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ON THE INFLUX OF SMALL COMETS INTO THE EARTH'S UPPER ATMOSPHERE
II. INTERPRETATION

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Abstract. Large, transient decreases of atmospheric dayglow intensities at ultraviolet wavelengths, primarily the atomic oxygen emissions at 130.4 nm, are interpreted in terms of an influx of heretofore undetected comet-like objects. The primary composition of these comet-like objects is water snow or clathrate in the form of a fluffy aggregate. These small comets are covered with a dust mantle and the tensile stress at fracture is estimated to be ~ 0.1 dyne/cm^2. The water molecules that form the absorbing blanket for ultraviolet emissions arrive at the top of the earth's atmosphere as a piston of gas with bulk speed $\lesssim$ 20 km/sec. The mass of each of these comet-like objects is ~ 10^8 gm, or ~ 100 tons. The global influx rate is ~ 20 comets per minute. The global mass accretion rate by the earth's atmosphere is ~ 10^{12} kg/year, and sufficient to replace the atmospheric mass in ~ 5 × 10^6 years. The earth and the other bodies in the solar system would be thus more strongly coupled to cometary matter than presently thought.

Introduction

The findings of decreases of ultraviolet dayglow intensities are reported in the companion paper (Frank et al., 1986a). In overview these objects are detected as dark spots, or holes, on a radiant screen of ultraviolet atmospheric dayglow. The duration of these dark spots is ~ several minutes. Because the area of an individual dark spot is large, estimated to be ~ 2,000 km^2, the mass of the occluding material must be correspondingly large. We present below our interpretation of this phenomenon.

Interpretation

The diurnal variations of the rates of atmospheric holes link this phenomenon to the influx of extraterrestrial objects. The severe decrease of ultraviolet emissions over wavelengths ~ 120 to 170 nm establishes that a blanket of absorbing molecules must momentarily exist between the spacecraft position and altitudes for significant dayglow emissions in this wavelength range. An approximate altitude for this blanket of gas can be gained with the calculations of Meier and Lee (1982) for the vertical intensities of the optically thick OI 130.4-nm emissions as a function of altitude. The present observations of intensity decreases at 130.4 nm to ~ 5% to 20% of full values place the absorbing cloud initially above the altitude range of ~ 250 to 350 km. The maximum values for volume excitation of N_2(LBH) are located at significantly lesser altitudes, ~ 150 km (Meier et al., 1980).

We find three initially plausible explanations for the transient appearance of an absorbing molecular cloud at ~ 300 km altitude: (1) the influx of molecules capable of catalytically forcing the recombination of the dominant oxygen atoms to form O_2, (2) the thermal upwelling of O_2 from lower altitudes, ~ 100 km, to 300 km by the heat dissipated by a chondritic or metallic meteor, and (3) the injection of a cloud of H_2O molecules from a comet-like object. For (3) we will show that the momentum of the absorbing cloud will also drive the ambient OI to lower altitudes. Both O_2 and H_2O molecules possess a substantial ultraviolet cross-section over the required wavelength range ~ 120 to 170 nm, although the O_2 absorption cross-section for Lyα is relatively small.

A catalytic reaction for forming O_2 from the dominant neutral species OI at 300 km, (1) above, is capable of providing the absorbing blanket with considerably lesser mass influx than the remaining two possibilities. However, no reasonable catalyst is currently identified. The large mean free paths for collisions, ~ 10 km, and the low thermal speeds, ~ 1 km/sec, further discredit the possibility of an effective catalytic reaction.

A lower limit for the meteoric mass required to heat a sufficient amount of O_2 at ~ 100 km for upwelling to 300 km, (2) above, can be obtained with the oversimplified assumptions that the meteor's kinetic energy is dissipated entirely into O_2 heating at 100 km and that the hot cloud of O_2 molecules subsequently rises to 300 km. The total absorption cross-section at 130.4 nm for an O_2 molecule is ~ 5 × 10^{-19} cm^2 (Watanabe et al., 1953). In order to provide one optical depth over an area of 2,000 km^2 a total of ~ 4 × 10^{31} O_2 molecules is required. If the thermal upwelling is associated with an increase of O_2 temperature by ~ 100 K, then the corresponding meteoric mass is ~ 70 kg with initial speed of 40 km/sec. The observed occurrence frequency for the atmospheric holes in the dayside atmosphere is ~ 10/min, a frequency that is greater than that reported by Nilsson and Southworth (1967) for meteors of the required masses by factors ~ 10^4 to 10^5. In addition it is also not clear that the temporal evolution of such upwelling of O_2 from ~ 100 km to 300 km is consistent with that observed for the decreases in dayglow intensities. For these reasons the above interpretation in terms of the infall of rocky or metallic meteors is considered implausible.

Finally we are left with the injection of an absorbing gas cloud from the infall of a comet-like object, (3) above. An abundant molecule in cometary material with a relatively large absorption cross-section at ultraviolet wavelengths is H_2O. The total absorption cross-section varies from ~ 1 to 8 x 10^{-18} cm^2 over the wavelength

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range 120 to 170 nm (Watanabe and Zelikoff, 1953). Because the total absorption cross-section at 130.4 nm for a H_2O molecule is ~ 5 × 10^{-18} cm^2 one optical depth over an area of ~ 2,000 km^2 corresponds to ~ 4 × 10^{30} molecules, or ~ 10^8 gm. It is clear that an object with mass ~ 10^8 gm will pass through the earth's upper atmosphere and dissipate at altitudes < 100 km if it retains a relatively compact form, e.g., a diameter of ~ 12 m for a density of 0.1 gm/cm^3. However a variety of disruptive forces await a fluffy aggregate of water snow and dust as it approaches the earth's upper atmosphere. Three identifiable disruptive forces are (1) tidal, (2) electrostatic (cf. Fechtig et al., 1979) and (3) ram forces. For this analysis we are assuming that the density of the water snow is 0.1 gm/cm^3 and the other properties noted above. In lieu of any other benchmark for the binding forces within cometary material, we shall use the self-gravitational pressure, ~ 5 × 10^{-4} $dynes/cm^2$, as a reference value for the disruptive forces.

Tidal disruption forces increase rapidly and are proportional to r^{-3}, where r is the radial distance to earth's center. The distance R_g at which the force per unit area in the center of the comet becomes equal to the central gravitational pressure is given by the approximate relationship

$$R_g \simeq 2 \, (\rho_1/\rho_2)^{1/3} \, R_E$$

where ρ_1 and ρ_2 are the mean densities of the earth and comet, respectively, and R_E = 1 Earth radius. For ρ_1 = 5.5 gm/cm^3 and ρ_2 = 0.1 gm/cm^3, R_g = 7.6 R_E. The atmospheric ram pressure equals the comet gravitational pressure at an altitude of ~ 600 km above the earth's surface and a speed of 20 km/sec.

The speeds of the small comets at impact with the earth's upper atmosphere are deduced to be $\lesssim$ 20 km/sec for the following reasons. An accurate assessment of the speed is not possible with our present set of observations. The ionization potentials for H_2O, O and OH are in the range 12.5 to 13.5 eV. For a H_2O molecule with a speed 40 km/sec and impacting an atmospheric OI atom, the center of mass energy available for ionization is ~ 70 eV. Thus each water molecule can produce ionization with its first impact with an atmospheric OI atom. A crude estimate of the intensities of OI 630.0 nm can be obtained as follows. Assume that the cloud of 4 × 10^{30} H_2O molecules comes to rest with a small fraction, 10^{-2}, of the total OI in the excited state $O^*(^1D)$ via plasma recombinations. The lifetime for this excited state is ~ 100 seconds. On the other hand, water molecules efficiently quench the 630.0-nm emissions by collisional deexcitation at the rate γ [A-B], where $\gamma \simeq 5 \times 10^{-11}$ cm^3/sec and [A-B] is the molecular concentration (Roble et al., 1976). For H_2O densities in the water vapor cloud of ~ 6 × 10^{10} cm^{-3}, the lifetime of O^* against quenching is ~ 0.3 second. Then during the initial interval of ~ 0.3 second, the total number of photons at 630.0 nm is ~ 10^{-2} × (4 × 10^{30}) × (0.3/100) = 1.2 × 10^{26}. If the area of this cloud is ~ 2000 km^2, then its apparent brightness is 2 × 10^{13} $photons/cm^2$-sec, or 2 × 10^7 rayleighs. This value is a factor $\gtrsim 10^4$ greater than the visual threshold. No such phenomenon is observed in our atmosphere. Thus the speed of entry into the atmosphere must not be much greater than that corresponding to the ionization potentials, ~ 16 km/sec. Because quenching is significant and ionization cross-sections are relatively low just above the ionization potential we adopt a value of ~ 20 km/sec as an upper limit to the gas bulk speed. The minimum speed of an object for impact with the earth's atmosphere from a position outside the influence of the planetary gravitational field is 11.2 km/sec, i.e., the escape velocity. Because the energies for the H-OH and O-H bonds are approximately 5.0 and 4.3 eV, respectively, dissociation is expected to accompany the impact of these small comets with the upper atmosphere. However the H_2O and its products H, OH, and O from the comet are mixed with the same constituents of the lower thermosphere and upper mesosphere. This depth of penetration into the upper atmosphere is estimated in a following analysis. In summary these small comets traverse the earth's atmosphere with relatively little ionization along their paths.

The impact speeds of the small comets with the earth's atmosphere as deduced above imply important features relative to their orbital motion and interaction with other solar system bodies. In order to maintain an atmospheric impact speed of $\lesssim$ 20 km/sec for an ensemble of small comets in earth-crossing orbits with perihelia and aphelia ranging from the orbit of Venus to beyond Pluto's orbit, the comet motion must be direct, or prograde, and generally confined to the ecliptic plane. The interaction of these small comets with other bodies in the solar system will also depend upon the acquired gravitational energy. The impact speed at the Moon is ~ 10 km/sec because the escape speed is only ~ 2.4 km/sec. Little impact ionization and no intense light flashes are expected. Ionization is expected in the atmospheres of Jupiter, Saturn and Uranus because the impact speeds must exceed ~ 60, 36 and 22 km/sec, respectively. The effects of impacts on their satellites depend on position in the gravitational well of the planet.

The altitude for disintegration of the comet, and its tensile strength, can be estimated from the size of the atmospheric hole. After fragmentation the total vaporization rate increases rapidly due to increasing total fragment area with freshly exposed surfaces. The mean speeds of the vaporizing molecules are ~ 0.3 km/sec at 200 K (Delsemme, 1982). If the speed of the comet is 20 km/sec and the radius of the atmospheric hole is 25 km, then the altitude for catastrophic break-up is ~ (25 km)/(0.3 km/sec) × 20 km/sec, or ~ 1700 km, and in coarse agreement with the off-limb Lyα observations. Tidal stress at this altitude is ~ 0.1 $dyne/cm^2$, and provides an estimate of the tensile strength at fracture for the small comet. The tensile strength of water snow at the earth's surface is ~ 5 × 10^4 $dynes/cm^2$.

A minimum altitude for atmospheric penetration of ~ 125 km can be obtained by equating the column density through the cloud center with the atmospheric column density. Thus in consideration of the momentum of the cloud, the H_2O molecules should not directly penetrate below ~ 100 km. Thermospheric molecules and atoms are similarly driven to lower altitudes by collisions with the piston of H_2O molecules. Subsequent atmospheric diffusion and advection can convey the cometary molecules to lower altitudes.

The recovery of dayglow intensities appears to be consistent with the diffusion of OI into the atmospheric hole produced by the piston of incoming H_2O molecules. The 1/e recovery time for intensities can be estimated as R^2/VL where R is the radius of the hole, V is the mean molecular speed for ambient OI, and L is the mean free path. For $L \approx 10$ km (rough estimate), V = 1 km/sec and R = 25 km, this recovery time is ~ 1 minute. These recovery times are in agreement with observed values (Frank et al., 1986a).

Discussion

The most consistent explanation for the occurrence of atmospheric holes as seen in images of the ultraviolet dayglow emissions at ~ 120 to 170 nm in the earth's upper atmosphere is the influx of small comet-like objects. The mass of each of these small comets is ~10^8 gm, or ~ 100 tons. This mass corresponds to the number of H_2O molecules required to provide an absorbing blanket of one optical depth with area ~ 2,000 km^2. The total content of each small comet is ~ 4 × 10^{30} molecules. In order to provide the required piston of gas at the top of the earth's atmosphere, a fluffy water snow aggregate similar in nature to that proposed by Whipple (1950) is required. The average occurrence rate over the dayside atmosphere is approximately 10 events per minute. With the assumption that the dark side impacts are with similar frequency, the average global influx rate is about 20 events per minute.

If the density of the H_2O snow in this small comet-like object is assumed to be 0.1 gm/cm^3 and the total content is 4 × 10^{30} H_2O molecules, then the diameter is ~ 12 m. The lifetime at 1 A.U. for these small comets can be estimated from the vaporization curves corresponding to the light curves for comet P/Encke, for example (Delsemme, 1982). The rate of loss of H_2O molecules is ~ $10^{16}/cm^2$-sec. For these small comets the corresponding lifetime is ~ 30 years. The vaporization rate for water snow is negligible beyond heliocentric radial distances of 2.5 A.U. Such a lifetime is consistent with a source due to fragments from comets, material from the Oort cloud (Oort, 1950), and/or a galactic stream of such objects passing through the solar system. However for the number density of this comet swarm, and for a vaporization loss of $10^{16}/cm^2$-sec, mass loss and subsequent ion pick-up inside a heliocentric radial distance of 1 A.U. corresponds to an unrealistic increase in solar wind densities of ~ 100 cm^{-3}. Thus the vaporization rate must be much less than that cited above and is presumably suppressed with dust mantles encompassing the small comets. A small density of cometary pick-up ions may be found in the solar wind. These comets are long-lived.

The atmospheric holes and their startling implications for the earth, and other bodies in the solar system, have been extensively studied since their first unexpected sighting in late 1981. For an average global rate of incidence into the upper atmosphere of 20 comets per minute and an average size of 4 × 10^{30} molecules per comet, the equivalent rate of increase in column density as averaged over the entire surface of the earth is ~ 3 × 10^{11} molecules/cm^2-sec. These estimates are accurate only to within a factor of ~ 5, due to uncertainties in determining the volume of the absorbing H_2O cloud. This accretion rate corresponds to a total mass influx into the atmosphere ~ 4 × 10^4 kg/sec, or ~ 10^{12} kg/year. For comparison it is noted here that the mass of meteoric material swept up by the earth is ~ 10^5 to 10^7 kg/year (Hughes, 1978), the masses of comets are in the range of ~ 10^{10} to 10^{16} kg (cf. Donn and Rahe, 1982), and the rate of H_2O loss by an individual comet at 1 A.U. is in the range ~ 2 × 10^2 to 1.5 × 10^4 kg/sec (cf. Ney, 1982). The total mass of the earth's atmosphere is ~ 5 × 10^{18} kg. Thus an equivalent atmospheric mass from the influx of presently reported objects is acquired every 5 million years if the current rate is sustained over this period.

The averaged global cometary influx of 3 × 10^{11} H_2O molecules/cm^2-sec exceeds by at least three orders of magnitude the corresponding escape rate of exospheric atomic hydrogen (Hunten and Donahue, 1976). The rate of loss is regulated by the total amount of H in the lower thermosphere and subsequent diffusion at higher altitudes below the exospheric base. The boundary between eddy transport of gases and the higher region of diffusive equilibrium, i.e., the homopause, is located at altitudes ~ 100 to 120 km in the lower thermosphere. Diffusion modeling of the exospheric H escape by Hunten and Donahue (1976) is found to be in good agreement with observations of the geocorona. The primary source of H is assumed to be H_2O via vertical transport from the stratosphere, and ultimately from the earth's surface. No other sources or sinks of total H are employed in the above formulation.

On the other hand, the piston of cometary molecules, primarily H_2O and its dissociation products, reaches altitudes estimated to be ~ 100 to 125 km before its momentum is expended. Indirect observations of the mixing ratio of H_2O at these altitudes indicate values of 1 to 10 ppmv (Solomon et al., 1982). For a typical vertical eddy diffusion coefficient of ~ 10^6 cm^2/sec and for a transport scale length of 10 km, it is clear that the corresponding diffusion speed of ~ 1 cm/sec is not consistent with an average global accretion rate of 3 × 10^{11} H_2O molecules/cm^2-sec. This transport by molecular and eddy diffusion can support only a net vertical flux of the order of ~ 3 × $10^8/cm^2$-sec, a value consistent with geocoronal observations. A possible resolution of this dilemma may lie with the existence of significant downward advection at these altitudes. If the mixing ratio of H_2O and its impact and photolytic dissociation products is 30 ppmv at 90 km, then an average downward transport of ~ 2 m/s is required over one hemisphere, for example. Mean meridional speeds are ~ 10-30 m/s at these altitudes. If the above vertical motion is present then the mesosphere and upper stratosphere are expected to be wetter over the winter hemisphere relative to the summer hemisphere for a circulation pattern similar to that for a Hadley cell. This circulation pattern may be driven in part by the energy deposited in the lower thermosphere by the comets, ~ 10 ergs/cm^2-sec. Considerable spatial and temporal variabilities will reflect those of the source. Because the H mixing ratio above the homopause is only ~ 30 ppmv the exospheric losses remain ~ 3 × $10^8/cm^2$-sec. Inferred H_2O densities in the lower thermosphere suggest the presence of a sporadic extraterrestrial source (Solomon et al., 1982).

The presence of these small comets may be relevant to, for examples, the injection of water vapor into the Venusian and Martian atmospheres, the heating of the thermospheres of the cold outer planets Jupiter, Saturn and Uranus, the accretion of water ice on outer planets' satellites, the deposition of interplanetary dust, and the formation of spokes in Saturn's B Ring. It is noted that an ice epoch for the earth occurs approximately every 250 million years and that the solar system drifts through the spiral arms of the Milky Way on a similar time scale (Friedman, 1986). Since one optical depth for these small comets is ~ 30 parsecs, it appears unlikely that their major source is galactic unless there is a local stream of such objects in the vicinity of the solar system. The origins of these objects may be an Oort cloud at the rim of the solar system. If this cometary cloud is perturbed by passage through the galactic arms then the ice epochs may well be attributed to atmospheric modification from enhanced impact rates. We are currently in the Cenozoic ice age (cf. John, 1979). Total accretion of water by the earth during these ice ages would be similar to the current oceanic mass if the present cometary mass influx is typical for previous ice ages. Fluctuations in the rate of mass accretion may be large enough for rapid climatic fluctuations sufficiently severe to account for the massive extinction of species in lieu of a catastrophic infall of a single large object (Alvarez et al., 1982).

The number density of these small comets in the vicinity of earth is ~ 10^{-20} comet/m^3, including a factor of ~ 2 for gravitational focusing. If these comets are distributed with constant number density in a disk in the ecliptic plane, and centered on the sun, with thickness 1 A.U. and radius 1000 A.U. the total number of comets in this volume is ~ 10^{20}. The corresponding mass is ~ 10^{25} kg, somewhat larger than the earth's mass.

For earth the kinetic energy of a single small comet is large, ~ 2×10^{20} ergs and equivalent to ~ 5 kilotons of TNT. At Jupiter's atmosphere, this kinetic energy is greater by a factor of ~ 10. However, due to weak tensile strength and to disruption by tidal and other forces prior to impact into the atmospheres of planets or the surface of the Moon, for examples, the overall effect is relatively benign. The occasional bursts of gases observed on the Moon may be the direct signature of the impact of these small comets rather than impulsive ejection of gases from the Moon's interior (Friesen, 1975; Freeman, 1973). Perturbations of the interplanetary magnetic field are also interpreted as the possible signatures of otherwise undetected comets (Russell et al., 1984). Although the vaporization rates of snows of such gases as nitrogen and methane are sufficiently high that their lifetimes as small (~ 10-m diameter) bodies are inadequate to reach 1 A.U. from positions in the outer solar system, these gases could reach the earth's atmosphere if buried deeply within the water snow, perhaps as clathrates (Delsemme, 1982). Furthermore aerosols, metallic ions and organic molecules can be similarly injected into the lower thermosphere and upper mesosphere.

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