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PHOTOMETRIC ANALYSIS OF A SPACE SHUTTLE WATER VENTING

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ABSTRACT

A photometric-photogrammetric analysis of intensified-video images from AMOS and onboard Shuttle Orbiter "*Discovery*" of a sunlit venting of supply water has shown that the 1½ mm-diameter liquid stream breaks up within ~1 m to form ice/snow particles of two characteristic sizes, much as was observed in earlier space-tank simulations. Discrete droplets produced by the flash evaporation are the principal feature in the photographs of the wake trail taken from the bay and crew cabin; these particles have an "average" diameter comparable with that of the initial continuous flow. Unresolved submicron ice droplets formed by recondensation when the evaporated water gas overexpands dominate the images of the ~2½ km of trail detectable by the groundbased tracking telescope-camera; these particles sublimate at rates that we modeled from the decrease in visible radiance of the trail by applying energy balance arguments for spherical Rayleigh-Mie scatterers/radiators in low earth orbit that undergo the (small) surface roughening seen in laboratory experiments. The angular spreads of the two types of ice particle are the same within observational error, and the kinetic energy imparted by the boiling-explosion of the superheated (in vacuum) quasi-cylindrical water stream is about an order of magnitude less than the injection energy.

INTRODUCTION

We present here a preliminary interpretation of a recent experiment conducted on Space Shuttle *Discovery* (mission STS 29-orbit 49, 16 Mar 1989) in which a stream of liquid supply water (1) was vented into space at twilight. The data consist of video images of the sunlight-scattering water/ice-particle cloud that formed, taken by visible light-sensitive intensified cameras both onboard the spacecraft and at the AMOS ground station near the trajectory's nadir. This experiment was undertaken to study the phenomenology of water columns injected into the low earth-orbital environment, and to provide information about the lifetime of ice particles that may recontact Space Shuttle several orbits later (2). The findings about the composition of the cloud have relevance to ionospheric plasma depletion experiments (3) and to the dynamics of the interaction of orbiting spacecraft with the environment (1).

EXPERIMENTAL

Pure and largely gas-free liquid water produced in the vehicle's fuel cells was forced out through a 0.14-cm diameter nozzle, which was heated to ~70° C to prevent its blockage by icing; 19.4 g/s was vented within a few degrees of the wake direction. The experiment was planned so that the spacecraft would be directly solar illuminated just before dawn, while the atmosphere below ~100 km altitude remained in the hard earth's shadow. *Discovery* was in a southwest-to-northeast circular orbit at 329 km that passed almost directly over AMOS (the Air Force Maui Optical Station), which is atop 3.0 km high Mt. Haleakala, HI (21° N - 204°E). The radiance distributions of the water trail were measured for about 2 min in three projections: to a closed circuit zoom television camera in the open bay just forward of the spacecraft's tail, 18 m from the nozzle; to a similar camera handheld to point out of a crew cabin window a few m forward of and above the nozzle; and to the ground station, where an ISIT low-light-level video camera with 55 cm-diameter objective lens, 0.4° by 0.3° field of view, and S-20 spectral response (FWHM 0.4-0.65 μm) precisely tracked the spacecraft. Examples of the imagery from the three intensified electronic cameras are in Figure 1.

Discovery came into direct sunlight at 62° elevation southwest of the ground station, and the water trail remained above background until it moved to about 5° in the northeast. The solar scatter angles, aspect angles to the

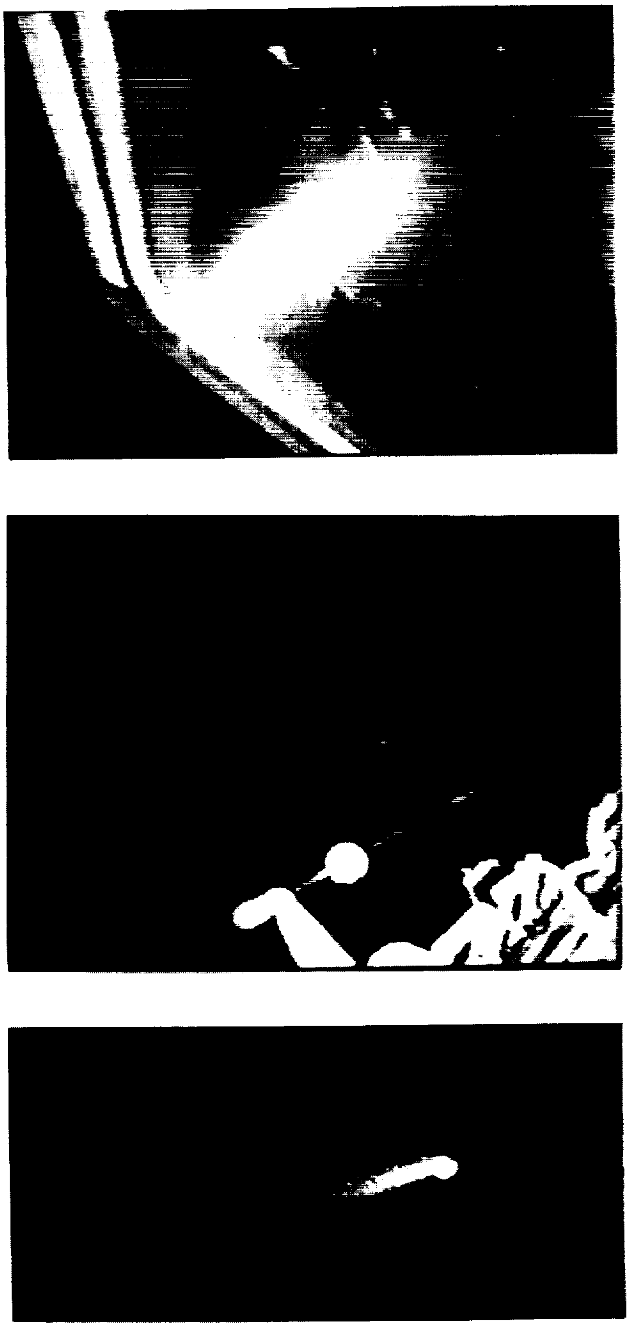

Figure 1. Views of the sunlit water/ice particle trail from onboard *Discovery* (a and b) and from AMOS with a 0.37°-wide field (c). a) is a projection to crew cabin window W1 and b) is a view from the zoom camera mounted just forward of the vertical stabilizer. In c) the solar-scatter angle is 48°, and the equivalent stellar magnitude of Orbiter (whose bloomed image is at the head of the water trail) is + 3.6.

trail's symmetry axis, zenith angles, and slant range to AMOS are in Figure 2. Both onboard cameras could view the essentially-backlit water cloud (the rising sun being toward the northeast) beyond about 5 m from the ejection nozzle. The bay camera, whose maximum field of view encompassed most of the detectable length of the trail, was at times pointed in azimuth to include its vanishing point. The groundbased camera's projected field varied between about 1¼ times (at culmination) and 5 times (near the horizon) the maximum above-threshold longitudinal extent of the optically thin sunlight-scattering volume.

DATA

The video images represent a series of illumination/viewing conditions of a time-stationary physical phenomenon. We analyzed radiometrically the AMOS scene at zenith angle 61° and azimuth 70° (Figure 1c), in which the high differential cross-section for forward scattering of sunlight (scattering angle 48°) and moderately elongated sight path (angle to long axis of cloud 33½°) resulted in the best video signal/noise ratios. *Discovery*, whose visual magnitude at this range (640 km) is about +3½, appears as a strongly bloomed, photocurrent-saturated feature at the head of the quasiconical extended water-containing volume. Figure 3 plots the relative brightnesses along the long axis of this trail (the instrumental baseline is subtracted, and a linear dependence of photocurrent on cathode irradiance characteristic of is its assumed), and these brightnesses summed over pixels along lines transverse to this direction. (This latter, rapidly decreasing quantity is the sterance per unit longitudinal path.)

The two onboard cameras show principally a flow of densely-packed discrete particles, with a relatively broad size distribution indicated by the variability of the video photocurrents from particles at sensibly the same range. This cloud diverges at about the same angle as the trail in the AMOS images (see Figure 1), and its "edge" projects back to an apex within a meter from the nozzle. We measured the longitudinal velocity as 23 m/s ±30% by following individual strong sunlight-scatterers in successive video frames, finding the variation among particles to be less than the precision of this measurement. The mean cross-track speed in the essentially-perpendicular view directions to the two onboard cameras can be seen to be about ¼ this axial speed, which indicates that the transverse momentum imparted to these particles is small compared with their wake-directed momentum. Many of these particles flicker, with characteristic periods near ½ s, and are therefore more likely tumbling ice/snow crystallites than spheres; indeed, erratic droplet shapes as well as a broad "size" distribution have been observed in a laboratory simulation of the venting of water into near-space (4).

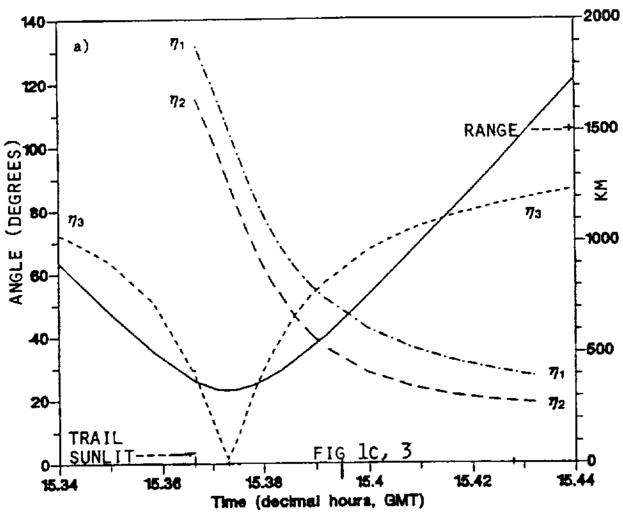

Figure 2. Solar scatter angle (η_1), aspect angle to the trail axis (η_2), zenith angle of *Discovery* and the trail (η_3), and slant range to *Discovery* from AMOS (solid line) during the water venting.

Approximately 100 of these large particles per m path can be resolved in the video frames from *Discovery's* camera. This number would be expected from the laboratory finding (4-7) that the mean diameters of the explosion-product ice particles are comparable with the diameter of the ejection nozzle.

INTERPRETATION

We interpret the discrete sunlight scatterers seen by *Discovery's* onboard cameras to be the product of the cavitational bursting of initially-coherent water streams in vacuum, which results from the rapid formation of bubbles ("steam") in the superheated liquid (4-8). A cloud of much smaller (tenths-micron diameter) particles that has also been identified in laboratory tank experiments is not unambiguously detectable against these bloomed images of the close-lying large droplets. This second component of the flow is formed by recondensation of water molecules that had been evaporated from the original and flash-exploded stream after this gas becomes overexpanded. On the basis of the following observations, we judge these much smaller particles to be responsible for the major fraction of the radiances of the trail that were measured by the groundbased camera (Figure 1c).

[1] Thermodynamic arguments (3) show that most (~70%) of the water mass remains in the large ice particles, while a laboratory simulation (6) indicated that the small recondensate particles contain less than 2%. We applied standard light scattering theory for 0.2 μm and 0.7 mm radius ice, finding that despite the great differences in both the fraction of initial water in and the absolute scattering amplitudes of the two populations, the much larger number of small particles results in considerably more visible radiance over the length of water trail detectable by the AMOS camera. (That is, the particles whose circumference is comparable with the photon wavelength have higher scattering "efficiency".)

[2] The surface brightnesses of the trail measured from the ground exhibit a very weak dependence on the solar-scatter angle, which is a behavior characteristic of Rayleigh rather than geometric scattering (particle large compared with the photon wavelength). Specifically, the fractional increase in the axial brightnesses beyond about 1 km from the nozzle, corrected for sight path length, remains small as the sunlight scattering angle decreases from 107° (when the trail was at AMOS zenith) to 48° (to which Figure 3 refers). This small change is consistent with the differential cross-sections of submicron particles, while in contrast scattering of visible light per unit solid angle from mm spherical ice drops would increase by about a factor 50 over this range of angles.

[3] The dependence of axial and crosswise-integrated radiance of the optically thin trail on distance from *Discovery* (Figure 3) is consistent with a simple model of the energy balance of the smaller ice particles. We applied standard Mie radiation theory with the known dependence of the real and imaginary components of the index of refraction of ice on wavelength to calculate the sublimation rate of smooth spheres in vacuum, taking into account the energy they absorb from earthshine and the incident solar flux and the energy they lose by thermal emission and sublimation. (Collisional heating and recondensation can be readily shown to be negligible.) The equilibrium 166K temperature is reached within less than a second after the particles form.

Since the emissivity of weakly-absorbing spheres is proportional to their radius r when r is less than ~1 μm, their radiance decreases exponentially with time, or distance x from the spacecraft. That is, r of submicron particles with axial velocity v (which we took as the velocity of the large particles, in view of the similar cone angles) varies as exp [-ax/v], where a ($\simeq$ 0.004 s^{-1} for smooth spheres) is the fractional loss rate due to sublimation. Thus the scattering in the "geometric" particle size range, which we take to be where the cross-section at fixed angle varies with r^2, would exhibit an exp [-2ax/v] dependence. In contrast scattering in the Rayleigh size range, where the cross-section varies as $r^2 \cdot r^4 = r^6$, would vary as exp[-6ax/v]. The "break" near x=1400 m in Figure 3 is due to the transitioning of the radius of the subliming particles from the geometric to the Rayleigh-scatter regime. (The familiar Mie oscillations in this transition region are

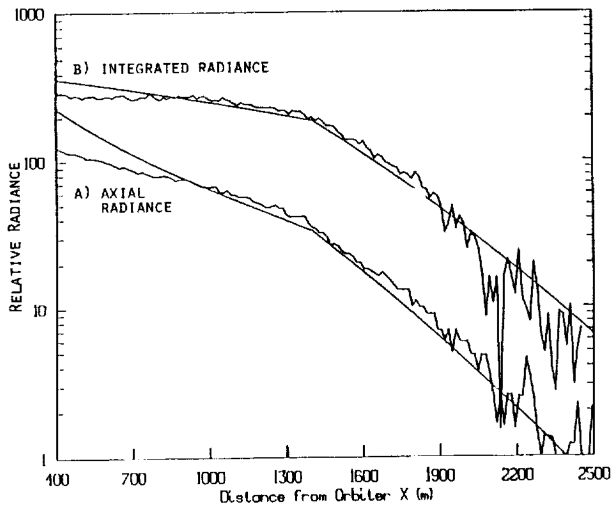

Figure 3. a) Relative radiance along the line of maximum brightness extending out from *Discovery* in the AMOS image (Figure 1 c), with background subtracted (and a linear relationship between the video photocurrent and scene radiance assumed). b) Radiances summed along lines transverse to this long axis. The data are contaminated by video blooming from *Discovery's* image when $x \lesssim 500$m.

largely washed out by the polychromatic sunlight illumination.)

Figure 3 indicates that the radiances measured from AMOS can be described by geometric scattering over the first ~1400 m and by Rayleigh scattering over the remaining ~1000 m (beyond which the trail's brightnesses fall below the camera's threshold), when a small correction for the progressive roughening of the particles is included in the calculation. The correction assumes a linear increase in sublimation rate with time, so that the radius decreases about as exp $[-ax/v-bx^2/v^2]$. That somewhat-larger ice droplets in vacuum indeed develop irregular surfaces that lead to more rapid sublimation was observed in laboratory experiments in which the chamber walls were held at low temperatures (9). The roughening required to achieve the fit of the data shown to an energy-balance model that includes this effect increases the rate of decay of mean radius by sublimation from the submicron particles by up to only a factor 2, which is in general agreement with the laboratory findings. The small downward curvature of the radiances in the two scattering regimes is also predicted by the progressively-increasing surface roughness that we assumed.

These calculations also showed that sublimation would result in a virtually negligible decrease in the sunlight-scattering cross-sections of one-mm ice droplets over the ~100-sec length (2½ km/23 ms^{-1} in the spacecraft's frame of reference) of the visible trail. The substantial measured decrease in total sterance per unit longitudinal path shown in Figure 3 and a calculation of the absolute mean radiances from solar scatter with the observed 100 such particles per m path, both further show that these much larger ice droplets could be responsible for only a minor fraction of the optical signal at AMOS.

The transition to Rayleigh scattering near $x = 1.4$ km indicates that the mean particle radius at this distance from *Discovery's* nozzle is between 0.1 and 0.3 μm. Our sublimation model gives an estimate of the mean initial radius as 0.3 ± 0.15 μm. The corresponding radius inferred in a space-simulation chamber (6), in which the water stream had 1.6 mm diameter, 20°C temperature, and a somewhat higher total flow rate, was 0.08 ± 0.03 μm.

CONCLUSION

The cloud of discrete particles that results when mm-diameter continuous water streams are vented into the low earth-orbital environment is found to have three components. Macroscopic (from laboratory observations, also mm-diameter) ice/snow particles are created by the explosive bursting of the supersaturated high-vapor pressure liquid, producing irradiances that were readily detectable in the images from the intensified video cameras onboard *Discovery*. The narrow cone angle in which these particles appear indicates that this flash evaporation imparts relatively little momentum compared with the longitudinal momentum of these particles. Much smaller droplets that theory indicates result from condensation of gaseous water produce radiances that dominate the images from the much more distant groundbased ISIT telescope-camera, in a volume with essentially the same angular spread as the large particles. The ~25% water gas, which is not detectable by either type of camera, is evolved from vaporization and sublimation of the liquid and solid (3, 7, 8). We have estimated the mean diameter of the submicron particles from an analysis of the dependence shown in Figure 3 of the relative brightnesses from scattering of sunlight at visible (S-20 photocathode response) wavelengths on distance into the wake of the spacecraft. The surface roughening that has been reported from laboratory experiments is interpreted as accelerating the sublimation rates of these small particles by factors up to about 2.

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REFERENCES

1. Pickett, J. S., D'Angelo, N., and Kurth, W. S., Plasma Density Fluctuations Observed During Space Shuttle Orbiter Water Releases, J. GEOPHYS. RES., 94, 12081-12086, 1989.

2. Fowler, M. E., Leger, L.J., Donahoo, M. E., and Maley, D. D., Contamination of Spacecraft by Recontact of Dumped Liquids, Third Annual Workshop on Space Operations and Robotics (SOAR 89), NASA Conf. Pub. 3059, p. 99, 1989.

3. Bernhardt, P. A., A Critical Comparison of Ionospheric Depletion Chemicals, J. GEOPHYS. RES., 92, 4617-4628, 1987.

4. Kassal, T. L., Scattering Properties of Ice Particles Formed by Release of H_2O in Vacuum, J. SPACECRAFT ROCKETS, 11, 54-55, 1974.

5. Curry, B. P., Bryson, R. J., Seibner, B. L., and Jones, J. H. Selected Results from an Experiment on Venting an H_2O Jet into a High Vacuum, Technical Report AEDC-TR-84-28, January 1985.

6. Curry, B. P., Bryson, R. J., Seibner, B. L., and Kiech, E. L., Additional Results from an Experiment Venting an H_2O Jet into a High Vacuum, Technical Report AEDC-TR-85-3, June 1985.

7. Fuchs, H., and Legge, H., Flow of a Water Jet Into Vacuum, ACTA ASTRONAUTICA, 6, 1213-1226, 1979.

8. Muntz, E. P., and Orme, M., Characteristics, Control, and Uses of Liquid Streams in Space, AIAA J., 25, 746-756, 1987.

9. Patashnick, H., and Rupprecht, G., Sublimation of Ice Particles in Space, Technical Report ED-2002-1654, March 1973.