). Current SPS system studies call for space transportation activities on a far larger scale than any carried out heretofore. The proposed

primary cargo vehicle, called the "heavy lift launch vehicle" (HLLV), is approximately six times larger than the NASA space shuttle vehicle (see, for example, the NASA SPS Concept Evaluation document⁵), and HLLV launches would occur with a frequency of several per day. The present paper is concerned with prediction of the ionospheric and environmental effects of HLLV launches.

According to current design studies,⁵ the HLLV will be a two-stage vehicle with the capability of second-stage flyback. It is to be used for transportation between the surface and a low-earth orbit (LEO) at 450- to 500-km altitude. The second-stage engines are to be fueled with 300 metric tons of liquid hydrogen and 2000 tons of liquid oxygen. Hence, the exhaust gases will consist primarily of H_2O and H_2 in the molar ratio 3:1, about 9×10^{31} molecules in all.

Present launch plans, designed in part to minimize F-layer depletion effects, call for ignition of the second-stage engines at 75-km altitude

and engine shutdown with orbital insertion at 108 km, after descent from an intermediate apogee at 123 km. This launch trajectory⁵ leads to an eccentric initial orbit with an apogee at about 480 km. Upon arrival at apogee, the vehicle executes a circularization maneuver, involving the burning of 21 metric tons of propellant and emission of 9×10^{29} exhaust molecules. Upon completion of its mission in LEO, the HLLV returns to earth. The deorbit maneuver requires 11 tons of propellant and emission of 5×10^{29} exhaust molecules.

It is interesting, if not altogether relevant, to note that the number of exhaust molecules from a single HLLV, about 10^{32} , is similar to the total number of electron-ion pairs in the global ionosphere, again about 10^{32} . Since each H_2 molecule is capable, under proper circumstances, of destroying two ion pairs, the effect of one HLLV is potentially large. Fortunately, those circumstances are seldom met.

This paper examines the conditions that determine the "chemical efficiencies" of exhaust molecules for destroying F-layer ions. It describes two-dimensional computer model studies of an HLLV launch and a circularization maneuver, and a model simulation of the Skylab I launch (see also Zinn et al.⁶).

II. BACKGROUND

Observations of the creation of a large ionospheric hole by the launch of Skylab I (Saturn V rocket launch, 1230 EST, May 14, 1973) were reported by M. Mendillo et al.^{1,2} The ionospheric electron column density was observed to be reduced by 50% or more over a period commencing within ten minutes after the launch and persisting for about four hours. The depletion extended over a region of approximately 1000-km radius. The observations were made in the course of routine Faraday-rotation measurements of the VHF signals from geostationary satellites ATS-3 and ATS-5.

The ionospheric depletion is attributed to injection of rocket exhaust products, primarily H_2O and H_2 , which lead to enhancement of the effective electron-ion recombination rate through the substitution of polyatomic ions H_2O^+ , H_3O^+ , and OH^+ , etc., in place of the normally occurring

O^+ . The effect is confined to the F-layer above 200-km altitude where O^+ is the dominant positive ion. The main reactions are

and

Reaction (2) is about 10^5 times faster than the direct recombination of electrons with O^+ , i.e.,

Reaction (1) is much faster than either of the normally occurring F-layer charge-transfer reactions

or

The OH radical formed in Reaction (2) can react further with O^+ . The dominant reaction path is

which is followed by rapid neutralization of the O_2^+ :

In most cases, however, the OH radical is destroyed by reaction with atomic oxygen, i.e.,

before Reactions (6) and (7) can occur to a significant extent.

The result of the two cycles, Reactions (1) and (2) and Reactions (8), (4), and (7) in sequence, is the destruction of two electron-ion pairs by each H_2O molecule.

Similar processes occur with other common rocket-exhaust products, such as H_2 or CO_2 . With

H₂, the sequence is

followed by

[The O(¹D) is a metastable, electronically excited oxygen atom that decays primarily by emission of 630.0-nm radiation.]

The severity, geographic extent, and duration of the F-layer depletions produced by the exhaust product molecules are determined by a combination of interacting processes including chemistry, diffusion, gravitational settling, and advection by prevailing winds. The molecular diffusion and settling rates are both rapidly increasing functions of altitude. For a quantitative description of these coupled processes, we built a two-dimensional computer model. Some numerical results from the model are detailed in the following sections. Details of the model itself are amplified in Appendices A and B.

The strong ion-removal effects induced by exhaust product molecules are confined to the ionospheric F₂ layer above 200 km, where the normally occurring ion species is predominantly monatomic O⁺. Below 180 km, the dominant ion species are polyatomic (principally NO⁺ and O₂⁺), and the effective rates of recombination of these ions with electrons are not affected much by the addition of contaminant molecules such as H₂O or H₂. (In the E and F₁ layers, the addition of H₂O should not lead to a drastic enhancement in the effective recombination rate. It might produce a noticeable effect, nevertheless, by forming complex ions such as NO⁺ • nH₂O, H₃O⁺ and H₃O⁺ • nH₂O. The recombination coefficients for these complexes are believed to be from 3 to 10 times larger than those of the normally occurring simple ions, NO⁺ and O₂⁺).

The fastest process affecting the removal of exhaust product molecules from the F-layer is gravitational settling (regulated, of course, by molecular collisions). The time required for an isolated water molecule to fall across the F-layer from 400- to 200-km altitude is about two hours.

For an H₂ molecule, the time is about six hours. (The settling rates are computed in detail in the numerical model. The center of mass velocity of a gas cloud depends in detail on its vertical density profile. However, when the cloud is far from its final hydrostatic equilibrium distribution, a useful approximate value of the settling velocity is given by $\bar{w} \sim -(1/2)g/v$, where g is the acceleration due to gravity and v is the molecular collision frequency. For an H₂O cloud falling in an atomic oxygen atmosphere, the formula gives $\bar{w} \sim 5 \times 10^{12}/n$ m/s if n is the local number density in cm⁻³).

During their fall, the molecules diffuse laterally, and they react with O⁺ ions. An isolated H₂O or H₂ molecule falling across the daytime F-layer has a better-than-90% chance of reacting with an O⁺ ion, if the O⁺ concentration has not already been depleted by reactions with other H₂O or H₂ molecules. In most cases associated with large rocket exhausts, the descending H₂O and H₂ cloud is dense enough to react with all the O⁺ ions in its path. The concentration of molecules is overwhelmingly larger than the concentration of O⁺ ions, so effectively all the ions are removed. The excess H₂O and H₂ molecules fall through intact.

The diameter of the cloud increases with vertical distance fallen, and the cloud continues to spread after the settling has largely ceased. The H₂ cloud spreads about four times as fast as the water cloud.

If, after destroying the existing ionization, the excess H₂O and H₂ settled completely out of the F-layer, the ionization would soon return due to the action of solar extreme ultraviolet radiation. In the daytime, the ion replenishment would take about two hours. However, the H₂O and H₂ would not settle out completely. Instead, they would maintain a quasi-steady concentration profile, falling off exponentially with altitude (z) approximately as $\exp[-(z - z_0)/H]$. Here z_0 is the altitude of maximum concentration and H is a scale height equal to about 50 km for H₂O and 400 km for H₂. The base altitude z_0 descends with time, but at an ever-decreasing rate. After 8 hours it would be about 150 km, and after 24 hours it would be 120 km.

The H_2O and H_2 are gradually destroyed chemically, mainly by reactions with O^+ ions. The rate of destruction is essentially equal to the rate of production of ions by sunlight--a number of the order $10^3 \text{ cm}^{-3}\text{s}^{-1}$ at 150- to 200-km altitude. With this small destruction rate, the molecules can survive for several days.

It is also notable that the reactions leading to destruction of H_2O and H_2 all lead invariably to production of H atoms (Reactions 2, 6, 8, 9, and 10). Repeated HLLV launches will lead to production of very large quantities of H atoms, possibly enough to modify the upper thermosphere.

Dispersal of the exhaust products is hastened by the ionospheric winds. Typical wind speeds in the F-layer are 300 km h^{-1} , and they exhibit considerable shear.⁷⁻¹² This enhances the growth rate of the depleted region, but it also speeds up the recovery. Neutral winds in the ionosphere are believed to have a rather regular diurnal behavior. Therefore, to a limited extent, their effects may be regular and predictable.

The size and severity of the ionospheric depletion are influenced, of course, by the initial conditions of the problem, that is, by processes that occur early in time and determine the "initial" concentration and spatial distribution of the exhaust products. One such process is the condensation of water vapor to form ice crystals. Such condensation is to be expected on theoretical grounds,^{6,13,14} and it was observed to occur, in fact, during the translunar injection burn of Apollo 8 (Molander and Wolfhard¹⁵).

A similar ice cloud was observed in the Los Alamos-Sandia Lagopedo experiments (HE detonations in the F-layer).¹⁶ The condensation has an important influence on the rate of gravitational settling of the water. The ice crystals have an evaporative lifetime of about five minutes,⁶ long enough to fall a great distance before they evaporate. The net effect is that the condensation leads to rapid transport of some of the water to much lower altitudes.

The initial settling rates of the exhaust gases are also influenced by "hydrodynamic" processes (as opposed to "diffusive"). That is, at early times when molecular concentrations of those gases are large (i.e., comparable with the back-

ground air), the falling gases impart substantial velocity to the air. When the air participates in the downward motion, it is less effective for slowing the descent. During that early stage, the falling velocities can be quite large, and it is important to understand the processes in some detail. These details are not included in our model. We attempt to simulate their effects by the way we set initial conditions for the numerical problem, as we describe later.

III. SKYLAB I LAUNCH

The most complete set of actual data on an ionospheric depletion resulting from a rocket launch was obtained on the launch of Skylab I, as reported by Mendillo et al.^{1,2} An important test for our two-dimensional models, naturally, is to run a set of computations representing that specific case and to compare the computed results with the data.

The data of Mendillo et al. for ray paths penetrating the ionospheric F2 peak at a distance of 300 to 500 km from the rocket path (from an observing station at Sagamore Hill, MA), showed an abrupt drop in electron column density to below 50% of its normal value. The low electron densities persisted for about four hours. A similar but smaller drop was observed for a ray path passing 900 to 1000 km from the rocket track (as observed from a station at London, Ontario). A definite but still less abrupt drop was observed from Goose Bay, Labrador, on a ray path 1200 km from the track at the point of second-stage engine shutdown. A small but perceptible drop was observed from Urbana, Illinois, for a ray path about 1200 km from the rocket track. A possible but very indistinct drop was seen from Narssarsuaq, Greenland, on a ray path 2000 km from the engine shutdown point. From the aggregate of the observations, one must conclude that a substantial electron depletion was produced out to a distance of about 1000 km from the rocket burn trajectory, and a small but measurable depletion was produced as far away as 2000 km. The depletion lasted for about four hours.

An approximate altitude-vs-range trajectory for the Skylab launch is shown in Fig. 1. Also shown are linear rates of injection of exhaust

Fig. 1. Profile of the Skylab I launch trajectory, along with the calculated linear rate of exhaust emission per kilometer of ground track.

products (in molecules per kilometer) along the trajectory. These quantities are derived from the paper by Mendillo, et al.¹

The gases were injected at a velocity of 4.5 km s^{-1} relative to the rocket, while the rocket accelerated gradually to a final burnout velocity of 7.3 km s^{-1} . Therefore, for the lower part of the trajectory, the exhaust gases were injected tangentially downward; for the upper part (above 350-km altitude), they were projected forward along the trajectory. Because molecular collision mean-free paths above 350-km altitude are very long, most of the exhaust molecules released above that altitude tended to follow ballistic trajectories that carried them hundreds of kilometers downrange from their points of origin, and terminated at about 270-km altitude, i.e., about four mean-free paths deep in the atmosphere, where the falling molecules were stopped by collisions. The exhaust products were also released with some lateral velocity, amounting to about 1 km s^{-1} on the average. Accordingly, in the course of their ballistic fall to 270-km altitude, they were dispersed some distance out from the rocket trajectory plane. Through these considerations, we were able to calculate an approximate "footprint" of the rocket exhaust deposition on a horizontal plane at 270-km altitude, i.e., a set of contours of the number of molecules laid down per unit area. The calculated footprint is shown in Fig. 2. Also shown are some of the observational lines-of-sight for the total electron content

Fig. 2. Computed "footprint" of the Skylab I exhaust cloud on a plane at 270-km altitude. Contours of the concentration of exhaust molecules per square centimeter.

measurements (Mendillo et al.¹). The lines-of-sight all passed quite high above the rocket trajectory and above the altitude of the F-layer peak in the trajectory plane (altitude tick marks are indicated on the lines-of-sight in Fig. 2).

The two-dimensional computer model uses cartesian coordinates (x, z), where the x coordinate is horizontal, z is vertical, and the xz plane coincides with a geomagnetic meridian plane. In a computation designed to model some aspects of the Skylab launch, we chose a magnetic meridian (x, z) plane that intersects the launch trajectory plane 1300-km downrange (at an angle of 70°). The particular meridian plane was chosen because it includes the Sagamore Hill-ATS-3 observational line-of-sight. Some details of the model are described in Appendices A and B.

Initial conditions for the computations were taken from the 270-km footprint contours in Fig. 2, but with the following additional adjustments:

- It was assumed that ten percent of the water molecules, upon their arrival on the 270-km horizontal plane, were in the form of $0.1\text{-}\mu\text{m}$ diameter ice crystals (percentage estimated by P. Bernhardt¹⁴). These ice crystals subsequently fell under gravity while evaporating, with the falling rates and evaporation rates calculated by Zinn et al.,⁶ as described in Appendix C. This process led to a fairly

rapid redistribution of some of the water molecules from 270 km down to about 150 km. The computer code contains automatic algorithms to generate this redistribution.

- b. The initial mass density of H_2 and H_2O molecules at 270-km altitude was comparable with, and in some cases larger than, the local density of the air. This would have led to Taylor-unstable mixing and hydrodynamic settling. The mixing would have proceeded rapidly until the excess density was reduced to about 10% over ambient, or perhaps less. The computer code contains automatic algorithms to simulate the effects of this mixing process.

After these preliminary manipulations, the computer model enters its free-running mode. The model includes chemistry, photochemistry, and diffusion with gravitational and electromagnetic terms, and horizontal winds, under assumed conditions of quasi-steady flow. Further details are described in Appendices A and B. The code output includes two-dimensional contours of concentrations of H_2O , H_2 , H, and electrons at predetermined intervals of time. It also produces vertical profiles of concentrations of ions and of neutral molecules, and vertical integrals of electron concentrations (TEC) for comparisons with Faraday-rotation data.

Figure 3 shows some results. The figure consists of computed contours of H_2O , H_2 , and electron concentrations one hour after the launch. By this time, according to the model, the exhaust gases have diffused 1000- to 2000-km laterally. The spreading is fastest at 300- to 500-km altitude, and it is faster for H_2 than for H_2O . The peak electron concentration directly under the trajectory has been reduced to about one-twentieth of its original value. However, along the Sagamore Hill-ATS-3 line-of-sight, the reduction is less severe. (The approximate line-of-sight is shown in the figure.) The influence of the winds is evident. The centers of the H_2 and H_2O clouds have been displaced about 200 km in the magnetic southward direction. The plasma hole moves downwind with the exhaust cloud, influenced only slightly by the geomagnetic field.

Fig. 3. Computed concentration contours for H_2O , H_2 , and electrons (number per cubic centimeter) one hour after launch of Skylab. The (x, z) coordinates are in the magnetic meridian plane 1300-km downrange from the launch point, and the cross-sectional view is perpendicular to the launch plane at an angle of 70° looking back along trajectory. The original exhaust deposition was in the central plane $x = 0$. Also shown are the B-field direction and the observational lines-of-sight from Sagamore Hill to satellites ATS-3 and -5.

The Sagamore Hill-ATS-5 line-of-sight is also represented schematically in Fig. 3 as a vertical line on the magnetic northward side of the trajectory plane. The computations show the ionospheric hole blowing rapidly away from this line of sight. The same is indicated by the data.¹

Fig. 4. Computed concentration contours for H_2O , H_2 , and electrons (number per cubic centimeter) three hours after launch of Skylab. The (x, z) coordinates are in the magnetic meridian plane 1300-km downrange from the launch point, and the cross-sectional view is perpendicular to the launch plane at an angle of 70° looking back along trajectory. The original exhaust deposition was in the central plane $x = 0$. Also shown are the B-field direction and the observational lines-of-sight from Sagamore Hill to satellites ATS-3 and -5.

Figures 4a, b, and c contain similar contour plots from the same computation, but for a time three hours after the launch. By this time, according to the computation, the center of the

exhaust product cloud has blown out of the Sagamore Hill/ATS-3 line-of-sight, and the electron density integral is beginning to return to normal. It also blows out of the Sagamore Hill-ATS-5 line of sight.

Figures 5a and b are plots of total electron content vs time for the Sagamore Hill/ATS-3 line-of-sight. Figure 5a is the observational data on the Skylab launch day, taken from the paper by Mendillo et al.¹ Figure 5b is a plot of the computed TEC for the same line-of-sight for the 24 hours preceding and 6 hours following the Skylab launch. The qualitative features of the computed TEC-vs-time curve agree with the data. The same can be said for comparisons of the computed results with the data from the other lines of sight.

From the computations, we draw the conclusion that the ionospheric hole did not actually recover after four hours, but rather blew out of the observational lines-of-sight. According to the computations, a significant plasma depletion still existed at sunset and persisted overnight.

The model results depend critically on the thermospheric wind description used in the computations. We made a considerable effort to arrive

Fig. 5. (a) Measured total electron content vs time following Skylab I launch on line-of-sight from Sagamore Hill Observatory to ATS-3 (from Mendillo et al.^{1,2}). (b) Model computation of TEC vs time for same line-of-sight for the 24 hours preceding and 4 hours following the Skylab launch.

at a reasonable model for the winds (see Appendix B). Our current results with respect to wind fields on the Skylab launch trajectory are quite different, and probably more reliable, than our previous published results in Ref. 6.

We still conclude, as in Ref. 6, that the ionospheric hole blew out of the observational lines of sight and did not actually recover in four hours as the TEC records seem to imply. However, it is fair to ask what other evidence exists to support our current belief that the dominant F-layer wind direction was magnetic southward, rather than some other direction. Some supporting evidence comes from the general character of the diurnal TEC variations observed during the month of May 1973, which are shown by Mendillo et al.¹ The steady increase in electron column density from morning through afternoon implies an F-layer wind system that is dominantly northward in the morning and southward in the afternoon, according to our computer model. Also, the similar character of the post-launch TEC records for the several different lines of sight¹ is further evidence of a southward wind.

It is noted by Mendillo et al.¹ that a geomagnetic storm occurred on the afternoon of May 13, and that somewhat depressed TEC levels were therefore to be expected on May 14, the day of the Skylab launch. The depressed electron column densities would probably be associated with enhancements in ionospheric east-west E fields and vertical plasma drifts. E-field effects are not included in this set of computations.

IV. HLLV SECOND-STAGE BURN AT 75- TO 124-km ALTITUDE

The current Solar Power Satellite HLLV launch scenario, designed to minimize F-layer problems, calls for burning the second-stage engines only up through 124-km altitude. This leads to an eccentric initial orbit, which is later circularized by a brief burn near the apogee point at 477 km.

With respect to F-layer depletion problems, this launch scenario is definitely preferable to the "direct insertion" alternative where the second-stage engines are burned all the way to the circular-orbit altitude. The ion chemistry in the 75- to 124-km altitude range (D and E layers) is

very different from that which occurs in the F-layer. The normally occurring ion species are NO^+ and O_2^+ instead of O^+ . These ions rapidly recombine with electrons, but they are continually replenished in the daytime by solar photoionization. At night they largely disappear. Addition of water vapor or H_2 does not have a very drastic effect on these processes.

Diffusion and gravitational settling are both much slower at these altitudes than they are in the F-layer. Horizontal spreading of the exhaust products would be caused primarily by fluctuating horizontal wind shears, and might amount to 1000 km per day. (The estimate of 1000-km per day for the spreading of exhaust products in the altitude range 75 to 125 km is based on theoretical estimates of the vertical shear of the tidal wind, from Garrett and Forbes.¹⁰ A typical value is 1 m/s/km, or a velocity difference of 50 m/s over 50 km. A velocity difference of 50 m/s, if extended over a 24-hour period, would lead to a lateral displacement of 4000 km. The shear would actually vary in an irregular but quasi-periodic fashion. These numbers suggest that 1000 km is a reasonable order-of-magnitude estimate of the net daily dispersion). A gradual upward diffusion would also occur, bringing some H_2 and H_2O molecules into the F-layer in the course of one or two days.

We run a computation that represents a portion of the HLLV second-stage burn trajectory, covering a ground distance of 300 km and an altitude range between 118 and 123 km, with deposition of 2.54×10^{31} molecules of H_2O and 8.5×10^{30} molecules of H_2 . The launch was assumed to occur at Cape Canaveral at noon.

The computed results showed, as expected, that exhaust-cloud diffusion and settling rates are quite slow. In the course of 24 hours, some water and H_2 does diffuse up to the F2 layer, where it reacts with O^+ ions. Because the molecular diffusion rate is very slow, the O^+ ions are replaced by solar photoionization about as fast as they are destroyed. At the same time, the H_2O and H_2 molecules are destroyed as fast as they diffuse into the F2 layer. Although the O^+ ions are replaced rapidly, the reaction sequence leads to a net production of H atoms. The H atoms are not

Fig. 6. Computed concentration contours for H_2O , H_2 , and electrons (number per cubic centimeter) 24 hours after hypothetical HLLV launch, which was assumed to occur at Cape Canaveral at noon on May 14. The view is perpendicular to the launch plane looking west.

destroyed, and they may accumulate in the upper thermosphere.

Figures 6a, b, and c include sets of contours of H_2O , H_2 , and electron concentrations at noon, 24 hours after the launch. They show that the H_2O and H_2 molecules are destroyed almost as fast as they diffuse into the F2 region, and, in the daytime, the electrons are replaced as fast as they are removed. At night the electrons are not replaced, and their concentration at the F2 peak is decreased to about 70% of the normal value.

It is possible that the H atom production could be a significant environmental problem. Its

net effect could be to increase the density of the upper thermosphere. Within the first 30 hours after the HLLV launch, 1.3×10^{31} H atoms are produced above 100-km altitude from the added H_2O and H_2 . This can be compared with the normal global inventory of H atoms above 100 km, which is of the order of 4×10^{32} , and it implies that each HLLV launch could increase the thermospheric H inventory by about 3% per day if other sources and loss rates remained unchanged. From each launch the H production would continue for about five days, leading to a maximum upper limit global H atom inventory change of about 15%. However, an increase of thermospheric H-atom concentration would probably lead to an increased exospheric escape rate. The consensus of a number of studies on the global H-atom escape rate gives a value of about 1×10^{32} atoms per day. Thus, the normal thermospheric residence time for an H atom is of the order of four days (or perhaps one to ten days).

The subject of thermospheric H-atom inventories and escape rates needs to be studied more carefully. The present calculations suggest that a doubling of the upper thermospheric density might be possible if a schedule of frequent HLLV launches were initiated. The possible consequences of a density doubling could be serious, though presently a matter of vague speculation. Thermospheric wind patterns could be affected, as well as relativistic electron precipitation rates and global climate.

The HLLV would also deposit large quantities of water vapor in the mesosphere. At the mesopause (~ 85 -km altitude), the normal temperature is about 180K, and the saturation concentration of water vapor in equilibrium with ice at that temperature is 2.6×10^{12} molecules cm^{-3} . According to the design rate of output of water vapor in the HLLV exhaust (4×10^{29} molecules per linear kilometer), we would expect a large contrail to form at 85-km altitude with crosswise dimensions of at least 14 km. A contrail of this size would persist for at least several hours. [At the normal mesopause temperature of ca 180K, the saturation vapor pressure of water would be .05 d/cm², corresponding to an H_2O number density of 2×10^{12} molec/cm³. The normally existing H_2O concentra-

tion at the mesopause is less than a thousandth of this value. The HLLV, in its flight across this region, would emit about 4×10^{24} H_2O molecules per linear centimeter, resulting in local H_2O concentrations that would exceed saturation for some period of time. The length of time required for the concentration to drop below the 2×10^{12} molec/cm³ saturation level would be determined by wind shears and turbulent diffusion. Effective diffusion coefficients in this altitude regime, determined from radio meteor and chemical release data, vary between 10^6 and 10^7 cm²/s, see S. Zimmerman and Murphy,¹⁷ leading to supersaturation lifetimes of the contrail ranging between five hours and two days.]

A cumulative effect is possible over the course of many HLLV launches. Under normal conditions, water vapor is a major contributor to radiative cooling at the mesopause, due to molecular rotation transitions in the wavelength range 20 to 100 μm . The normal contribution of H_2O to the cooling rate is about one degree Kelvin per day. A local increase of H_2O concentration would lead to an increase in the cooling rate and a lower equilibrium temperature. It is possible that a ten-fold increase in the mesopause H_2O concentration, resulting from many HLLV launches, would lead to a temperature decrease sufficient to produce a permanent ice cloud. The photochemical lifetime of mesospheric H_2O vapor is about 40 days.

V. HLLV ORBIT CIRCULARIZATION AND DEORBIT MANEUVERS

With the main HLLV second-stage burn confined to altitudes below 120 km, the effects on ionization in the F-layer are, as we have shown, fairly small. However, relatively small but significant amounts of H_2O and H_2 are deposited directly into the F-layer during the orbit circularization and deorbit maneuvers. The rates of exhaust emission per linear kilometer during those maneuvers are expected to be about one-tenth of the emission rate of the Saturn V, S II engines during the Skylab launch. However, since the burn would occur at a high altitude (477 km), the efficiency for ion removal would be high.

We ran a computation to represent an HLLV orbit circularization burn occurring at noon over the Philippine Islands. The assumed exhaust deposition rate was 4.9×10^{26} H_2O molecules and 1.6×10^{26} H_2 molecules per kilometer, extending over a linear distance of 1400 km. (These parameters were furnished by H. P. Davis, NASA JSC, based on expected characteristics of the HLLV orbital-maneuvering system.) After injection, the gases were assumed to fall rapidly to 270-km, while spreading crosswise to the trajectory plane over a perpendicular distance of 400 km (full width).

According to the computation, a small but definite ionospheric hole is produced, illustrated in Figs. 7a, b, and c. These figures represent a cross section perpendicular to the vehicle trajectory and lying in the geomagnetic meridian plane. The time is 2.4 hours after launch, the time of maximum ion depletion. The electron density has been reduced to one-third of its normal value over a geographic area approximately 1000 by 2000 km. The ionosphere returns to normal in about five hours.

VI. THE COMPUTER MODELS Two-Dimensional Cartesian Model

Structurally, the code includes an array of two-dimensional Eulerian mesh cells with coordinates x (in the geomagnetic meridian plane) and z (the vertical). The z -coordinate extends from 50- to 700-km altitude; the x -coordinate extends from 0 to 2000 km on either side of the trajectory plane. There are 13 vertical and 21 horizontal cells, for a total of 273 cells.

The following physical and chemical processes are considered.

- a. Chemistry - Time-dependent chemical/photochemical kinetics with 28 species and 277 reactions. The rate equations are integrated in each of the 273 cells. The more important chemical reactions in the reaction set are listed in Appendix A.
- b. Solar radiation - The nominal spectral intensity of sunlight in each of 40 wavelength bands is stored by the computer code. To simulate expected solar-activity-related variations in the EUV region below 1000 Å,

Fig. 7. Computed concentration contours for H_2O , H_2 , and electrons (number per cubic centimeter) 2.4 hours after a hypothetical HLLV orbit circularization maneuver over the Philippine Islands. The cross-sectional view is perpendicular to the orbital plane and parallel to the magnetic meridian plane looking back along trajectory. The original exhaust deposition was in the central plane $x = 2000$ km, and extends 1400-km lengthwise in that plane.

the nominal intensities are scaled up or down by a nominal factor, usually in the range 0.5 to 2. Attenuation of the solar radiation in each wavelength band at each of the 13 altitudes due to absorption by O , O_2 , N_2 , and O_3 is computed from the computed concentrations of those species and the computed solar zenith angles. The rate coefficients for photo-

dissociation, photoionization, and photoexcitation reactions are computed from the computed spectral intensities and tabulated wavelength-dependent cross sections.

- c. Diffusion and transport - Diffusion rates are computed for each species under the influence of gravity under assumed conditions of steady flow (near hydrostatic equilibrium). Advection effects due to horizontal winds are included. The ion transport equations incorporate effects of the electric and magnetic fields. The transport equations are described in more detail in Appendix B.
- d. Time-varying temperatures - The temperature array is generated as a function of altitude and time based on fits to standard empirical models, scaled to the assumed exospheric temperature, which is specified as an input variable. Daytime electron and ion temperatures are generated with a set of algorithms that relates them to the neutral temperatures and local electron concentrations. The chemical rate coefficients, diffusion rates, and vertical winds are computed from these temperatures.
- e. Cosmic rays, precipitating electrons, and He^+ 304-Å radiation - These ionization sources are included because of their importance in the D-layer and the night-time E-layer.
- f. Horizontal winds - Tidal-wind velocities and E-fields are specified as functions of altitude, latitude, and time, based on models fit to experimental observations.⁷⁻¹² The wind model is described in Appendix B.

One-Dimensional Codes and Computations of the Normal Ionosphere

The two-dimensional code can be operated in a one-dimensional mode for computing the structure and diurnal variability of the normal ionosphere. The one-dimensional computations are used to furnish starting conditions for the two-dimensional rocket exhaust injection problems.

The two-dimensional code (or its one-dimensional version) provides a reasonably accurate description of the normal ionosphere above 90-km altitude (E- and F-layers). However, its 28-species chemistry model is not adequate for the D-

layer (below 90 km). To cope with the D-layer chemistry, and to model the E- and F-layers with better spatial resolution, we constructed a larger one-dimensional code for the CRAY computer. This code includes 84 chemical species and 1600 chemical reactions in 40 vertically stratified mesh layers. It seems to generate a fairly accurate representation of the normal atmosphere/ionosphere over the entire altitude range (50 to 700 km). Detailed comparisons with experimental data are still in progress.

Some computed chemical composition profiles, representing the normal ionosphere as generated with the smaller one-dimensional code, are shown in Figs. 8a and b. They contain sets of profiles of neutral molecular and ion concentrations, respectively, for noontime, May 14, 1973, at 38° N latitude, near Wallops Island, VA, assuming low solar activity and a noontime exospheric temperature of 1048 K. They represent the ionospheric configuration 30 minutes before the Skylab launch and the initial conditions for the two-dimensional Skylab computation.

Inputs to these computations, including time-dependent temperature profiles, solar x-ray and

ultraviolet (UV) spectra, night-time intensities of scattered UV radiation from the geocorona, intensities of cosmic rays and precipitating relativistic electrons, and specifications of the thermospheric winds, were chosen to represent the expected average conditions for the selected location and local time. The assumed temperature and wind profiles one hour after the Skylab launch are plotted in Figs. 9a and b.

VII. CONCLUSIONS

We have run a set of numerical simulations of the effects of a single HLLV launch on the earth's upper atmosphere and ionosphere, and we have checked the computer code against experimental data for the case of the Skylab I launch and data on the ambient ionosphere.

The principal environmentally significant effects that show up in the HLLV computations are

- large-scale ionospheric plasma depletions,
- production of massive quantities of atomic hydrogen in the thermosphere, and
- formation of persistent ice clouds near the mesopause.

Fig. 8. Computed vertical concentration profiles for neutral species and positive ion species respectively at noon on May 14 at 38° latitude off Wallops Island, VA, 30 minutes before the Skylab I launch.

Fig. 9. (a) Computer-generated vertical profiles of neutral gas temperature (T_n), ion temperature (T_i), and electron temperature (T_e) for 1330 hours May 14, 1973 off Wallops Island, VA (one hour after Skylab I launch). (b) Corresponding neutral wind profiles. Positive u_n is magnetic northward, positive v_n is magnetic westward, and w_n is vertical.

The F-layer plasma depletion resulting from the main HLLV second-stage burn is less pronounced than the depletion observed after the Skylab launch. This is because the burn is confined to altitudes below 124 km. The computed electron density reduction at the F2 peak amounts to about thirty percent at night (12 hours after launch) and ten percent the following day.

The F-layer depletion resulting from the orbit circularization maneuver at LEO apogee is more severe, but relatively short-lived. The F2 peak electron density is reduced to one third of its normal value over a region approximately 1000 by 2000 km for a period of about four hours. The hole would be longer-lasting if the orbital maneuver occurred at night.

The computed rate of production of hydrogen atoms reaching the upper thermosphere (above 300-km altitude) amounts to 1.3×10^{31} per HLLV launch for the first 30-hour period. This might be sufficient to double thermospheric H-atom concentrations after six launches.

An HLLV launch would produce a large contrail in the mesosphere at about 85-km altitude, 10- to 20-km wide, and extending several hundred kilometers downrange. The contrail would persist for several hours. Repeated HLLV launches could lead to cumulative effects, which need to be investigated.

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APPENDIX A

CHEMICAL REACTIONS IN THE TWO-DIMENSIONAL IONOSPHERIC MODEL

Table A-1 is a computer listing of the most important chemical reactions and rate parameters used in the two-dimensional code. They are a computer-selected subset of the 277 reactions

TABLE A-I
THE DOMINANT CHEMICAL REACTIONS

Reactants	Products	A	B	C	References
O ₂	CO ₂	1.35E-13	0.00	0.	DEMORE (NASA), 1979
N ₂	CO ₂	3.20E-13	0.00	1711.	KONDRATIEV (NBS), 1972
N ₂	O ₂	5.30E-11	0.00	0.	HAMPSON (NBS), 1978
N ₂ (D)	O ₂	5.00E-11	0.00	0.	BORTNER (DNA), 1978
O	O ₂	4.00E-11	0.00	0.	DEMORE (NASA), 1979
H	O ₂ (D)	2.50E-14	0.00	0.	HAMPSON (NBS), 1978
H	O ₃	1.40E-10	0.00	470.	DEMORE (NASA), 1979
O ₂ (D)	H ₂	9.90E-11	0.00	0.	DEMORE (NASA), 1979
H ₂	O	9.00E-12	1.00	4480.	HAMPSON (NBS), 1978
O ₂ (D)	H ₂ O	2.30E-10	0.00	0.	DEMORE (NASA), 1979
O ₂	O ₂	1.00E-11	0.00	500.	DEMORE (NASA), 1979
O ₂	H ₂	1.20E-11	0.00	2200.	DEMORE (NASA), 1979
O ₂	N ₂ (D)	1.50E-12	.50	0.	BORTNER (DNA), 1978
O ₂	N ₂ (D)	6.00E-12	.50	0.	BORTNER (DNA), 1978
N ₂	O ₂	4.40E-12	0.00	3220.	DEMORE (NASA), 1979
N ₂ (D)	NO	6.00E-11	0.00	0.	BORTNER (DNA), 1978
N ₂	NO	3.40E-11	0.00	0.	DEMORE (NASA), 1979
CO ₂	H	4.95E-11	-.30	12321.	REVERSE
O ₂	H	6.47E-10	0.00	8407.	REVERSE
H	O ₂	4.14E-12	1.00	3478.	REVERSE
H ₂ O	O	4.54E-11	.40	8960.	REVERSE
H ₂ O	H	2.50E-11	.40	8658.	REVERSE
O	O	1.40E-30	0.00	650.	BORTNER (DNA), 1978
CO	O	6.50E-33	0.00	2180.	HAMPSON (NBS), 1978
H ₂	H	8.30E-33	0.00	0.	HAMPSON (NBS), 1978
H ₂	O ₂	6.78E-31	-2.00	0.	HAMPSON (NBS), 1978
O	O ₂	1.13E-34	0.00	-510.	DEMORE (NASA), 1979
O	N	1.90E-17	-.40	0.	BORTNER (DNA), 1978
N ₂ (D)	N	1.60E-05	0.00	0.	BORTNER (DNA), 1978
O ₂ (D)	O ₂	2.60E-04	0.00	0.	BORTNER (DNA), 1978
O ₂ (D)	O ₂	8.30E-02	0.00	0.	BORTNER (DNA), 1978
O ₂ (D)	O ₂ (D)	2.50E-03	0.00	0.	NOXON, CAN. J. PHYS., 1961
E	N ₂ (D)	4.32E-09	-.10	3551.	BORTNER (DNA), 1978
O ₂ (D)	E	1.00E-11	0.00	0.	BORTNER (DNA), 1978
O ₂ (D)	O	2.00E-11	0.00	-107.	DEMORE (NASA), 1979
N ₂ (D)	N	6.00E-15	0.00	0.	BORTNER (DNA), 1978
O ₂ (D)	O	7.50E-12	0.00	0.	BORTNER (DNA), 1978
O ₂ (D)	O ₂	2.90E-11	0.00	-67.	DEMORE (NASA), 1979
O ₂ (D)	O ₂	2.20E-18	.80	0.	BORTNER (DNA), 1978
O ₂ (D)	H	1.63E-15	0.00	0.	BORTNER (DNA), 1978
E	O	5.51E-09	-.20	26310.	REVERSE
O ₂	O ₂ (D)	1.00E-11	0.00	11594.	REVERSE
O	N ₂ (D)	7.60E-13	0.00	4162.	REVERSE
E	O ₂	1.73E-07	0.00	0.	SUTHERLAND, 1975
E	O ₂	2.20E-08	0.00	0.	SUTHERLAND, 1975
E	O ₂	4.40E-09	0.00	0.	SUTHERLAND, 1975
E	H ₂ O	2.00E-08	0.00	0.	SUTHERLAND, 1975
E	H ₂ O	1.00E-08	0.00	0.	SUTHERLAND, 1975
E	H ₂ O	1.70E-07	0.00	0.	SUTHERLAND, 1975
E	H ₂ O	1.30E-06	-.70	0.	BORTNER (DNA), 1978
E	NO	4.00E-07	-1.00	0.	BORTNER (DNA), 1978
E	O ₂	1.89E-07	-.60	0.	BORTNER (DNA), 1978
E	O ₂	2.10E-08	-.60	0.	BORTNER (DNA), 1978
N ₂	H	3.60E-12	0.00	0.	CONSTANTINIDES, 1979
N ₂	NO	1.90E-09	0.00	0.	BORTNER (DNA), 1978
N ₂	NO	3.00E-10	0.00	0.	J. ZINN ESTIMATE
N ₂	H	3.00E-10	0.00	0.	J. ZINN ESTIMATE
N ₂	O ₂	3.00E-10	0.00	0.	J. ZINN ESTIMATE
O ₂	H	6.80E-10	0.00	0.	BORTNER (DNA), 1978
H ₂	O ₂	5.00E-10	0.00	0.	W. MAIER ESTIMATE
O ₂	O ₂	3.00E-10	0.00	0.	J. ZINN ESTIMATE
N ₂	O ₂	2.00E-10	0.00	0.	BORTNER (DNA), 1978
H ₂ O	H ₂ O	2.60E-09	0.00	0.	BORTNER (DNA), 1978
N ₂	NO	3.00E-10	0.00	0.	J. ZINN ESTIMATE
N ₂	H ₂ O	6.10E-10	0.00	0.	TIERNAN, 1969
O ₂	H ₂ O	2.30E-09	0.00	0.	BORTNER (DNA), 1978
H ₂ O	O ₂	2.00E-10	0.00	0.	BORTNER (DNA), 1978
H ₂	H ₂ O	3.00E-10	0.00	0.	J. ZINN ESTIMATE
N ₂	O	2.20E-12	0.00	0.	CONSTANTINIDES, 1979
N ₂	O ₂	2.80E-10	0.00	0.	BORTNER (DNA), 1978
O ₂	NO	4.50E-10	0.00	0.	BORTNER (DNA), 1978
N ₂	O	1.00E-11	-.20	0.	BORTNER (DNA), 1978
N ₂	O ₂	5.00E-10	-.80	0.	BORTNER (DNA), 1978
O ₂	O ₂	2.00E-11	-.40	0.	BORTNER (DNA), 1978
H ₂	O	7.73E-10	-.10	215.	REVERSE
O ₂	CO ₂	1.10E-09	0.00	0.	BORTNER (DNA), 1978
O ₂	O ₂	1.00E-09	0.00	0.	ESTIMATE
O ₂	H ₂	2.00E-09	0.00	0.	BORTNER (DNA), 1978
O ₂	H ₂	1.50E-09	0.00	0.	FEMSENFELD, 1967
O ₂	H ₂ O	1.50E-09	0.00	0.	GUPTA, 1967
H ₂ O	H ₂	1.40E-09	0.00	0.	FEMSENFELD, 1967
H ₂ O	H ₂ O	1.60E-09	0.00	0.	BORTNER (DNA), 1978

TABLE A-I (continued)

Reactants	Products	A	B	C	References
N+ O2	NO+ O	2.80E-10	0.00	0	BORTNER(DNA), 1978
O2+ N	NO+ O	1.20E-10	0.00	0	BORTNER(DNA), 1978
N+ O3	NO+ O2	5.00E-10	0.00	0	W. MAIER ESTIMATE
O+ N2	NO+ N	1.20E-12	-1.00	0	BORTNER(DNA), 1978
N2+ O	NO+ N	1.30E-10	-1.50	0	BORTNER(DNA), 1978
O2+ N2	NO+ NO	1.00E-16	0.00	0	BORTNER(DNA), 1978
N2+ O3	O2+ O N2	1.00E-10	0.00	0	W. MAIER ESTIMATE
O+ OH	H+ O2	2.70E-11	.10	0	REVERSE
O+ N2	NO+ N M	6.00E-29	-2.00	0	BORTNER(DNA), 1978
CO2 + HV	CO O				BORTNER(DNA), 1978
H2O + HV	H OH				BORTNER(DNA), 1978
NO + HV	N O				PARK, 1974
N2 + HV	N N				HUFFMAN, 1969
N2 + HV	N N(2D)				HUFFMAN, 1969
O2 + HV	O O				BORTNER(DNA), 1978
O2 + HV	O O(1D)				YOCKARTS, 1976
O3 + HV	O2(1D) O(1D)				ACKERMAN, 1971
O + HV	O(1S)				ALLEN, ASTRO. QUANT.
O2 + HV	O2(1D)				BORTNER(DNA), 1978
O2 + HV	O2(5G)				BORTNER(DNA), 1978
H + HV	H+ E				W. HUEBNER, PR. COMM.
N + HV	N+ E				W. HUEBNER, PR. COMM.
N(2D) + HV	N+ E				W. HUEBNER, PR. COMM.
NO + HV	NO+ E				ALLI(NRL), 1973
N2 + HV	N2+ E				W. HUEBNER, PR. COMM.
N2 + HV	N+ E N				W. HUEBNER, PR. COMM.
O + HV	O+ E				W. HUEBNER, PR. COMM.
O2 + HV	O2+ E				W. HUEBNER, PR. COMM.
O2(1D) + HV	O2+ E				HUFFMAN, 1971

actually implemented in the code. The chemical reaction rate coefficients (excluding photochemical rates) are expressed in the form

$$k = A(T/300)^B \exp(-C/T) .$$

The parameters A, B, and C are tabulated for each reaction. For reactions involving only neutral molecules, the neutral temperature is used. If the reactants include electrons, the electron temperature is used. If the reactants include ions but not electrons, the ion temperature is used.

Bibliographic references for the rate data are indicated in the last column. "Reverse" means that we have computed the rate coefficient using the computed thermodynamic equilibrium constant combined with the measured rate of the reverse reaction.

APPENDIX B THE TRANSPORT EQUATIONS

I. GLOSSARY OF TERMS

Coordinates and velocities:

- x = horizontal coordinate in magnetic meridian plane (northward)
- y = coordinate perpendicular to meridian plane (westward)
- z = vertical coordinate
- u = x velocity
- v = y velocity
- w = z velocity

Species subscripts:

- e = electrons
- + = positive ions
- n = neutrals
- i = ith individual species
- n(n_e, n₊, n_n, n_i) = number densities
- p(p_e, p₊, p_i) = partial pressures
- T(T_e, T₊, T_n) = temperatures
- v(v_e, v_i) = collision frequencies
- Ω(Ω_e, Ω_i) = gyrofrequencies
- m(m_e, m_i, $\bar{m}$, $\bar{m}_+$) = species mass
- H(H_i, $\bar{H}$, $\bar{H}_+$) = scale heights

$D(D_{in}, D_{ai}, D_{eddy})$ = diffusion coefficients

t = time

λ = latitude

I = magnetic dip angle

δ = magnetic declination

B_x, B_z = magnetic field components

E_x, E_y, E_z = electric field components

k = Boltzmann's constant

g = gravitational constant

e = electron charge

c = speed of light

II. NEUTRAL WIND VELOCITIES

The neutral temperatures are assumed to vary with z and t in a prescribed manner, derived from fits to model atmosphere data. If overall hydrostatic equilibrium is assumed, it can be shown that the macroscopic average vertical wind velocity must be given by the differential equation

$$\frac{\partial \bar{w}_n}{\partial z} - \bar{w}_n \frac{\partial \ln H}{\partial z} = \frac{\partial \ln H}{\partial t} \quad (B-1)$$

where $H = (kT_n/mg)$ and

$$\bar{m} = \frac{\sum_i n_i m_i}{\sum_i n_i} \quad .$$

The solution of Eq. (B-1) is

$$\bar{w}_n = H \int_{z_0}^z \frac{1}{H^2} \frac{\partial H}{\partial t} dz \quad (B-2)$$

which can be evaluated by quadrature.

The horizontal neutral wind components $\bar{v}_N$ (toward the north) and $\bar{v}_W$ (toward the west) are represented as linear superpositions of seasonal average, diurnal (S_{11} and $S_{1,-2}$ modes) and semidiurnal terms. The separate terms are generated from fits to the data of R. M. Harper¹⁸ and of P. Amayenc¹⁹ and computations of Roble et al,¹¹ and of Forbes and Garrett.^{8,9,10} We are grateful for the advice of R. M. Harper, J. M. Forbes, and H. B. Garrett.

We represent the meridional wind component as

$$\begin{aligned} \bar{v}_N = & A_{0N} - A_{11N} \cos[2\pi(\tau - \Delta_{11N})/24] \\ & - A_{12N} \cos[2\pi(\tau - \Delta_{12N})/24] \end{aligned}$$

$$- A_{2N} \cos[2\pi(\tau - \Delta_{2N})/12] \quad ,$$

where τ is the time of day in hours and the subscripts 11N, 12N, and 2N refer respectively to the diurnal S_{11} mode, diurnal $S_{1,-2}$ mode, and the semidiurnal mode. A_{0N} is the seasonal average northward velocity. The A's and Δ 's are generated as fitted functions of altitude, latitude, time of year, and solar activity level, or a subset of these variables.

The seasonal average term A_{0N} is generated with a computer subroutine that was kindly furnished by J. M. Forbes. It is based on fits to results of computations by Roble, Dickinson, and Ridley.¹¹

Values of the parameters A_{11N} , A_{12N} , A_{2N} , Δ_{11N} , Δ_{12N} , and Δ_{2N} were determined as functions of altitude by R. M. Harper^{12,18} from incoherent scatter measurements at Arecibo for solar minimum non-winter conditions. We have fitted Harper's data with approximate analytic functions of altitude. Of the two diurnal modes S_{11} and $S_{1,-2}$, the former is dominant at low latitudes, while the latter dominates at high latitudes. The relative strengths of the two modes as functions of latitude have been computed by Forbes and Garrett.⁸ We use Forbes' and Garrett's results to scale Harper's Arecibo values of A_{11N} and A_{12N} to non-Arecibo latitudes. The scaled amplitudes are in rather good agreement with amplitudes computed by Forbes and Garrett for solar minimum conditions at 45° latitude. For solar maximum conditions, A_{11N} increases at low latitudes (R. M. Harper, private communication²⁰). The quantities A_{2N} , Δ_{11N} , Δ_{12N} , and Δ_{2N} are all assumed, for lack of detailed information, to be independent of latitude, season, and solar activity.

For the zonal wind system, $\bar{v}_W$, we again use a linear superposition of seasonal average, diurnal, and semidiurnal terms; i.e.,

$$\begin{aligned} \bar{v}_W = & A_{0W} + A_{1W} \cos[2\pi(\tau - \Delta_{1W})/24] \\ & + A_{2W} \cos[2\pi(\tau - \Delta_{2W})/12] \quad , \end{aligned}$$

where A_{0W} is the seasonal average velocity, and the subscripts 1W and 2W refer to diurnal and

semidiurnal modes. A_{0W} is computed with a subroutine supplied by J. M. Forbes. The diurnal amplitude A_{1W} is assumed to be the same as A_{12N} , the amplitude of the meridional component of the $S_{1,-2}$ mode. The phase shift λ_{1W} is set equal to -4 hours. For the semidiurnal mode, we assume $A_{2W} = 25$ m/s and $\lambda_{12} = 6$ hours, independent of altitude, latitude, and season.

The velocity components $\bar{v}_N$ and $\bar{v}_W$, which are in geographic coordinates, must be transformed to geomagnetic coordinates (x,y,z) via

$$\bar{u}_n = \bar{v}_N \cos I + \bar{v}_W \sin I, \quad (B-3)$$

and

$$\bar{v}_n = -\bar{v}_N \sin I + \bar{v}_W \cos I, \quad (B-4)$$

where $\bar{u}_n$ and $\bar{v}_n$ are the macroscopic average neutral wind velocities in the magnetic coordinate system.

III. NEUTRAL SPECIES TRANSPORT

The quasi-steady velocity components for the i th neutral species above the turbopause are

$$u_i = \bar{u}_n - D_{in} \frac{\partial \ln p_i}{\partial x}, \quad (B-5)$$

$$v_i = \bar{v}_n - D_{in} \frac{\partial \ln p_i}{\partial y}, \quad (B-6)$$

and

$$w_i = \bar{w}_n - D_{in} \left[\frac{\partial \ln p_i}{\partial z} + \frac{1}{H_i} \right], \quad (B-7)$$

where $p_i = n_i k T_n$, and $H_i = k T_n / m_i g$, and D_{in} is the molecular diffusion coefficient of species i .

Below the turbopause (~100-km altitude) the eddy diffusion coefficient, D_{eddy} , is larger than the molecular diffusion coefficients. In that altitude range, the equations must be modified by replacing H_i with H and replacing D_{in} by D_{eddy} . Although we have included the term $\partial \ln p_i / \partial y$ in Eq. (B-6), we assume, for the present two-dimen-

sional model, that $\partial / \partial y = 0$.

The rate of change of the i th species concentration is computed as

$$\frac{\partial n_i}{\partial t} = -\nabla \cdot (n_i \vec{v}_i) + P_i - L_i, \quad (B-8)$$

where P_i and L_i are the chemical production and loss terms.

IV. ION TRANSPORT EQUATIONS

The transport of ions is influenced strongly by the geomagnetic field. For this reason we have chosen coordinates which are aligned with the magnetic field. $\vec{B}$ is in the xz plane and has components $B_x = B \cos I$ and $B_z = -B \sin I$.

The electron and ion Larmor frequencies are $|eB/m_e c| = \Omega_e$ and $|eB/m_i c| = \Omega_i$. For compactness of notation, we refer to the Larmor frequency components: $\Omega_{ex} = \Omega_e \cos I$, $\Omega_{ez} = -\Omega_e \sin I$, $\Omega_{ix} = \Omega_i \cos I$, and $\Omega_{iz} = -\Omega_i \sin I$.

Where plasma density gradients are present, the dominant parallel component of the electrostatic field will be

$$E = -\frac{1}{n_e |e|} \nabla p_e, \quad (B-9)$$

where

$$n_e = \sum_i n_i$$

(sum over positive ions) and $p_e = n_e k T_e$. Then, including the effects of the E and B fields, the force of gravity, the neutral winds, and diffusion regulated by ion-neutral (but not ion-ion) collisions, the ion transport velocities are given by

$$u_i = -D_{ai} A_{ix} \frac{\partial}{\partial x} \ln [n_i (T_e + T_+)] + \phi_{ix}, \quad (B-10)$$

and

$$w_i = -D_{ai} A_{iz} \left\{ \frac{\partial}{\partial z} \ln [n_i (T_e + T_+)] + \frac{1}{H_{i+}} \right\} + \phi_{iz}, \quad (B-11)$$

where

$$D_{ai} = D_{in}(1 + T_e/T_+) \quad (\text{ambipolar diffusion (B-12) coefficient}) ,$$

$$H_{i+} = \frac{k}{g} \left[\frac{T_+(T_e + T_+)}{m_i(T_e + T_+) - m_+T_e} \right] \quad (\text{the effective equilibrium scale height for ion species } i) \quad (\text{B-13})$$

$$A_{ix} = \frac{\frac{v_i^2}{2} + \frac{\alpha_{ix}^2}{2}}{\frac{v_i^2}{2} + \frac{\alpha_{iz}^2}{2}} , \quad (\text{B-14})$$

$$A_{iz} = \frac{\frac{v_i^2}{2} + \frac{\alpha_{iz}^2}{2}}{\frac{v_i^2}{2} + \frac{\alpha_{iz}^2}{2}} , \quad (\text{B-15})$$

$$\phi_{ix} = \frac{1}{\frac{v_i^2}{2} + \frac{\alpha_{iz}^2}{2}} \left[\alpha_{ix} \alpha_{iz} w_i + \frac{v_i^2}{2} \left(\bar{u}_n + \frac{eE_x}{m_i v_i} \right) + \alpha_{ix} \alpha_{iz} \left(\bar{v}_n + \frac{eE_y}{m_i v_i} \right) \right] , \quad (\text{B-16})$$

and

$$\begin{aligned} \phi_{iz} = A_{iz} & \left\{ \bar{u}_n \left(1 + \frac{m_e v_e}{m_i v_i} \right) + \frac{\alpha_{ix} \alpha_{iz}}{\frac{v_i^2}{2} + \frac{\alpha_{iz}^2}{2}} \left(\bar{u}_n + \frac{eE_x}{m_i v_i} \right) \right. \\ & + \frac{\alpha_{ex} \alpha_{ez}}{\frac{v_e^2}{2} + \frac{\alpha_{ez}^2}{2}} \left[\bar{u}_n \left(\frac{m_e v_e}{m_i v_i} \right) - \frac{eE_x}{m_i v_i} \right] \\ & \left. - \frac{\alpha_{ix} v_i}{\frac{v_i^2}{2} + \frac{\alpha_{iz}^2}{2}} \left(\bar{v}_n + \frac{eE_y}{m_i v_i} \right) \right. \\ & \left. + \frac{\alpha_{ex} v_e}{\frac{v_e^2}{2} + \frac{\alpha_{ez}^2}{2}} \left[\bar{v}_n \left(\frac{m_e v_e}{m_i v_i} \right) - \frac{eE_y}{m_i v_i} \right] \right\} . \quad (\text{B-17}) \end{aligned}$$

though we have made minor modifications.

In the computations to date, we have assumed that the external electrostatic field components E_x and E_y are zero. We have also assumed that temperatures do not vary in the x-direction, and nothing varies in the y-direction.

V. BOUNDARY CONDITIONS

The concentrations of N_2 , O_2 , CO_2 , H_2O , H_2 , He , and NO are held constant in the bottom row of mesh cells. For all other species, the bottom boundary fluxes are set to zero. In this connection, it is relevant to note that the photochemical time constants of odd oxygen and odd hydrogen species at 50-km altitude are less than one hour, whereas the time constant for odd nitrogen is about 100 days.

The horizontal boundary flux conditions are recursive; that is, the fluxes at the left boundary at each altitude are set equal to the corresponding fluxes at the right-hand boundary.

In the top row of mesh cells, we assume that all species are in hydrostatic equilibrium. That is, all concentrations in the top row of cells are related directly to the concentrations in the row below according to the diffusive equilibrium relationship

$$n_{i2} = n_{i1} (T_1/T_2) \exp \left\{ - \int_{z1}^{z2} dz/H_i \right\} , \quad (\text{B-18})$$

where subscript 2 refers to the top cell (median altitude $z2$), and subscript 1 refers to the cell below (median altitude $z1$). For neutrals, T_1 and T_2 are the neutral gas temperatures T_n , and H_i is the neutral scale height $kT_n/m_i g$. For ions, the temperatures are the sums of ion and electron temperatures, $T_+ + T_e$, and H_i is the ion scale height given by Eq. (B-13).

Equations (B-9) through (B-17) are based on the formulation given by Banks and Kockarts,²¹ al-

APPENDIX C
ICE CONDENSATION, EVAPORATION, AND
GRAVITATIONAL SETTLING

The importance of condensation as a process for removing the rocket exhaust H_2O molecules from the F-layer depends on the lifetimes of the ice crystals and on their settling rates. We suspected at first that the particles would evaporate rapidly in sunlight, before they could fall to an appreciable extent. However, we will show that this is not the case.

There is not much question that condensation of water must occur, because of the rapid cooling by adiabatic expansion of the exhaust cloud into the surrounding vacuum. Condensation rates, including supersaturation and nonequilibrium effects, have been calculated by P. Bernhardt.¹³ According to Bernhardt's calculations, the ice crystals grow to radial dimensions of about 0.1 μm .

A large ice cloud was observed on the occasion of the translunar injection of Apollo-8 from its temporary parking orbit at 185-km altitude. The ice cloud was photographed in morning twilight from Mt. Haleakala, HI, where it appeared in reflected sunlight as an object as bright as the moon. From the observed characteristics of the scattered light, it was inferred that the particle radii were smaller than 0.08 μm .¹⁵

In pre-event planning of the LASL-Sandia Lagopedo experiments (high-explosive detonations in the F-layer, September 1977), we predicted a similar ice cloud. The ice cloud was indeed observed, and spectra of the scattered sunlight were recorded.¹⁶ From these spectra, together with color photographs, we have tentatively deduced particle radii. They appear to be in the Rayleigh limit of 0.1 μm or smaller.

Evaporation rates of small ice crystals in the near-vacuum of space are controlled by the rates of absorption and emission of radiation, as well as the rate of evaporative cooling. There are two distinct radiative absorption (heating) terms, one due to sunlight, and the other due to earthshine radiation in the infrared. Both are important, although the tiny ice crystals are nearly transparent at all wavelengths. Also im-

portant is radiative cooling by emission of infrared radiation.

Since the particles are optically thin at all wavelengths, the fraction of the radiation incident on the particle that it absorbs is $4/3 \bar{\kappa} a$, where $\bar{\kappa}$ is the spectrally weighted average absorption coefficient and a is the particle radius (assumed spherical). The average κ for ice over the solar spectrum is $\bar{\kappa}_{\text{sun}} = 78 \text{ cm}^{-1}$, as calculated by Bernhardt¹³ from the data of Irvine and Pollack.²² For the earthshine spectrum, which we take to be a 220-K Planckian, the weighted average κ is $\bar{\kappa}_{\text{earthsh}} = 225 \text{ cm}^{-1}$. (We choose 220 K because earthshine radiation in the wavelengths of water absorption bands are effectively absorbed in the troposphere. The emergent earthshine radiation in these bands, therefore, arises from near the tropopause, where the temperature is about 220 K). For the infrared emission spectrum of the ice crystals themselves, the weighted average κ is $\bar{\kappa}_{\text{emission}} = 500 \text{ cm}^{-1}$. Here the spectrum was taken to be a 160-K Planckian, since we find that the particle temperatures tend to stabilize at 160 K.

The evaporative loss rate of molecules from a spherical particle in vacuo is²³ $\dot{N} = -\pi a^2 \bar{c} p/kT$, where a is the particle radius, $\bar{c}$ the thermal speed, p the vapor pressure, and k is Boltzmann's constant. The thermal speed is $\bar{c} = (8RT/\pi m)^{1/2}$, where m is the molecular weight. The vapor pressure, including surface tension or curvature effects, is given by

$$p = p_0 \exp \left[-\frac{\lambda}{R} \left(\frac{1}{T} - \frac{1}{T_0} \right) \right] \exp \left(\frac{2\gamma m}{\rho a R T} \right).$$

Here, λ is the heat of vaporization, R the gas constant, γ the surface tension, and ρ the mass density. For ice at a temperature $T_0 = 175 \text{ K}$, the vapor pressure is $p_0 = .01 \text{ dyn/cm}^2$ (for large or infinite radii), and $\lambda/R = 6174 \text{ K}$. The second exponential term embodies the surface curvature effects. The surface tension, γ , is 77 dyn/cm, and it follows that the curvature term is effectively 1 for radii $a \geq 0.02 \mu m$.

In the equation for $\dot{N}$, we have ignored the so-called "evaporation coefficient," E , which is usually found to be 1.

Having $\dot{N}$, we can calculate the evaporative energy loss rate, which is $\lambda \dot{N}/A$, where A is Avogadro's number.

Combining these terms, we find that the particle heating/cooling rate is given by

$$\frac{dT}{dt} = \frac{1}{\rho C} \left[\bar{\kappa}_{\text{sun}} F_{\text{sun}} + 2\bar{\kappa}_{\text{earthsh}} \sigma T_{\text{earthsh}}^4 - 4\bar{\kappa}_{\text{emission}} \sigma T^4 - \frac{3}{4} \lambda \left(\frac{8}{\pi m R} \right)^{1/2} \frac{p}{T^{1/2}} \right],$$

where F_{sun} is the solar constant, 1.39×10^6 erg/cm²s, σ is the Stefan-Boltzmann constant, $T_{\text{earthsh}} = 220$ K, and C is the specific heat of ice.

The rate of change of the particle radius due to evaporation is

$$\frac{da}{dt} = -\frac{1}{4n} \left(\frac{8m}{\pi R} \right)^{1/2} \frac{p}{T^{1/2}}.$$

The behavior of these equations is such that, for a given value of a , the temperature of the particle rises or settles rapidly to a quasisteady level such that $dT/dt \approx 0$. For an 0.1- μ m particle, this temperature is 160 K. The corresponding vapor pressure is 7.5×10^{-4} dyn/cm² and the radius decreases at the rate of 1.1×10^{-8} cm/s. At this rate, the particle has an evaporative e-folding lifetime of about 900 s. Particles with smaller radii equilibrate at lower temperatures and evaporate more slowly, with similar e-folding lifetimes.

The ice particles drop rapidly, though impeded by collisions with the background air. The collisional drag force, calculated from kinetic theory, is $F_{\text{drag}} = 4\pi a^2 (8mkT/\pi)^{1/2} n v_d$. Here m is the average mass of the air molecules, n is the molecular number density, T is the air temperature, and v_d is the falling velocity of the particle. Starting from rest, a particle accelerates until it reaches a terminal velocity

$$v_{\text{df}} = -\frac{\rho a g}{3n} \left(\frac{\pi}{8mkT} \right)^{1/2},$$

which, of course, decreases with increasing air density. Values of the terminal velocities of 0.1- and 0.03- μ m particles at several ionospheric

TABLE C-1

z (km)	n (cm ⁻³)	v_{df} (km/s) for $a =$	
		0.1 μ m	0.03 μ m
450	2.0×10^8	39.9	12.0
400	3.5×10^8	21.6	6.5
350	6.5×10^8	11.6	3.5
300	1.3×10^9	5.8	1.7
250	3.4×10^9	2.0	0.60
200	9.1×10^9	0.74	0.22
175	1.6×10^{10}	0.46	0.14
150	3.6×10^{10}	0.22	0.066
125	2.7×10^{11}	0.045	0.013
100	1.0×10^{13}	0.0017	0.00005

altitudes (for daytime temperatures and densities) are shown in Table C-1.

A particle starting in the F-layer will spend some time in accelerating free fall before it reaches the local terminal velocity. As the particle falls, it evaporates gradually; thus its radius decreases, as does its falling velocity. From the equations above, it is simple to compute the fraction of water evaporated from a particle per unit altitude along its descent. Particles with initial radii of .03- to 0.1- μ m, starting in the F2 region, will evaporate a significant fraction of their mass during their accelerating free-fall phase near the starting point. Most of the remaining mass will evaporate near the terminal altitude, i.e., between about 130 and 170 km. Figure 10a is a graph of altitude vs time for ice particles of 0.1- μ m initial radius, starting at 300-km altitude. Figure 10b is a plot of mass fraction evaporated vs altitude. Evaporation is essentially complete within ten minutes.

We have automated these algorithms in the two-dimensional ionospheric model so that the water component of the exhaust gases is redistributed in altitude at the start of the computation, given an assumed initial size for the particles.

We have recently come upon a paper by W. K. McGregor,²⁴ which suggests that our treatment, in this Appendix, of the radiation emitted and absorbed by small particles is incorrect. McGregor states that emission and absorption coefficients are both zero for wavelengths greater than $\sqrt{2\pi}$

Fig. 10. (a) Altitude vs time for an ice crystal of .03- μ m initial radius falling under gravity while evaporating. (b) The corresponding curve of fraction evaporated per kilometer vs altitude.

times the particle diameter. If his arguments are correct, then the evaporation rates that we have calculated are too large, and they must be controlled by collisional, rather than radiative, energy transfer rates. Then the particles must survive longer and fall further. We are currently studying this matter.

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