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 barotrope 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 dynes/cm². 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 < 20 km/sec. The mass of each of these comet-like objects is ~10⁸ gm, or ~100 tons. The global influx rate is ~20 comets per minute. The global mass accretion rate by the earth's atmosphere is 10¹² kg/year, and sufficient to replace the atmospheric mass in ~5 x 10⁹ years. The earth and the other bodies in the solar system would 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., 1985a). 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 km², 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 Lao (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 ~2% 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 N₂(L[1]) are located at significantly lesser altitudes, ~130 km (Meier et al., 1980).

We find three primary 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 O₂, (2) the thermal upwelling of O₂ 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 H₂O 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 O₂ and H₂O molecules possess a substantial ultraviolet cross-section over the required wavelength range ~120 to 170 nm, although the O₂ absorption cross-section for Lyα is relatively small. A catalytic reaction for forming O₂ 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 O₂ 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 O₂ heating at 100 km and that the hot cloud of O₂ molecules subsequently rises to 300 km. The total absorption cross-section at 130.4 nm for an O₂ molecule is ~5 x 10⁻¹⁰ cm² (Watanabe et al., 1953). In order to provide one optical depth over an area of 2,000 km² a total of ~4 x 10¹¹ O₂ molecules is required. If the thermal upwelling is associated with an increase of O₂ temperature by ~100 K, then the corresponding meteoric mass is ~70 kg with initial speed of 60 km/sec. The observed occurrence frequency for the atmospheric holes in the daytime 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 ~10⁻³ to 10⁻⁵. In addition it is also not clear that the temporal evolution of such upwelling of O₂ 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 impact of rocky or metallic meteorites 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 H₂O. The total absorption cross-section varies from ~1 to 8 x 10⁻¹⁸ cm² over the wavelength

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range 120 to 170 km (Watanabe and Selkirk, 1953). Because the total absorption cross-section at 130.4 nm for a H₂O molecule is $\sim 5 \times 10^{-18}$ cm², one optical depth over an area of $\sim 2,000$ km² corresponds to $\sim 4 \times 10^{10}$ molecules, or $\sim 10^5$. It is clear that an object with mass $\sim 10^5$ gm will pass through the earth's upper atmosphere and dissipate at altitudes $\lesssim 100$ km if it retains a relatively compact form, e.g., a diameter of $\sim 12$ m for a density of 0.1 gm/cm³. However, a variety of disruptive forces wear a fluffy aggregate of watersnow and dust as it approaches the earth's upper atmosphere. Three identifiable disruptive forces are (1) tidal, (2) electrostatic (cf. Rechting et al., 1979) and (3) ram forces. For this analysis we are assuming that the density of the water snow is 0.1 gm/cm³ and the other properties noted above. In lieu of any other benchmark for the binding forces within cometary matter, we shall use the self-gravitational pressure, $\sim 5 \times 10^{-14}$ dynes/cm², 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 $R_e$ 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

$$R_e \approx 2 \left(\frac{\rho_1}{\rho_2}\right)^{1/3} R_e$$

where $\rho_1$ and $\rho_2$ are the mean densities of the earth and comet, respectively, and $R_e = 1$ earth radius. For $\rho_1 = 3.55$ gm/cm³ and $\rho_2 = 0.1$ gm/cm³, $R_e \approx 7.6$ km. The atmospheric ram pressure equals the comet gravitational pressure at an altitude of $\approx \frac{1}{2}$ of 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 H₂O, N, and OH are in the range 12.5 to 13.3 eV. For a H₂O molecule with a speed 40 km/sec and impacting an atmospheric OI atom, the center of mass energy available for ionization is $\approx 70$ 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 $4 \times 10^{10}$ H₂O molecules comes to rest with a small fraction, $10^{-7}$, of the total OI in the excited state $\text{O}^{(1)}$ via plasma recombinations. The lifetime for this excited state is $\approx 100$ seconds. On the other hand, water molecules efficiently quench the 630.0 nm emissions by collisional deactivation at the rate $9 \times 10^{-6}$ s⁻¹, where $n = \approx 5 \times 10^{11}$ cm⁻³/sec and [A-B] is the molecular concentration (Kolbe et al., 1976). For H₂O densities in the water vapor cloud of $6 \times 10^{10}$ cm⁻³, the lifetime of $\text{O}^{(1)}$ against quenching is $\approx 0.3$ second. Then during the initial interval of $\approx 0.3$ second, the total number of photons at 630.0 nm is $\approx 10^{-2} \times (4 \times 10^{10}) \times (1.3/100) \times 1.2 \times 10^{26}$. If the area of this cloud is $\approx 2000$ km², then its apparent brightness is $2 \times 10^{12}$ photons/cm²-s, or $2 \times 10^{17}$ lightyears. This value is a factor $2 \times 10^8$ 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, $\approx 16$ km/sec. Because quenching is significant and ionization cross-sections are relatively low just above the ionization potentials we adopt a value of $\approx 20$ 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 fields is $\approx 11.2$ km/sec, i.e., the escape velocity. Because the energies for the H-0H 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 H₂O and its products N, OH, and O from the comet are mixed with the same constituents of the lower thermosphere and upper atmosphere. The 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 $\approx 20$ km/sec for an ensemble of small comets in earth-crossing orbits with perihelia between 0.16 and 1.34 AU 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 earth's surface is $\approx 20$ km/sec, causing the escape speed is only $\approx 2.4$ 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 $\approx 60$, $36$, and $32$ 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 $\approx 0.3$ km/sec at 200 K (Heisemiller, 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 breakup is $\approx (25$ km)/$(0.3$ km/sec) $\approx 20$ km/sec, or $\approx 1700$ km, and in coarse agreement with the off-limit fly observations. Tidal stress at this altitude is $\approx 5 \times 10^3$ dynes/cm² 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 $\approx 5 \times 10^4$ dynes/cm². A minimum altitude for atmospheric penetration of $\approx 125$ 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 H₂O molecules should not directly penetrate below $\approx 100$ km. Thermospheric molecules and atoms are similarly driven to lower altitudes by collisions with the piston of H₂O molecules. Subsequent atmospheric diffusion and advection can convey the cometary molecules to lower altitudes. The recovery of daylight intensities appears to be consistent with the diffusion of OI into the atmospheric hole produced by the piston of incom-
ing H₂O molecules. The 1/e recovery time for inten-
sities can be estimated as 47/V where R is the
radius of the hole, V is the mean molecular
speed for ambient OI, and I is the mean free
path. For 1.10 km (rough estimate), V = 1 km/sec
and R = 25 km, this recovery time is 1 minute.
These recovery times are in agreement with ob-
served values (Frank et al., 1986a).

Discussion

The most consistent explanation for the occur-
rence 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 ~10¹⁵ g, or ~100 tons.
This mass corresponds to the number of H₂O mole-
cules required to provide an absorbing blanket
of one optical depth with area ~ 2,000 km². The to-
tal content of each small comet is ~ 4 × 10¹⁰
molecules. In order to provide the required pis-
ton of gas at the top of the earth's atmosphere, a
fluffy water snow aggregate exists in nature to
that proposed by Whipple (1950) is required.
The average occurrence rate over the dayside at-
mosphere is approximately 10 events per minute.
With the assumption that the dark comet nuclei
are with similar frequency, the average global
influx rate is about 20 events per minute.

If the density of the H₂O snow in a small comet-
like object is assumed to be 0.1 gm/cm³ and
the total content is 4 × 10¹⁰ H₂O 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/Shoemaker, for example (Belshe,
1982). The rate of loss of H₂O molecules is
~ 10¹⁰ cm²/sec. For these small comets the cor-
responding lifetime is ~ 30 years. The vaporiza-
tion 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 frag-
ments from comets, material from the Oort cloud
(U rt, 1950), and/or a galactic stream of such
objects passing through the solar system. Howev-
er for the number density of this comet swarm,
and for a vaporization loss of 10¹⁰ cm²/sec, mass
loss and subsequent ion pick-up inside a helio- 
centric 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-
u p ions may be found in the solar wind. These
comets are long-lived.
The atmospheric holes and their startling im-
plications for the earth, and other bodies in the
solar system, have been extensively considered
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 × 10¹⁰ molecules per comet, the
equivalent rate of increase in column density as
averaged over the entire surface of the earth is
~ 3 × 10¹¹ 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 H₂O cloud. This absorption rate corre-
sponds to a total mass influx into the atmosphere
~ 4 × 10⁴ kg/sec, or ~ 10¹² kg/year. For compar-
ison it is noted here that the mass of meteoric
material swept up by the earth is ~ 10⁵ to 10⁶
kg/year (Hughes, 1978), the masses of comets are
in the range of ~ 10¹⁵ to 10¹⁶ kg (cf. Donn and
Kahn, 1982), and the rate of H₂O loss by an in-
dividual comet at 1 A.U. is in the range ~ 2 ×
10⁴ to 1.5 × 10⁵ kg/sec (cf. Ney, 1982). The to-
tal mass of the earth's atmosphere is ~ 5 × 10¹⁸
kg. Thus an equivalent atmospheric mass from the
influx of presently reported objects is acquired
every 5 million years if the current rate is sus-
tained over this period.
The averaged global cometary influx of 3 ×
10¹¹ H₂O molecules cm⁻²/sec exceeds by at least
three orders of magnitude the corresponding es-
cape rate of exospheric atomic hydrogen (Hunten
and Donahue, 1976). The rate of loss is regulat-
ed by the total amount of H in the lower thermo-
sphere and subsequent diffusion at higher alti-
itudes below the exospheric base. The boundary
between eddy transport of gases and the higher
region of diffusive equilibrium, i.e., the homo-
opause, 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 ob-
servations of the geocorona. The primary source
of H is assumed to be H₂O 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 pion of cometary mo-
lecules, primarily H₂O and its dissociation prod-
ucts, reaches altitudes estimated to be ~ 100 to
125 km before its momentum is expended. Indirect
observations of the mixing ratio of H₂O at these
altitudes indicate values of 1 to 10 ppmv (Solo-
mon et al., 1982). For a typical vertical eddy
diffusion coefficient of ~ 10⁵ cm²/sec and for a
transport scale length of 10 km, it is clear that
the corresponding diffusion speed of ~ 1 cm/sec
in not consistent with an average global accre-
tion rate of 3 × 10¹¹ H₂O molecules cm⁻²/sec. This
transport by molecular and eddy diffusion can
support only a net vertical flux of the order of
~ 3 × 10⁸ cm⁻²/sec, a value consistent with geo-
coronal observations. A possible resolution of
this dilemma may lie with the existence of sig-
nificant downward advection at these altitudes.
If the mixing ratio of H₂O 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 pres-
ent then the mass of the upper thermosphere is
expected to be better over the winter hemi-
sphere relative to the summer hemisphere for a
circulation pattern similar to that of a Hadley cell.
This circulation pattern may be driven in part by
the energy deposited in the lower ther-
mosphere by the comets ~ 10 ergs/cm²/sec. Con-
siderable spatial and temporal variabilities will
reflect those of the source. Because the H mixing
ratio above the homopause is only ~ 30 ppmv the
exospheric density remains ~ 3 × 10¹⁰ cm⁻³. The
diffused H₂O densities in the lower thermosphere
suggest the presence of a sporadic extraterres-
tral source (Solomon et al., 1982).

The presence of these small comets may be rel-
vant to, for examples, the injection of water vapor
into the Venusian and Martian atmospheres, the
heating of the thermospheres of the cold out-
er planets Jupiter, Saturn and Uranus, the accre-
tion 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 end 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 ~ 2 x 10^10 comet/m^2, 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 AU and radius 1000 AU, the total number of comets in this volume is ~ 10^{20}. The corresponding mass available for rapid climatic fluctuations is ~ 0.5 x 10^17 kg, somewhat larger than the earth's mass.

For each the kinetic energy of a single small comet is large, ~ 2 x 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 example, 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 (~ 10^4 diameter) bodies are inadequate to reach 1 AU, from positions in the outer solar system, these gases could reach the earth's atmosphere if buried deep within the water snow, perhaps as clathrates (Delsemme, 1982). Furthermore, metallic ions and organic molecules can be similarly injected into the lower thermosphere and upper atmosphere.

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