# THE SMALL-COMET HYPOTHESIS

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**Abstract.** According to the small-comet hypothesis, small comets strike the Earth approximately 20 times per minute, each small comet nominally containing 100 tons ($10^5$ kg) of water-ice. The primary observations interpreted as evidence for these small comets are dark spots in the Earth's atomic-oxygen UV dayglow seen by the UV imager on the Dynamics Explorer (DE) satellite. These small comets must disintegrate near Earth and then sublimate within a few seconds, the water vapor expanding to form clouds of water vapor, nominally 50 km in diameter, that temporarily block the spacecraft's view of the dayglow, thus producing the dark spots. In this review we examine problems in basic mechanisms underlying the small-comet hypothesis. These include inconsistencies with known geophysical phenomena, conflicting results from independent searches for evidence of the presence of small comets, and inconsistencies within the small-comet hypothesis itself. No other geophysical interpretation that can account for the DE dark spots has been advanced. The only viable alternative in the literature is a nongeophysical one—the instrument-artifact hypothesis—in which it is proposed that the dark spots appear randomly in the DE pictures. Tests of this hypothesis, both qualitative and statistical, show that it, neatly and economically, explains the DE dark-spot data. Owing to the weight of accumulated evidence against the small-comet hypothesis, the lack of credible supporting evidence, and the plausibility of the instrument-artifact hypothesis, it is unlikely that the small-comet hypothesis is valid.

## 1. INTRODUCTION

In early February 1986, L. A. Frank, J. B. Sigwarth, and J. D. Craven (FSC henceforth) submitted two papers to *Geophysical Research Letters (GRL),* the subsequent publication of which resulted in spirited scientific response and public attention. The first of the two papers reports data from the Dynamics Explorer 1 (DE 1) spacecraft showing transient dark spots in the ultraviolet (UV) glow of atomic oxygen (at 130.4 nm) in the Earth's sunlit upper atmosphere [*Frank et al.*, 1986*a*]. Plate 1 is a reproduction of the cover of the April 1986 issue of *GRL.* (Besides the obvious dark spot highlighted by the inset, there should be, on average, an additional three or four atmospheric dark spots in such a picture, as explained in section 2.3.) The discovery of dark spots would have been scientific mystery enough but in their second paper, *FSC* [1986*b*] interpreted these spots as signatures of 100-ton ($10^5$ kg) clouds of water vapor moving above the Earth's upper atmosphere and blocking the spacecraft's view of the atomic-oxygen UV dayglow. Figure 1 provides a pictorial overview. They proposed that these clouds of water vapor are created by previously undetected, small, nearly pure-water comets that break into fragments whenever they come within ~3000 km of the Earth. The fragments then vaporize, and the resulting water vapor expands to a radius of at least 50 km before striking the Earth's atmosphere. The mass of the small comets is adjusted to provide an area and column density of water vapor that, when DE is at or near apogee, appears as a single-pixel dark spot against an otherwise smooth oxygen dayglow. *FSC* [1986*b*] further inferred from their data that these cometary water clouds strike the Earth's atmosphere at a rate of 20 per minute. Inferred properties of small comets are listed in Table 1.

I had assumed responsibility as Editor-in-Chief of *GRL* only 1 month before these papers were submitted. In the January issue I had laid out an editorial philosophy stressing our intent "to publish forefront, interesting science and minimize the publication of work that is routine" [*Dessler,* 1986*a*]. The editorial concluded, "*Geophysical Research Letters* welcomes submissions describing forefront research in all fields of interest to the AGU, even if such letters prove to be controversial. *GRL* is prepared to handle controversy." FSC provided a test of the editor's intent. The April 1986 issue of *GRL* carried these two papers in spite of objections of the referees, and the controversy was launched. A variety of disciplines within the scientific community responded critically [e.g.,

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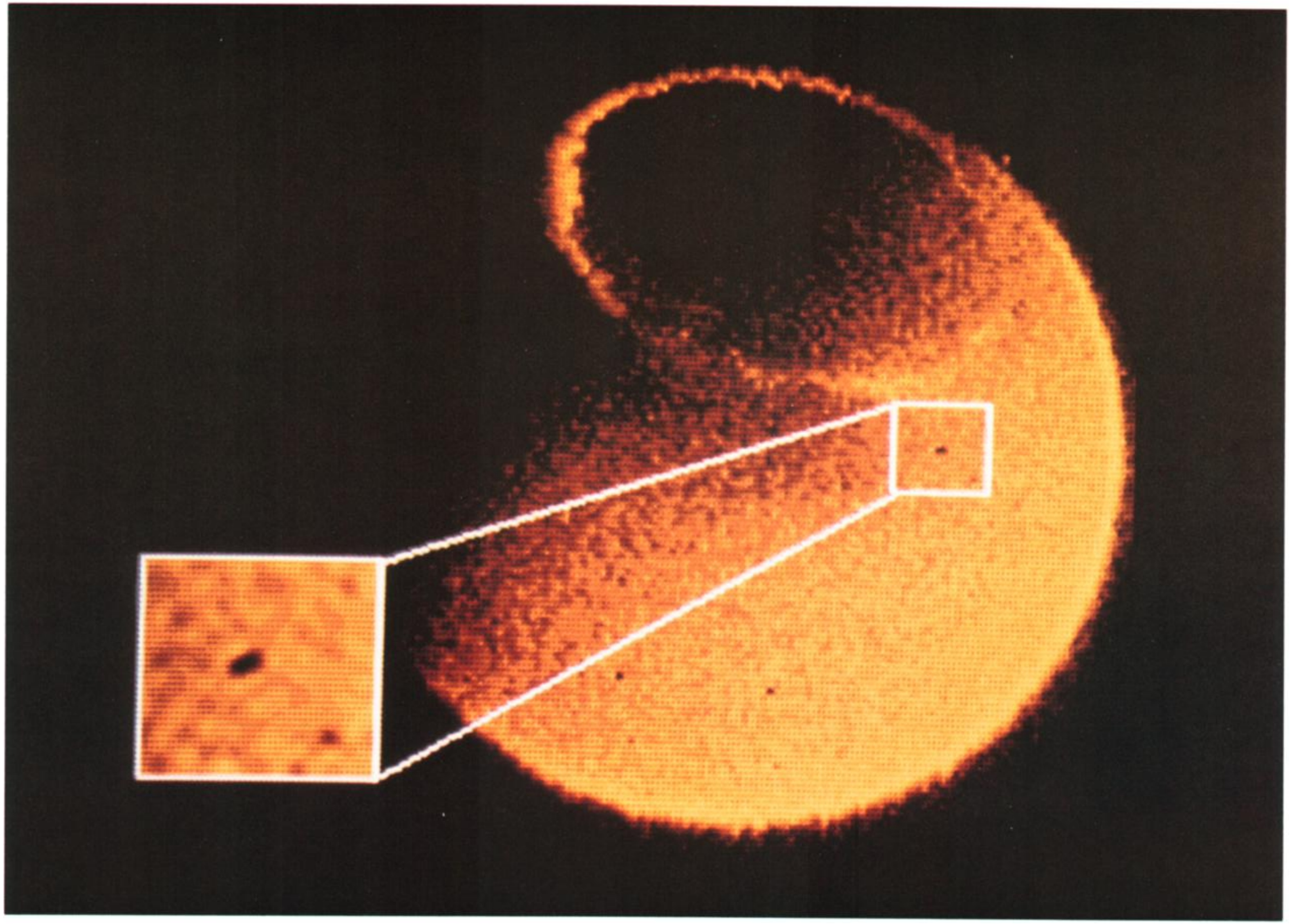


**Plate 1.** The cover of the April 1986 issue of *Geophysical Research Letters* showing the Earth as seen by the UV imager on Dynamics Explorer 1 [*Frank et al.*, 1986*a*, *b*]. FSC propose that the especially prominent dark spot in the center of the box is caused by occultation of the Earth's upper atmosphere by a 100-ton cloud of water vapor from a small comet that has just broken up and vaporized above the atmosphere (see Figure 1). FSC deduce that there are 20 such small-comet events per minute over the entire Earth. As explained in section 2.3, there are another three or four slightly less conspicuous dark spots in this picture that should be apparent to the discerning reader.

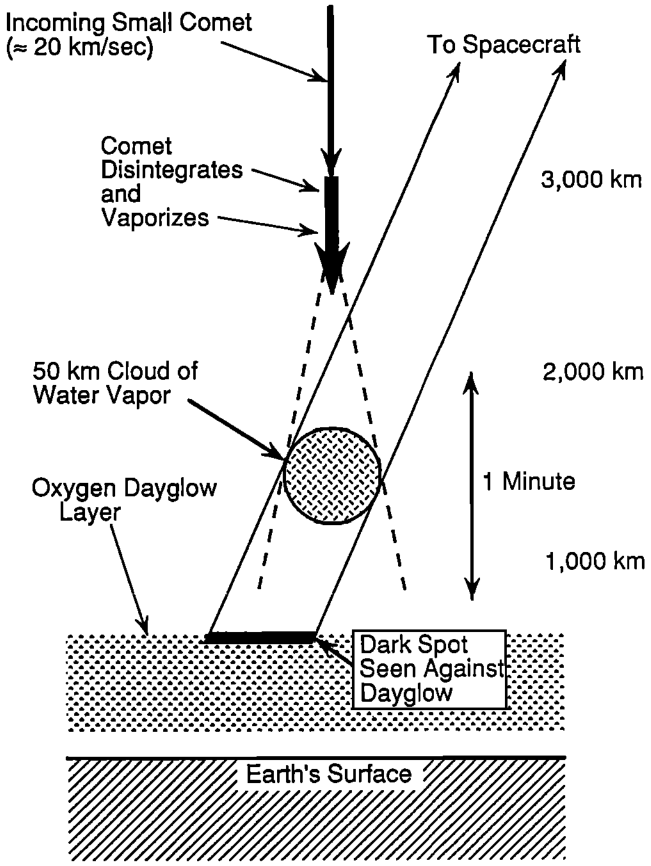


**Figure 1.** Overview of small-comet impacts with Earth as proposed by *FSC* [1986*b*]. The small comet, containing 100 tons of water-ice, approaches Earth, disintegrates, and vaporizes below 3000 km altitude to form a water-vapor cloud having a nominal (optically thick) lifetime of about 1 min. A water-vapor cloud is seen by the Dynamics Explorer 1 spacecraft as a dark spot against the atomic-oxygen dayglow. The cloud must appear above at about 600 km altitude to appear as a dark spot [*Meier*, 1987]. Because the dayglow layer is optically thick, the solar shadow of the water-vapor cloud is filled in, i.e., there is no second dark spot created by a shadow. The vertical axis is drawn to scale; the diameter of the cloud is exaggerated by a factor of 10 for clarity.

**TABLE 1. Deduced Properties of Small Comets**

| *Property* | *Numerical Value* | *Section for Primary Discussion* |
|---|---|---|
| Mass | $\geq 10^5$ kg water plus insulating outer layer | 1 |
| Mass density | 0.1 g/cm$^3$ | 1 |
| Diameter | 12 m sphere | 1 |
| Tensile strength | $5 \times 10^3$ dyn/cm$^2$ = $5 \times 10^2$ N/m$^2$ | 2.1 |
| Insulating layer | 1–4 cm thick, tensile strength $5 \times 10^2$ N/m$^2$ | 2.1, 4.2 |
| Albedo | 0.02–0.005 | 5.2 |
| Vaporization rate | $5 \times 10^8$/(cm$^2$ s) (ordinary comets = $5 \times 10^{17}$/(cm$^2$ s)) | 4.2 |
| Space density (1 AU) | $1.2 \times 10^{-19}$/m$^3$* = $30/R_E{}^3$* | 4 |
| Orbits | direct (prograde), perihelia > 0.7 AU, aphelia ~500 AU, orbital inclination <±20° to ecliptic, 42.1 km/s at 1 AU | 3 |
| Breakup altitude | 1700–10,000 km, ~3000 km (nominal*) | 2.1 |
| Combined breakup and vaporization time | <40 s* | 2.2 |
| Impact speeds | | |
| Earth's atmosphere | 16.6 km/s (minimum), 20 km/s (maximum) | 3 |
| Lunar surface | 11.6 km/s (minimum), 17 km/s (nominal maximum*) | 4.1 |
| Impact rate | 20/min (Earth), 0.86/min (Moon*) | 2.3, 4.1 |

*Indicates values derived in this paper that differ from values given by FSC.

*Stewart et al.*, 1986]. It seemed as though the scientific community perceived the small-comet hypothesis as containing an unlimited number of flaws. In a 14-month period (June 1986 to July 1987 inclusive), 11 Comments were published along with 10 Replies from FSC. (One of the Replies responded to two Comments.) In addition, over a slightly longer interval, four independent papers were published containing arguments critical of the small-comet hypothesis. With a second editorial [*Dessler*, 1986*b*] announcing that "there is a limit to the number of Comments that will be accepted on even the most controversial of Letters," the flow of Comments and Replies in *GRL* on these two papers slowed and then stopped.

FSC proposed applications of their hypothesis to include the extinction of the dinosaurs (and other mass extinctions); evidence for a new long-period massive planet; the formation of spokes in the rings of Saturn; iridium and carbon deposits on Earth; the D/H ratio on Venus; the excess thermal radiation (over solar input) exhibited by the outer planets; and the (apparently) water-formed channels on Mars [*Frank et al.*, 1987*a*; *Frank and Craven*, 1988, pp. 273–274]. Supportive papers by Frank and coworkers continue to be presented at scientific meetings [e.g., *Frank et al.*, 1988*b*; *Sigwarth et al.*, 1988, 1989], published in scientific journals [e.g., *Frank*, 1989; *Frank and Craven*, 1988; *Yeates*, 1989; *Frank et al.*, 1989, 1990*a*, *b*], and published in a book intended for the lay reader [*Frank*, 1990]. It is interesting that, except for two alternative hypotheses suggested and dismissed by FSC in their first paper, no geophysical alternative to the small-comet hypothesis has been proposed to account for the dark spots. A nongeophysical alternative, the instrument-artifact hypothesis, has, however, been seriously pursued (section 6).

In a logical sense, there are actually four hypotheses to be reviewed:

*Hypothesis 1.* Atmospheric dark spots (Plate 1) are caused by occultation of the Earth's oxygen dayglow by water-vapor clouds (Figure 1).

*Hypothesis 2.* Small comets exist in numbers and with properties roughly as listed in Table 1.

*Hypothesis 3.* Small comets break up and vaporize when sufficiently near Earth (section 2).

*Hypothesis 4.* The dark spots are not a geophysical phenomenon; the dark spots are caused by an instrument artifact (section 6).

The first three hypotheses are logically independent in that affirmation or denial of any one does not compel affirmation or denial of the other two. FSC state that they have carefully considered hypothesis 4 and cannot accept it; therefore they accept hypothesis 1 and use hypotheses 2 and 3 to explain the dark spots.

The layout of this review is phenomenological rather than either a description in chronological order of the various publications or an examination of the above four hypotheses. Finally, the reader should note that a review of the small-comet hypothesis, which touches on a variety of disciplines, is not neatly compartmentalized, and there is cross-referencing between sections.

## 2. DISRUPTION, VAPORIZATION, AND EVENT RATE

According to the small-comet hypothesis, small comets arrive in the vicinity of Earth intact, then break up, vaporize, and enter the atmosphere. Figure 1 illustrates the vertical trajectory used by FSC in their various considerations of the vapor cloud entry into the Earth's atmosphere. There are, of course, shallow-angle entry trajectories as well as near-miss trajectories. The implications of these alternative trajectories are examined in section 3. In this section we follow a small comet through the FSC scenario of (1) the breakup of a ~12-m-diameter object into micron-sized pieces, (2) the sublimation of these pieces (flakes, crystals) of ice, and (3) the determination of the rate at which such events occur.

### 2.1. Breakup of a Small Comet

A number of stringent requirements are placed on the small comets. One of these is that small comets must be easily, rapidly, and completely broken into small pieces whenever they get near the Earth. In their interpretation paper, *FSC* [1986*b*] offered three forces that might disrupt a small comet: (1) tidal, (2) electrostatic, and (3) ram forces. In this first paper they chose the tidal (gravity gradient) force. They assumed the small comet was only weakly bound and called on the differential gravitational force across the comet (i.e., tidal stress) to break up the comet at an altitude of ~1700 km with a disrupting pressure of ~$5 \times 10^{-4}$ dyne/cm$^2$. They noted that this is approximately $10^{-8}$ the binding strength of freshly fallen terrestrial snow. FSC reject the atmospheric-ram-pressure mechanism because it is too weak.

FSC abandoned the tidal breakup mechanism (in favor of the electrostatic mechanism) following consideration of a Comment by *McKay* [1986] in which he points out that the vapor pressure of water-ice at the inferred temperature of the small comets (which must have perihelia of 1 AU or less if they are to strike the Earth) exceeds the binding strength initially postulated for the small comets. In their Reply, *FSC* [1986*c*] propose a $10^7$ increase in tensile strength to bring it to $5 \times 10^3$ dyne/cm$^2$, one-tenth that of freshly fallen, powdery, terrestrial snow. The electrostatic breakup mechanism is the default choice. In their review paper, *Frank and Craven* [1988, p. 269] state, "The comets are assumed to be disrupted, perhaps by electrostatic forces in the near-Earth plasma . . . at altitudes 1000–3000 km above the dayglow layer before the subsequently formed water clouds impact the atmosphere." In this review I adopt a nominal breakup altitude of 3000 km and, following *Meier* [1987], place the effective top of the dayglow layer at 600 km. This puts the typical breakup altitude 2400 km above the dayglow layer, consistent with an altitude selected by *FSC* [1986*d*] (see their Figure 2, reproduced below as Figure 4).

FSC give no details of the electrostatic disruption mechanism, so a review of the mechanism is not possible. However, we know the electric field must be large if its pressure is to exceed the small comet's tensile strength. For example, for a simple smooth sphere I obtain a value for $E$ of just over $1 \times 10^7$ V/m. The potential of body of radius 6 m with such a surface field in a plasma with a Debye length of, say, 10 cm is $10^6$ V. In sunlight and at altitudes where these comets must disintegrate to form the dark spots in the UV dayglow, such potentials are not credible [*Garrett*, 1981; *Whipple*, 1981]. At altitudes of a few thousand kilometers, spacecraft potentials of only a few volts are observed (except while passing through an active aurora when potentials can rise to ~1 kV). At geostationary orbit (~6 $R_E$), while in darkness, spacecraft potentials of a few kilovolts are observed occasionally, but such potentials are not observed where small-comet disruption must occur. Of course, breakup potentials are reduced on localized areas of the small comet if one assumes nonspherical shapes or rough surfaces. However, improvement by a factor of $10^5$–$10^6$ seems out of reach. A preliminary conclusion is that the mechanism for small-comet breakup needs study.

The tensile strength of the insulating layer raises another possible problem. In their Reply to a Comment by *Rubincam* [1986], *FSC* [1986*e*] argue that small comets are insulated by a porous mantle having a thickness of 1 cm. The material they propose for the covering is derived from a theoretical model by *Fanale and Salvail* [1984]. In laboratory experiments, *Saunders et al.* [1986] produced a material compatible with the Fanale and Salvail theory, that, although a good thermal insulator, is described as having strong bonding forces between particles, which results in a strong, elastic material. An insulating cover such as this would impede the breakup process. An additional problem with this insulating material, namely its disposal on atmospheric entry, is discussed in section 4.2.

To break a 12-m object into smithereens with the weak forces available at high altitude takes time. But, moving toward the Earth at 20 km/s, the small comets do not have much time (e.g., see Figure 1). Why is ~3000 km the nominal breakup altitude? There are no planet-wide sharp gradients of anything magnetospheric near 3000 km. The breakup process is a difficulty for the small-comet hypothesis.

## 2.2. Vaporization of Ice Particles

To proceed with the review, I assume that some physical force is present near 3000 km to break the comet up into small ice crystals within a fraction of a minute. FSC do not discuss the time allowed for breakup, but it is obviously a function of the breakup altitude, the time growing shorter with decreasing altitude. Then the ice crystals must sublimate to form a water-vapor cloud. The vaporization problem is treated in one sentence in the initial interpretation paper: "After fragmentation the total vaporization rate increases rapidly due to increasing total fragment area with freshly exposed surfaces" [*Frank et al.*, 1986*b*, p. 308]. Their subsequent papers do not elaborate on this point.

Ices in space are more stable than one might first suppose. Two documented experimental examples can be cited: (1) liquid hydrogen and oxygen dumped from the S-IVB stage of Apollo 14 on its way to the Moon and (2) water dumped during the Space Shuttle flight STS-29. The released liquid droplets cool by evaporation, freeze, and continue to cool by sublimation and blackbody radiation until they reach an equilibrium temperature. In each of these events, hydrogen, oxygen, or water-ice were observed to survive in the vacuum of space at 1 AU, in full sunlight, for tens of minutes. There was no sign of rapid sublimation as required by the small-comet hypothesis.

**2.2.1. Apollo and Space Shuttle Events.** Apollo spacecraft on their way to the Moon dumped excess fuel and oxidizer while still relatively near the Earth. The Apollo 14 hydrogen and oxygen dumps (1.2 tons of liquid hydrogen and 1.15 tons of liquid oxygen) are described in the April 1971 issue of *Sky and Telescope* (p. 251). The liquid hydrogen became a cloud of $H_2$ ice crystals that reached a maximum brightness estimated as near zero magnitude and looked like "the full moon covered by a very thick haze." There is fair agreement between observers that in 30 min the hydrogen cloud grew to 2° in diameter, and the cloud was visible for about 45 min. The $O_2$ ice cloud reached a brightness of approximately 3rd magnitude and was visible for at least 15 min. Even though the clouds were in full sunlight, the fading from view is not attributed to sublimation but to cloud expansion causing a decreasing surface brightness until overwhelmed by sky brightness (see the Appendix).

There have been several occasions in which water released into space formed visible ice particles. A useful case for us to consider is the water dump from the space shuttle *Discovery* in March 1989 (mission STS-29). As an operational procedure, twice each day, ~50 kg of pure water produced by the shuttle's fuel cells and some waste water are dumped out of vents on the side of the vehicle. *Fowler et al.* [1990] report that as the water exits into space, it freezes almost instantaneously into small (~100–500 μm) ice crystals that move away from the spacecraft. They also report that 45 min after a water dump (and on one occasion after a longer interval), the orbiter recontacted some of the ice crystals as their respective orbits crossed.

**2.2.2. Application to Small Comets.** It may at first seem surprising that small ice crystals can live for 1 hour or more in low Earth orbit. It appears that ice does not sublimate rapidly in space. However, the time available for sublimation of the small-comet ice is only a fraction of a minute, and none of the publications by FSC treat this problem.

According to *FSC* [1986*b*, p. 308] after sublimation of the comet ice the water cloud expands, and "the mean speeds of the vaporizing molecules are 0.3 km/sec at 200 K [*Delsemme*, 1982]." But, in the cited paper, *Delsemme* [1982, p. 98] derives an expansion speed of 860 m/s for water vapor at 200 K. The mean Maxwellian speed of water molecules at 200 K is 483 m/s. Delsemme explains the factor of 1.8 higher final speed as caused by transfer of additional translational energy to the water molecules from rotational states. Direct measurements at comet Halley corroborate these higher speeds [e.g., *Mendis*, 1988, Figure 14]. As a minimum speed, I use an intermediate value of 500 m/s for the expansion of the water-vapor cloud; this is only slightly faster than the mean Maxwellian speed of 483 km/s for water molecules at 200 K. At a speed of 500 m/s the water vapor expands to a diameter of 50 km in 50 s. (With the full 860 m/s expansion speed the 50-km diameter would be reached in only 29 s.) To keep the entire 100 tons of water vapor contained within a 50-km cloud, the sublimation must be completed in a time that is short compared to the 30- to 50-s expansion time. A cloud produced by a sublimation time longer than about 10 s violates an essential assumption of the small-comet hypothesis, namely, the dark spots in the atomic oxygen UV dayglow are caused by 100 tons of water vapor confined to an optically thick 50-km cloud. Because the amount of water vapor is fixed, a 100-ton cloud expanding beyond 50 km diameter becomes optically thin and can no longer produce a dark spot. An ideal 50-km cloud of water vapor lasts only a few seconds. The lifetime of an optically thick cloud with a diameter large enough to be typical, say, growing from 40 km to 50 km, is no more than 10 s. We shall see shortly that this lifetime is significantly shorter than that tacitly assumed by FSC.

In accounting for a short sublimation time, we are at liberty to select any size we wish for the ice particles after breakup. Do small comets disintegrate into small clumps or into individual ice crystals? The most favorable assumption for rapid sublimation is small, separate ice crystals. If the ice is to sublimate in, say, 20 s (to be consistent with Figure 1), from the Appendix we estimate that the radius of the ice crystals must be ~0.2 μm, which is about the size of the smallest crystals in noctilucent clouds [*Gadsden and Schröder*, 1989]. In drawing Figure 1, and in the following discussions, we must assume that, following a complete disintegration that can take no more than about 10 s, the small-comet ice content is entirely converted to vapor within 20 s, consistent with the values in Table 1.

### 2.3. Small-Comet Event Rate

The conclusion reached by FSC (that 20 small comets strike the Earth each minute) is model dependent. To understand this rate dependence, we must briefly review how the imager on Dynamics Explorer (DE) builds a picture. (For additional details on this instrument, see *Frank et al.* [1981] and *Cragin et al.* [1987].) As the spacecraft spins at 60°/s, a photometer with an effective field of view of 0.29° and negligible vignetting, looking nearly perpendicular to the spin axis, scans a 30° line of pixels in 0.5 s. A single pixel formed from the moving circular spot has the shape of the rounded rectangle shown in Figures 2*a* and 2*b*. Each pixel thus formed is modestly large, subtending an angular extent equal to the full Moon in height and two-thirds the angular size of the Moon in width, but with weighting of the effective pixel area toward its center. Photometer counts (which indicate light intensity) are accumulated in 3.4-ms intervals. A 0.5-ms dead time follows each counting interval while the accumulated counts are read out; then the photometer reads light intensity again for another 3.4 ms. The photometer field of view moves 0.20° during each accumulation interval. It requires 12 min for the photometer to go through a complete scan and create a picture of the Earth as seen in Plate 1. Of the 12 min of scanning required to build this picture, the Earth is in the field of view for only 1 min (actually, 0.87 min when dead time is subtracted).

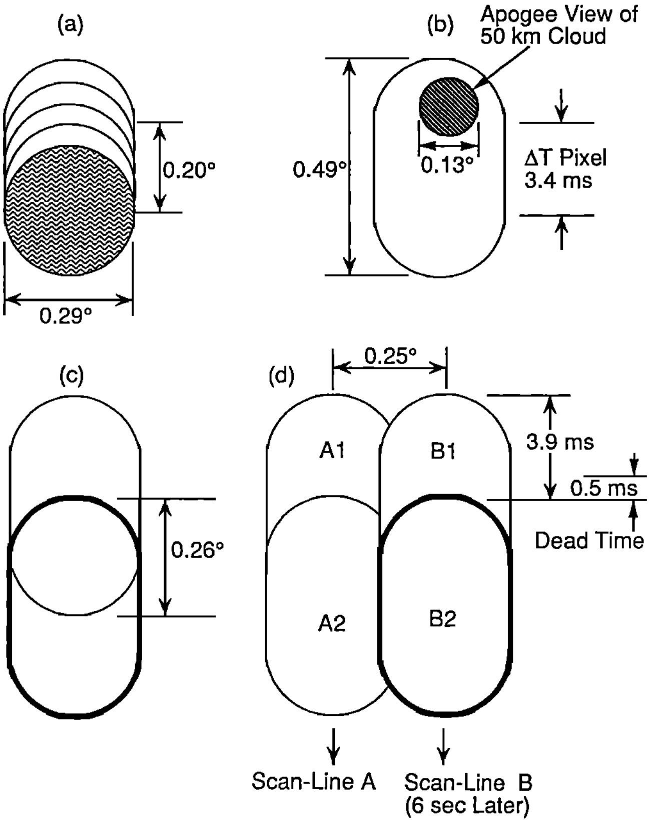


**Figure 2.** Pixel size and shape for the imager on Dynamics Explorer 1. (*a*) The center of an instantaneous field of view of diameter 0.29° moves 0.20° in a photon accumulation interval. (*b*) A single pixel is formed in 3.4 ms having an overall length of about $\frac{1}{2}°$ (i.e., the angular diameter of the full Moon). The hatched spot is the angular extent of a 50-km cloud as seen from 3.4 $R_E$ (i.e., near apogee). (*c*) Two sequential pixels showing the overlap between them are also illustrated, as well as (*d*) four pixels, two from one line scan and two from an adjacent line scan displaced by $\frac{1}{4}°$. Time separation is 3.9 ms between sequential pixels in a single line and 6 s between pixels in the adjacent line.

The rate at which small comets are detected is a function of both their number and their lifetimes. Large numbers of water-vapor clouds might be forming and disappearing on one part of the Earth while the photometer is looking at another. To go from a dark-pixel event rate to a small-comet event rate requires that a lifetime be assumed for the water-vapor cloud. Given a lifetime, the event rate can be obtained by simple statistical analysis. The sensitivity of the event rate to lifetime can be demonstrated with an example in which we assume the dark-spot lifetime is 60 ms and the darkness threshold such that 1 in 1000 pixels is dark. (This is approximately the actual ratio of dark to normal pixels seen by the DE imager [*Cragin et al.*, 1987].) When Earth effectively fills the image frame, a DE Earth image consists of ~$10^4$ pixels. Of these, $10^4/10^3 \approx 10$ are dark. We, therefore, on average, see 10 dark pixels in each full-Earth picture, independent of the dark-pixel lifetime or picture acquisition time. Plate 1, which is approximately half the full Earth, should contain five dark pixels. The other four are not too hard to spot, though they are less obvious than the one highlighted by the box. The event rate is roughly 10 (the number of dark pixels seen in the 1 min required to accumulate the $10^4$ pixels) divided by the lifetime of the dark pixel. For a 60-ms = $10^{-3}$-min lifetime the event rate is of the order of $10/10^{-3}$ = 10,000 dark spots per minute on the sunlit hemisphere, only 10 of which are observed per minute. This result is not exact because it was not obtained by starting with the probability of a single pixel being dark and proceeding from there, but the order of magnitude estimates given here illustrate the point that the event rate depends on our model of dark-spot lifetime. To get 10 comets per minute hitting the dayside Earth (and 20/min for the whole Earth), FSC assume a dark-pixel lifetime of approximately 1 min. Yet, FSC also show observations of three separate holes forming and recovering within ~3 min [*FSC*, 1986*a*, Figure 4]. If they were to use this 3-min lifetime, the event rate would be one-third their standard number, or ~7 per minute. If the lifetime of the occulting water cloud were 10 s as deduced in section 2.2.2, the event rate would rise by a factor of 6 to ~120 small comets per minute.

## 3. IONOSPHERIC AND ATMOSPHERIC EFFECTS

In this section I review possible ionospheric and atmospheric effects. I do not, however, review the recent findings of *Bonadonna et al.* [1990] of detections of transient enhancements of water vapor using microwave radiometry techniques; the abstract, which is all that is available thus far, does not provide enough information for a section of this review. Their results are interesting in that they report that their data are consistent with the small-comet hypothesis. A full paper is presently under preparation pending completion of special tests to be certain that all other explanations for these data have been exhausted (J. J. Olivero, personal communication, 1991).

To survey possible effects of small-comet passage through the upper atmosphere, we must first consider impact trajectories and speeds. This can be done with some precision because the orbits of small comets are well defined. *FSC* [1986*b*] argue that the small comets do not strike the Earth omnidirectionally. Instead, they are in restricted orbits, as illustrated in Figure 3. The small comets come from the Oort cloud and have highly eccentric orbits with aphelia of several hundred astronomical units [e.g., *Frank and Craven*, 1988]. FSC also propose that small comets are in direct, prograde orbits and their range of orbital inclinations is confined to ±20° of the ecliptic plane to keep impact speeds below about 20 km/s. They explain that at impact speeds greater than 20 km/s, small-comet-induced ionization of the upper atmosphere would produce a 0.3-s flash of 2 × $10^7$ rayleighs (R) at 630.0 nm from an area 50 km in diameter. Because such bright flashes are not commonplace, *FSC* [1986*b*]

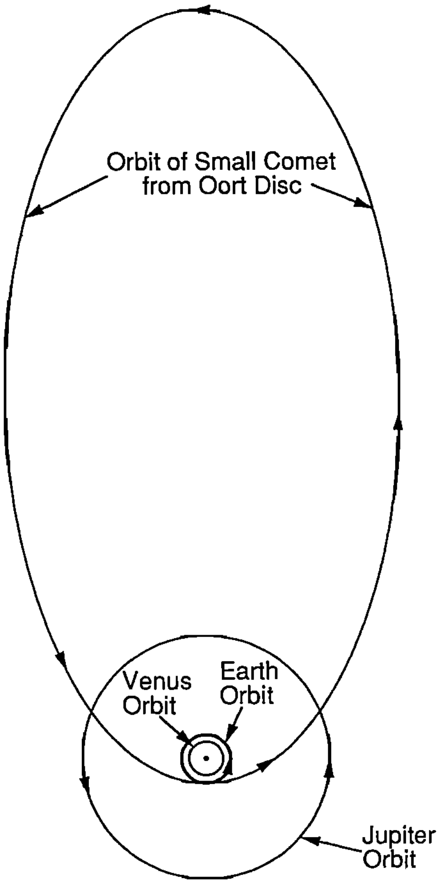


**Figure 3.** View from above the ecliptic plane showing Venus, Earth, Jupiter, and a small comet in essentially coplanar orbits. According to *FSC* [1986*b*] the orbital inclinations of small comets must be within ±20° of the ecliptic plane in order to keep their impact velocities with Earth near minimum values. The aphelia of small comets extend to several hundred astronomical units, and few have perihelia as small as the orbit of Venus (0.7 AU).

conclude that the impact speeds must be near the smallest possible value. At 1 AU the small-comet orbital velocity is 42.1 km/s. The Earth's mean orbital velocity is 29.8 km/s, so the minimum approach velocity before modification by the Earth's gravitational field is 42.1 − 29.8 = 12.3 km/s. In a retrograde orbit the small comets approach the Earth at 42.1 + 29.8 = 71.9 km/s. Before impact with the Earth's atmosphere, the comets pick up additional speed from Earth's gravity, the final minimum speed being 16.6 km/s. The maximum impact speed for a retrograde orbit is 72.8 km/s. The complete range of intermediate speeds is possible, depending on the angle of inclination of the comet's orbital plane relative to the ecliptic plane. To keep the speeds in the acceptable range of 16.6–20 km/s, FSC accept the restricted range of orbital inclinations. Difficulties with this narrow range of allowed orbits are discussed in section 4.2.

### 3.1. Ionospheric Effects

Some observable effects of small comets on the ionosphere are proposed in a Comment by *Hanson* [1986]. He argues that small comets should interact strongly with the ionosphere, both mechanically and chemically, to create easily observable ionospheric holes. The contrary view by *FSC* [1986*d*] is that the interactions are weak, and clouds of water vapor pass through the ionosphere with minimal disturbance.

The water-vapor clouds are dense and energetic compared to ionospheric constituents. A 50-km sphere containing $10^5$ kg of water vapor has a concentration of $5 \times 10^{10}$ $H_2O$ molecules/cm$^3$ and an average column number density of $2 \times 10^{17}$ $H_2O$ molecules/cm$^2$. For comparison, at the 350-km altitude of the principal daytime ionospheric maximum (the *F*2 peak), each of these ambient atmospheric quantities is about 30 times smaller than that of the water-vapor cloud. At 20 km/s a water molecule has a kinetic energy of 38 eV (compared to ~0.1 eV for the ionospheric ions), the column energy density is $1.2 \times 10^7$ erg/cm$^2$, and the entire cloud has a kinetic energy of $2 \times 10^{13}$ J (the energy of $10^7$ kg of TNT). Such numbers lead *Hanson* [1986, p. 981] to surmise that "there should be unmistakable evidence of their presence because each impact is a non-trivial event, and the influx is large."

*Hanson* [1986, p. 981] presents several mechanisms by which small-comet impacts would "modify the nature of the *F*2 region ionization, both in composition and concentration." He argues that as *F* region ionization enters the downward moving cloud, various charge-exchange and chemical reactions alter the composition. For example, water is known to lead to rapid recombination (hence removal) of ionospheric plasma [*Mendillo and Forbes*, 1978]. The mechanism for this removal of ionospheric electrons is charge-exchange and ion-atom interchange followed by dissociative recombination. Experiments have been performed, and the process is observed, as expected from theory, to proceed at a rapid rate (see section 3.1.1). Alternatively, *Hanson* [1986] points out that under certain conditions, there is the possibility of creating new ionization by the Alfvén critical-ionization mechanism. Hanson's primary theoretical thrust is that a significant change in *F* region ionization is expected. He then reports that in 85 hours of in situ measurements of daytime ionospheric ion concentration obtained principally between 220 and 390 km from three different satellites, fluctuations in ion concentration were smaller than 20%, although the satellites should have flown through 40 recent trails of small-comet passage through the ionosphere.

In their Reply to Hanson, *FSC* [1986*d*] introduce the idea that the water-vapor cloud becomes partially ionized before it enters the ionosphere, and this ionization causes ionospheric plasma to flow around the incoming cloud. In this way a water-vapor cloud sweeps up the neutral atmosphere but, except for a "turbulent wake," leaves the ions unperturbed. Using ionospheric data from Hanson's DE instrument, FSC report finding four examples of what they interpret as a turbulent wake. (FSC do not justify their assumption of atmospheric turbulence at altitudes near 300 km where the mean free path is of the order of 3 km.) Figure 4 (taken from *FSC* [1986*d*, Figure 2] shows the sequence of events proposed by FSC. Note that in this figure, as in the text of their Reply, they consider only the special case in which the Earth's magnetic field is perpendicular to the cloud's velocity vector. The electric field in the bottom three panels of Figure 4 is the motional electric field $\boldsymbol{E} = -\boldsymbol{V} \times \boldsymbol{B}$ that depends, among other things, on the sine of the angle between the velocity vector $\boldsymbol{V}$ and magnetic field $\boldsymbol{B}$. If the velocity vector is parallel (or antiparallel) to the magnetic field, there is no motional electric field, i.e., $E = 0$. For intermediate angles the electric field is reduced and the flow field is modified so, in these cases, the preservation of *F* region ionization called for by FSC is not possible. This is illustrated in Figures 5*a* and 5*b*.

With regard to the findings of turbulent wakes by *FSC* [1986*d*], W. B. Hanson (personal communication, 1990) states that examination of the data on which the FSC claim is based shows that none are valid examples of turbulence. According to W. B. Hanson (personal communication, 1990), one of the four examples is an instrument noise effect caused by an automatic gain change, and the other three were caused by "an interesting spacecraft-plasma interaction that takes place where the satellite velocity is nearly parallel to *B*." There may be no valid examples of a turbulent wake. The nondetection of small-comet wake effects either by Hanson or (apparently) by FSC is a worrisome point for the small-comet hypothesis because, in both papers, wake effects are expected.

**3.1.1. Water-Vapor Deposition in Ionosphere.** The effect of small comets on the atmosphere depends on the altitude at which the cloud of water is brought to rest. A well-documented effect of water vapor in the ionosphere is the creation of an "ionospheric hole," a localized decrease in the concentration of ionospheric plasma. The reader is referred to a recent review by *Mendillo* [1988] covering

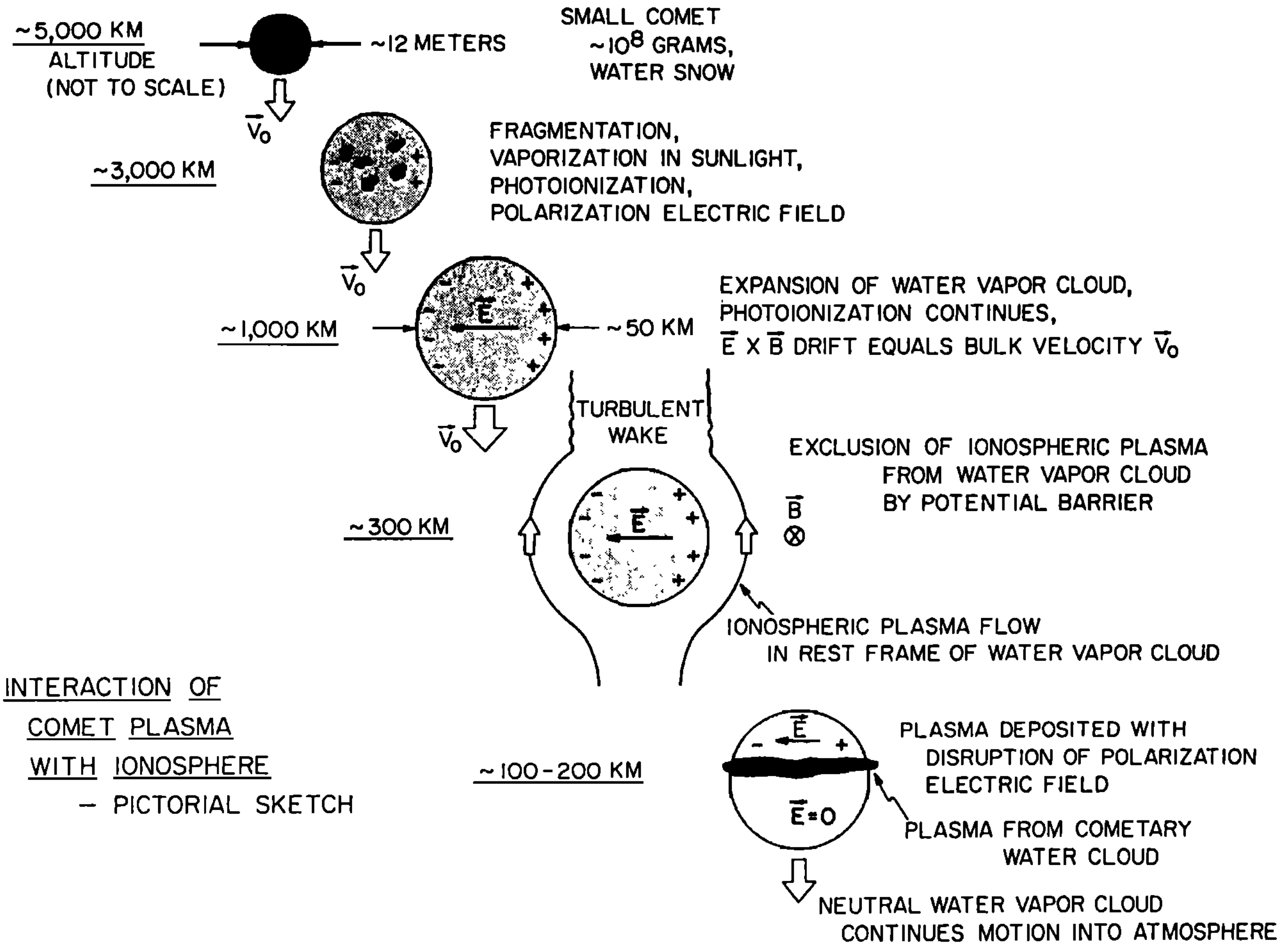
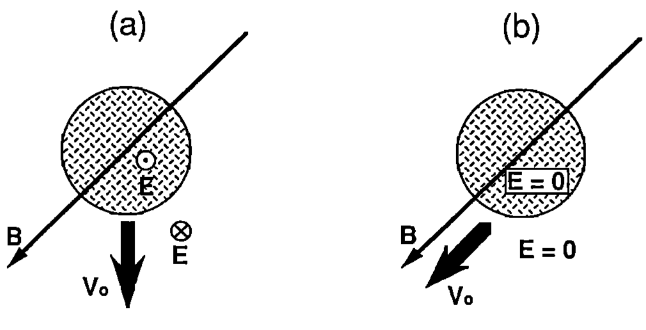


**Figure 4.** Sketch by *FSC* [1986*d*, Figure 2] showing how a small-comet water-vapor cloud passes through the ionosphere without disturbing it. The cloud first becomes partially ionized to create a low-$\beta$ plasma after breakup and vaporization near 3000 km altitude. As indicated in the fourth panel, FSC assume the magnetic field is perpendicular to the velocity vector. They argue that electric polarization of the partially ionized cloud creates an external electric field that causes ionospheric plasma to flow around the incoming cloud. They propose that un-ionized gas is swept up by the small-comet passage, but, except for a turbulent wake, the ionosphere is left undisturbed.



E X B DRIFT NOT EQUAL TO BULK VELOCITY Vo

NO E X B DRIFT

**Figure 5.** Two cases in which the velocity vectors of partially ionized water-vapor clouds are not perpendicular to Earth's magnetic field. (*a*) The magnetic field is at an angle of 45° to the velocity vector. The resulting electric field is weaker than in Figure 4 by a factor $\sqrt{2}$, so any **E x B** drift speeds are correspondingly slower, and the direction of drift is perpendicular to **B**, which means that the flow patterns are incompatible with the model offered in Figure 4. (*b*) An extreme case in which the magnetic field is parallel to $V_0$ is also shown. In this case, there is no electric field and, therefore, no **E x B** drift. The mechanism shown in Figure 4 will not function properly in case a, and it will not function at all in case b.

both theory and relevant space experiments. For example, *Mendillo et al.* [1989] report that the release of 265 kg of "water vapor, ice, carbon dioxide and particulate matter at 297 km" near local noon resulted in "a well-formed plasma depletion (>50%) extending throughout the *F*-region and spanning ~1° latitude and longitude." (See also *Mendillo et al.* [1990]).

Problems of water-vapor deposition in the high atmosphere were first raised in a Comment by *Donahue* [1986]. Starting with their Reply to Donahue's Comment, *FSC* [1986*f*] have been consistent in avoiding all such high-altitude water deposition problems by treating the special case of vertical incidence and regarding the water cloud as a 50-km-diameter "piston" that retains its size and shape down to at least ~85 km where, they calculate, it is still moving downward at 40 m/s. In the usual method of estimating stopping distance, and the one first used by *FSC* [1986*b*, p. 308], one equates the mass of an object with the mass it encounters in its motion through a medium. This criterion predicts an effective stopping altitude for a vertically incident small comet as the height at which

$$\rho H / \cos\theta = \sigma_0 \tag{1}$$

where $\rho$ is the atmospheric mass density at the altitude of interest, $H$ is the scale height at that altitude, $\theta$ is the angle between the local vertical and the velocity vector, and $\sigma_0 = 5.1 \times 10^{-6}$ g/cm$^2$ is the column mass density of a $10^8$-g small comet evenly distributed over a circle of radius 25 km. In their initial interpretation paper, *FSC* [1986*b*] give a minimum altitude of atmospheric penetration of ~125 km by using the equivalent of (1). (I obtained 140 km using the same model; I can account for part of the difference by noting that *FSC* [1986*b*, p. 308] used "the column density through the cloud center" for $\sigma_0$, which is 1.5 times greater than for the uniform cylinder of Figure 6.) In this first paper, *FSC* [1986*b*, p. 308] state, "Thus in consideration of the momentum of the cloud, the $H_2O$ molecules should not penetrate directly below ~100 km. . . . Subsequent atmospheric diffusion and advection can convey the cometary molecules to lower altitudes." However, *FSC* [1986*f*] switched to a model that, they argue, carries the water safely below 80 km.

The model presently used by *FSC* [1986*f*, p. 559] is straightforward. They describe their model as accounting for "the water cloud's deceleration in the upper atmosphere by the accumulation of all atmospheric gas in its path." In this model, to reduce the speed of the cloud, for example, from 20 km/s to 40 m/s, the cloud must sweep up 499 times its original mass. They approximate the shape of the water-vapor cloud as a 50-km-diameter right cylinder with column mass density uniform from center to edge (see Figure 6). The initial momentum per unit area $\sigma_0 v_0$ is equated with the momentum of the water column plus swept-up atmospheric gas $(\sigma_0 + \rho H)v$, where $v_0 = 20$ km/s is the initial speed of the water-vapor cloud, $v$ is its speed, and $\rho$ is the mass density of the ambient atmosphere. Thus

$$v = \frac{v_0}{1 + (\rho H / \sigma_0)} \tag{2}$$

Although the "piston" model of FSC overestimates the depth of penetration of a water cloud, it is useful to illustrate the effects of nonnormal incidence. We change the column mass of swept-up gas from $\rho H$ to $\rho H/\cos\theta$, so (2) becomes

$$v = \frac{v_0}{1 + [\rho H / (\sigma_0 \cos\theta)]} \tag{3}$$

Grazing incidence water-vapor clouds travel farther through the upper atmosphere than vertically incident clouds. In Figure 7 a small comet on trajectory 2 passes through the breakup radius at about $\phi = 39°$ (corresponding to a local time of 1436 LT), travels 1.3 $R_E$, and impacts the atmosphere at a grazing angle at about 1052 LT. The travel time from breakup to impact is 8.4 min. If we assume the rapid disintegration, vaporization, and expansion proposed by FSC (see section 2.2.2), the diameter of the resulting cloud, expanding for 8 min at a nominal radial speed of 0.5 km/s, is nearly 500 km at impact. Thus the value of $\sigma_0$ is reduced by a factor of $10^2$ from $\sigma_0(vrt) = 5.1 \times 10^{-6}$ g/cm$^2$ to $\sigma_0(grz) = 5.1 \times 10^{-8}$ g/cm$^2$. Substituting these values into (3), we find that when the cloud reaches 280 km, i.e., while it is still in the ionosphere, its velocity has dropped to 0.7 km/s. Because a grazing incidence cloud becomes so large, we can regard

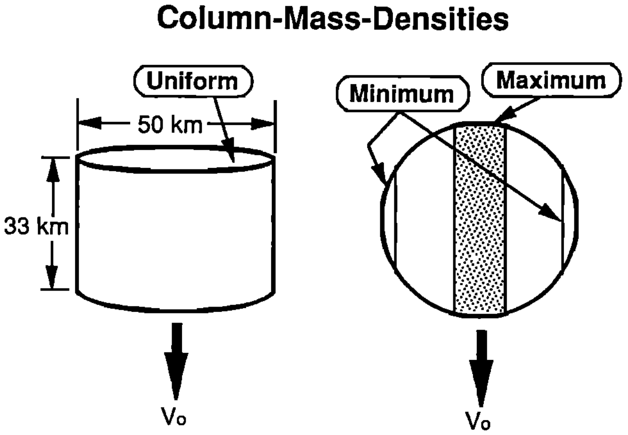
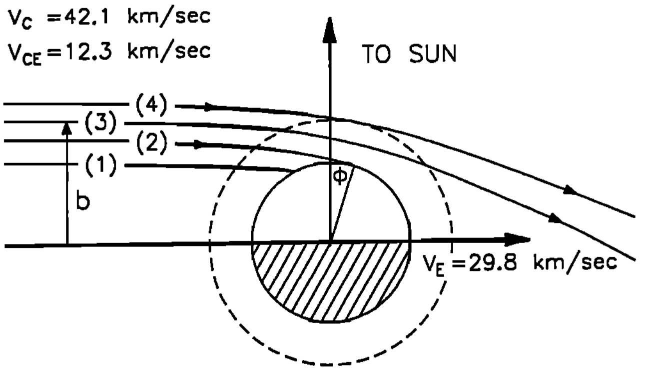


Figure 6. To calculate the depth of penetration of small-comet water-vapor clouds, *FSC* [1986*f*] assume a uniform 50-km-diameter cylinder of water vapor that they regard as a "piston" in which the water vapor is uniformly distributed (height of 33 km for the same volume as a 50-km-diameter sphere). For a sphere with uniform water-vapor concentration to the edge of the cloud, the ratio of cloumn mass density between the maximum at the central axis and the minimum at a position 1 km in from the edge of the cloud is a factor of ~$10^2$. This large difference in column mass density results in different stopping altitudes for inner and outer portions of the cloud. Six percent of the volume (6 tons of vapor) are contained in the outer stippled ring if its inner radius is 23 km.



| | $R_p$ ($R_E$) | b ($R_E$) | $V_p$ (km/sec) | $\Phi_p$ (deg) |
|---|---|---|---|---|
| (1) | — | 1.08 | — | — |
| (2) | 1.00 | 1.35 | 16.62 | -17 |
| (3) | 1.25 | 1.61 | 15.85 | -14 |
| (4) | 1.50 | 1.86 | 15.32 | -12 |

**Figure 7.** View from above the ecliptic plane showing small-comet trajectories (the near-Earth portion of Figure 3) in the ecliptic plane [after *Dessler et al.*, 1990]. Trajectories 1 and 2 impact Earth, while trajectories 3 and 4 pass through the breakup distance (placed at 0.5 $R_E \approx$ 3000 km altitude) but miss Earth's atmosphere. $R_p$ is the geocentric perigee distance, $b$ is the impact parameter, $V_p$ is the speed of the comet cloud at perigee, and $\phi_p$ is the angle to the perigee point measured positive clockwise from local noon.

the speed of 0.7 km/s at 280 km altitude as essentially stopped (e.g., if the cloud is 500 km in extent, it takes nearly 12 min to pass a given point at the 280-km altitude level). If we had used the more conventional equation (1) for this grazing incidence example, the stopping altitude would have been higher.

As implied by Figure 6, an atmospheric interaction would first wipe away the outer fringes of an incoming spherical cloud because of the smaller column mass density at the cloud's periphery. A Maxwellian velocity distribution for the water molecules and a finite sublimation time for the ice crystals lead to a fuzzy, even more tenuous outer surface for a small-comet water-vapor cloud, so even more of the outer cloud would be stripped away than suggested here. An analysis containing a complete set of terms that account for the deceleration of an entering cloud has yet to be accomplished. For example, if the cloud were to become partially ionized as suggested by *FSC* [1986*d*] (see Figure 4), would significant currents flow in response to the motional electric fields? Such currents are in the direction to decelerate the cloud. However, consideration of just nonvertical impacts leads one to conclude that small comets would inject unacceptable quantities of water into the ionosphere. The above ideas are combined in Figure 8 to show a possible scenario for the passage of a small comet through the atmosphere.

For the orbital restrictions *FSC* [1986*b*] impose on small comets in interplanetary space, daylight near-vertical incidence occurs most frequently at low latitudes and near the sunset meridian. Grazing-incidence impacts, while less frequent than the near-vertical impacts, occur at a consequential rate. Specifically, the ratio of grazing impacts (those between trajectories 1 and 2 in Figure 7) to the total is $(b_2^2 - b_1^2)/b_2^2 = 0.36$. If the total impact rate is 20/min, the grazing impact rate is 7/min. Deposition of 700 tons of water per minute into the ionosphere is, as noted by *Hanson*, [1986, p. 981] "a non-trivial event" when one considers the entire mass of the Earth's ionosphere is little more than 4000 tons.

All of the participants in this portion of the small-comet debate agree that deposition of even a fraction of the small-comet water vapor at high altitudes (as little as 0.1% at altitudes above 100 km or 10% at altitudes above 60 km) creates unacceptable consequences. But, even the 140-km stopping altitude calculated with equation (1) is a lower limit because we have not considered (1) nonvertical incidence, (2) stripping away the more tenuous outer portions of the vapor cloud (which have lower values of the column mass density $\sigma_o$), (3) the fact that at impact, a cloud, on average, must be larger than 50 km (which reduces $\sigma_o$), and (4) further reduction of $\sigma_o$ as the cloud expands because of collisional heating in the atmosphere. The array of implied chemical and compositional changes that would occur if this much water were injected into the upper atmosphere, as put forth by *Donahue* [1986] and *Hanson* [1986] in their respective Comments, raises formidable problems for the small-comet hypothesis.

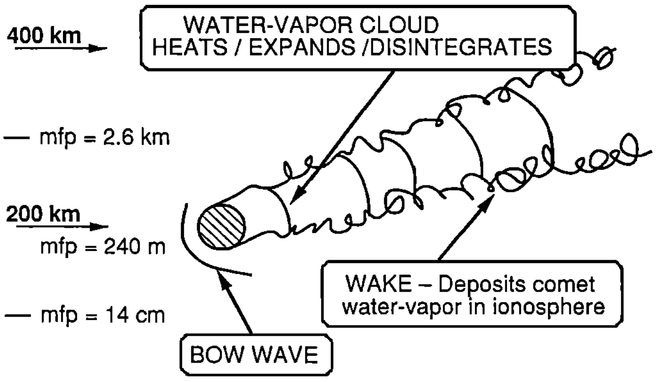


**Figure 8.** A possible scenario for oblique-incidence impact of a small comet on the upper atmosphere. The tenuous outer portions of the incoming cloud are stripped away first. A turbulent wake is suggested by *FSC* [1986*d*] (see Figure 4), although the long mean free path (shown on the left) at these altitudes make the concept of turbulence questionable. Gas swept up by the cloud causes internal heating through collisions with the incoming water molecules, each initially having an ordered kinetic energy of 38 eV. Wave drag further slows the cloud. For grazing impacts, much of the water vapor is deposited above 200 km. The injection into the ionosphere of even a fraction of the ~100 tons of water contained in a small comet would deplete ionospheric plasma over an area of tens of thousands of square kilometers.

### 3.2. Aeronomic Effects

Accounting for the state of the Earth's upper atmosphere consists of describing a delicate balance of various constituents, their transport, and their energy sources. As a dynamic system, it is difficult to change just one thing in the atmosphere without affecting almost everything else. Because small comets inject so much water into the upper atmosphere, modern aeronomic theory would require massive modification to accommodate the small-comet hypothesis.

An example of an aeronomic problem is the one introduced by *Reid and Solomon* [1986, p. 1129], who examine the flux of water through the middle atmosphere and conclude that "a modest influx of $H_2O$ from above could thus actually help to reconcile observations and model results." In considering only water in the middle atmosphere, they find that a comet flux 30 times smaller than proposed by *FSC* [1986*b*] would be permissible. (Their model for the dark spots differs from that of FSC in that they propose removing the atomic oxygen in the upper atmosphere by having it interact with the H and OH molecules that are produced by the dissociation of the incoming water.) In rebuttal, *Frank and Craven* [1988, p. 273] contend that this water problem is caused by two errors introduced by Reid and Solomon. First, Frank and Craven claim "a coarse estimate for the minimum altitude of direct deposition is ~50–60 km" while they say that Reid and Solomon have mistakenly brought the cometary water cloud "to rest at 116 km." Frank and Craven continue, "Furthermore, *Garcia and Solomon* [1983] have previously shown that a one-dimensional transport model for water in the middle atmosphere is inadequate because effects associated with meridional transport and the latitudinal variation of insolation are neglected. For these reasons the calculations by *Reid and Solomon* [1986] provide no useful limits on the influxes of extraterrestrial water." These arguments by FSC are not persuasive: (1) Reid and Solomon do not derive an altitude at which the water vapor stopped. They simply use the then current value of stopping altitude of 100–125 km published by *FSC* [1986*b*] and take 116 km as a convenient boundary-condition level for their calculations. As seen in section 3.1.1, the claim of FSC that all of the water in a small comet penetrates to 50–60 km is hard to understand. (2) For the small-comet problem a one-dimensional model is adequate because FSC claim the small comets strike everywhere on Earth, which makes horizontal gradients negligible. Reid and Solomon had the more complex two-dimensional model available [*Garcia and Solomon*, 1983], but they did not use it because it was not necessary.

**3.2.1. Atomic Hydrogen.** Disposing of the hydrogen derived from dissociation of the water is one of the more vexing problems to be addressed by the small-comet hypothesis. *FSC* [1986*f*] regard the water from small comets as a weak source of hydrogen. For example, they state [*FSC*, 1986*f*, p. 560], "The total hydrogen is assumed to be accounted for by water for simplicity," so there is no excess to create a disposal problem. FSC do not provide details to support this assumption, but *Donahue* [1986] presents quantitative arguments that the small comets create too much hydrogen by factors of $10^3$–$10^6$.

At 20 km/s an $H_2O$ molecule striking an oxygen atom is likely to dissociate into H and OH because the center-of-mass energy available is 17 eV, and the dissociation energy is only 5.1 eV. Some of the resulting OH radicals combine with O atoms in the path of the incoming cloud to produce $O_2$ molecules and more H atoms. Also, Donahue points out that at high altitudes, where much of the water is deposited, the flux of solar photons with energy above the dissociation limit is roughly equal to the globally averaged flux of $10^{11}$ $H_2O$ molecules/(cm$^2$ s) from small comets. Therefore it would appear that a reasonable first-order assumption would be that most of the incoming water molecules are dissociated at altitudes well above 100 km, either by atomic impact or by photodissociation. *Donahue* [1986] points out some ways such a large source of H violates observational constraints. A few are as follows: (1) The downward diffusing H and OH would remove all the ozone from the middle atmosphere. (2) The frost point would be exceeded globally near the mesopause, and a global cloud layer would blanket the Earth. (*FSC* [1987*a*] and *Frank* [1990] make a virtue of this point by expanding it into a theory of periodic mass extinction.) And (3) the amount of hydrogen diffusing upward to go into the geocorona exceeds measured amounts by more than a factor of $10^3$.

**3.2.2. Heating and IR Radiation.** There exists the possibility of extensive ionization by thermal effects if one were to apply the deceleration model of *FSC* [1986*f*] to a calculation of temperature within the water-vapor cloud as it slows "by accumulation of all atmospheric gas in its path" [*FSC*, 1986*f*, p. 559]. (This ionization mechanism is in addition to the Alfvén critical-velocity ionization mentioned earlier.) To estimate the temperature, we note that the ordered motion of the incoming water molecules is turned into thermal motion that is shared with the accumulated atmospheric gas as the cloud sweeps up gas and slows. At 120 km, according to *Frank et al.* [1986*f*], the cloud has slowed to 4 km/s; including swept-up gas, its total mass has increased by a factor of 5. Each water molecule is now accompanied by an average of 2.8 molecules of mass 26. The kinetic energy of the cloud is one fifth of its initial kinetic energy. (The mass has increased fivefold, but the corresponding fivefold decrease in speed leads to a factor of $5 \times 1/5^2 = 1/5$ remaining of the original kinetic energy.) The initial kinetic energy of a 20-km/s water molecule is 37 eV, so the thermal energy per molecule would be $37 \times (4/5)/3.8 = 7.8$ eV $= 9 \times 10^4$ K. Of course, such high temperatures are not reached for several reasons (some of which are illustrated in Figure 8): (1) as the cloud heats, it expands to increase its cross-sectional area and sweep up more atmospheric molecules to share the energy; (2) energy is expended in wave motion (including shock waves) in the ambient medium; (3)

energy is used to dissociate water molecules (as argued by *Reid and Solomon* [1986]); and (4) energy is carried away in IR and visible radiation. *Banks* [1989] has modeled the intensity of a portion of the IR signal; he calculates that the power radiated in the IR rises at 200 km altitude to $2 \times 10^9$ W/μm. In a 10-μm bandwidth the total IR power is $2 \times 10^{10}$ W. *Banks* [1989, p. 587] concludes that "the existing cross sections and the present simple model predict an important signature of IR radiation each time a comet-associated water cloud enters the Earth's upper atmosphere." These energy dissipation mechanisms contribute to high stopping altitudes, as discussed in section 3.1.1.

## 4. SOLAR-SYSTEM EFFECTS

If small comets strike the Earth 20 times per minute, we can estimate their space density with the help of the table in Figure 7. The small-comet flux is

$$F = nV_{CE}(\pi b^2) \qquad (4)$$

where $F$ is the rate at which small comets strike the Earth ($F$ = 20/min = 0.33 s), $n$ is the number density of comets far enough from Earth that the comet's speed and trajectory have not been significantly altered by Earth's gravity, $V_{CE}$ is the velocity of the small comets relative to Earth, which is the velocity to use if the comet number density is to be independent of Earth's motion ($V_{CE}$ = 12.3 km/s), and $b$ is the impact parameter (which would be the geocentric distance of closest approach if the small comet's trajectory were not modified by Earth's gravity). Comets inside trajectory 2, which has an impact parameter $b = 1.35\ R_E$ , strike the Earth. Equation (4) yields the number density $n = 1.2 \times 10^{-19}$ small-comets/m$^3$, which is consistent with the number density derived by *Soter* [1987] but is a factor of 12 larger than the number initially used by *FSC* [1986*b*, p. 310]. Concentrations near $10^{-19}$/m$^3$ are hard to visualize. If we move to a larger scale, we can better appreciate the value of $n$. There are well over 100 small comets in an Earth-sized sphere. A sphere bounded by the Moon's orbit contains $2.7 \times 10^7$ small comets [*Soter*, 1987]. The small comets are, on average, spaced $(1/n)^{1/3} = 0.32\ R_E$ apart.

A wide range of possible solar-system effects could be considered. Would stellar occultations by small comets occur frequently enough to be noticeable? Disposing of the hydrogen at Mars (which implies a sizable hydrogen geocorona around Mars) is a parallel to the terrestrial problem [*Donahue*, 1986]. However, we focus on just two effects: impacts of small comets on the Moon and injection of water vapor from small comets into interplanetary space. We again use the standard small-comet parameters of Table 1.

### 4.1. Lunar Impacts

The Moon should be struck by small comets arriving at a rate of nearly 1/min and with speeds ranging from a minimum of 12 km/s to 17 km/s (see Figure 9). (This range of speeds is smaller than the 16- to 20-km/s range of terrestrial impact speeds because of the Moon's smaller gravitational potential.) There is no evidence of such impacts either from the lunar record or from seismometers placed on the Moon during the Apollo program. I regard the nondetection of small-comet lunar impacts to be one of the most persuasive facts leading to the conclusion that small comets, as described by FSC, do not exist. *David* [1986] and *Nakamura et al.* [1986] published Comments detailing the nondetection of small-comet impacts on the Moon by the seismometers placed on the Moon during the Apollo program. (A third, similar comment was acknowledged by an editor's note (*GRL, 13,* 1181, 1986).) The Comments make the point that lunar seismometer data are inconsistent with the small-comet hypothesis by a factor of $10^5$ [*Davis*, 1986] to $10^6$ [*Nakamura et al.*, 1986]. The response of *FSC* [1986*g*] is summarized in Figure 10, which is taken from Figure 1 of their Reply to both Davis and Nakamura et al.

We first go through the collision process following the FSC scenario in Figure 10. The top panel shows the small comet arriving at the Moon's surface intact. (The Comments by Davis and Nakamura et al. discuss the size of the cloud hitting the Moon if the comet were broken up by tidal forces, but *FSC* [1986*c*] had earlier abandoned the tidal breakup mechanism in their Reply to *McKay* [1986] (see section 2.1), but this revision had not yet appeared in print.) In the second panel, *FSC* [1986*g*] show the small-comet impact producing an elastic wave in the body of the Moon. Because they claim the lunar response is elastic, FSC deduce that the impact leaves no significant crater. Nearly all the water vapor then expands at higher than escape speed, leaving the Moon unhydrated and unscarred. The impact, being elastic, takes place in a time of the order of the small-comet diameter divided by its velocity (10 m/(10 km/s) = 1 ms), shown at the bottom of the figure as ~1–10 ms. For an elastic impact the acoustic spectrum generated in the Moon is related to the 1-ms impact time. *FSC* [1986*g*, p. 1187] state, "The combined duration of the pressure wave and rarefaction wave is ~2 ms, or a fundamental frequency of 500 Hz." This frequency is what one expects in an elastic impact with a resilient surface. For example, if one were to drop a marble from a height of a few centimeters onto a ceramic plate, the marble would bounce, and the acoustic signal would be heard as a high-frequency "tink" that corresponded to the combined duration of the pressure and rarefaction wave. FSC combine their deduced small-comet 500-Hz lunar "tink" with a $1/r^{2.15}$ amplitude attenuation, where $r$ is the distance to the seismometer from the impact point. By combining this amplitude attenuation with their 500-Hz frequency estimate, the low sensitivity of lunar seismometers at frequencies greater than ~20 Hz, and an impact rate 5 times smaller than deduced from the small-comet terrestrial impact rate, *FSC* [1986*g*, p. 1187] conclude that "the maximum chord distance from the lunar

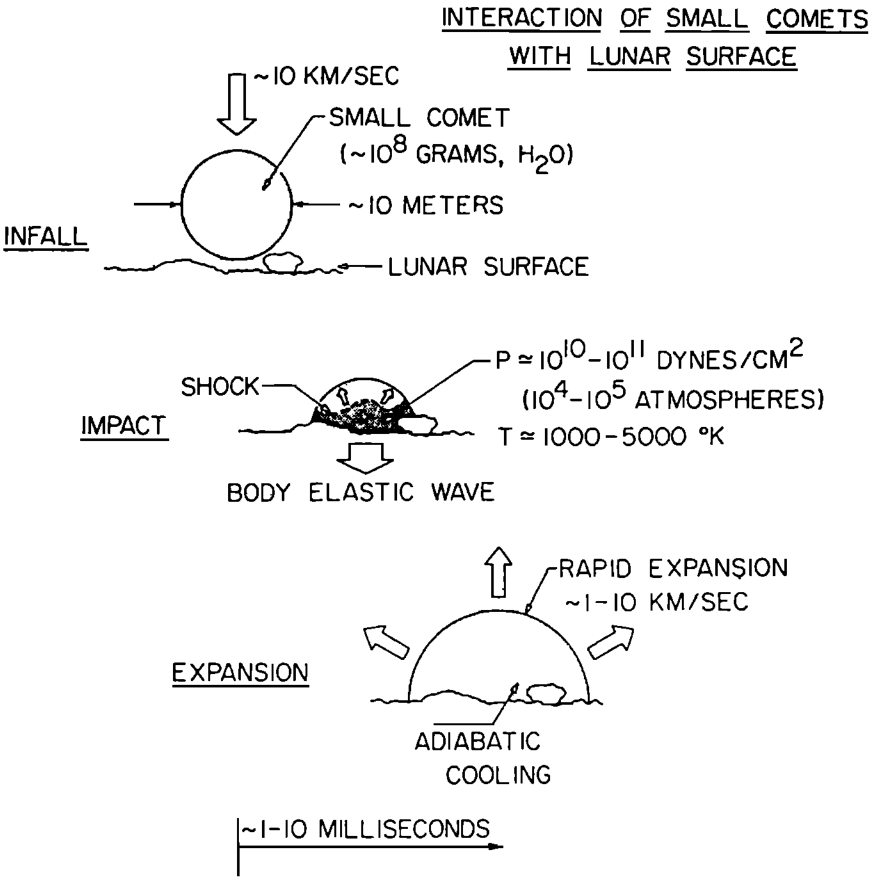


**Figure 9.** Small-comet impact speed with the Moon as a function of lunar phase. The speeds shown were calculated assuming that the stream of small comets is in the plane of the Moon's and Earth's orbit. Comets with inclined orbital planes have impact speeds approaching 20 km/s. At impact each water molecule has a directed energy of >17 eV, which exceeds molecular and intermolecular binding energies. Analogy with "fluffy" snowballs would not seem applicable.

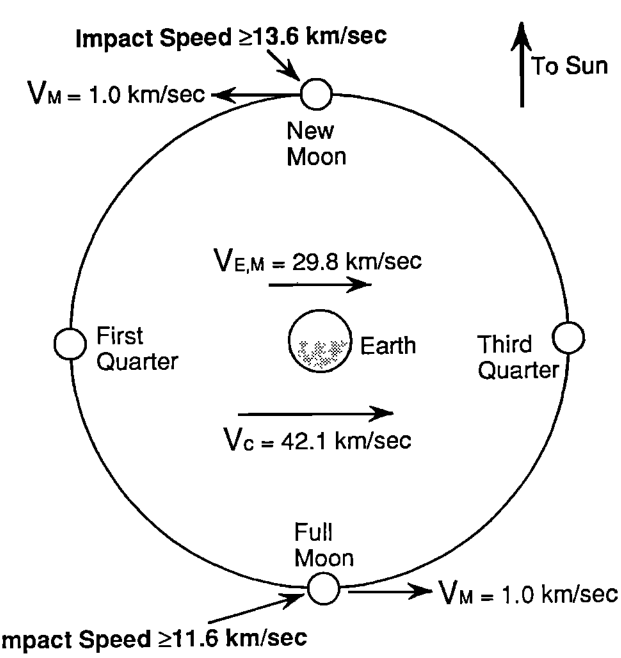


**Figure 10.** The features of a small-comet impact on the Moon is proposed by *FSC* [1896*g*, Figure 1]. They propose a near-elastic impact with negligible cratering and with water vapor escaping into space at a speed ~70% that of the incoming comet. The lower expansion speed of ~1 km/s in the third panel is a typographical error; the text of the FSC paper makes it clear that the minimum speed they intend is 5 km/s.

seismic station for detection of a comet impact is 1.5 × 10$^6$ cm, or 15 km." Their reasoning yields two detectable small-comet events per year at a seismic station, which would not be noticeable in the observed background of 200 seismic events per year.

I find this explanation of small-comet impacts on the Moon to be disconcerting. A 100-ton object traveling at 12.6 km/s has a kinetic energy of 8 × 10$^{12}$ J, which is the energy equivalent of a 2-kiloton TNT explosion. (At a density of 1 g/cm$^3$, 2 kilotons of TNT would, coincidentally, fit into a cube roughly the size of a small comet.) There is nothing soft or fluffy about any substance impacting at 12–17 km/s. The reader should not think of snow as soft and fluffy or rock as hard and strong when the impact energy per molecule exceeds the binding energy of the substance. Specifically, at lunar impact speeds of 12–17 km/s a water molecule in an ice crystal has a kinetic energy of 21 ± 7 eV, and a silicon dioxide molecule in a rock has a kinetic energy of 72 ± 24 eV, energies that exceed molecular binding energies by a factor ~10$^2$. My mental picture, which is that of an object the size and mass of a small house hitting the loose lunar dust and rock at speeds approaching 30,000 miles per hour, is not consistent with an elastic "tink." Rather, I would expect something appropriate to a 2-kT tactical nuclear bomb detonating with a satisfying low-frequency "boom" that rattles the Moon and leaves a crater whose dimensions are comparable to that of a football stadium. Alternatively, I would not want to be inside a building struck by a 100-ton snowball moving over 8 miles per second.

Reasons for the discrepancy between the above intuitive pictures and the one proposed by FSC (summarized in Figure 10) are not hard to find:

1. Most important is their assumption of a near-elastic impact of a small comet with the lunar surface. FSC, in panel 2 of Figure 10, show an elastic wave generated by the impact. They consider impacts with solid rock for which they quote a wave speed of ~5.8 km/s. This speed is correct for terrestrial rock, but it is nearly 10 times too high for lunar rock. At the new-Moon impact speeds of ≥13.6 km/s and the more appropriate seismic speed of 0.8 km/s in lunar rock [*Anderson et al.*, 1970], the small-comet impact speed is a hypersonic Mach 17. Because much of the lunar surface is loose dust and rubble, and because so much energy is irreversibly carried by the supersonic shock wave into the lunar material, the impact is best approximated as inelastic.

2. The $1/r^{2.15}$ falloff of seismic amplitude with distance that FSC use to explain the nondetection of the small-comet impacts is not correctly applied. *Davis* [1986, equation (2)], quoting the same reference used by FSC, gives the amplitude of the initial impulse falling as only $1/r$ out to 180 km from the impact. This is what is expected of a spherically expanding wave in a continuous medium. (Energy flux is proportional to $1/r^2$, so the amplitude is proportional to $1/r$.) Then, because of scattering inside the Moon (not attenuation), the pulse amplitude falls as $1/r^{2.15}$ Signals do not, in general, propagate directly to the seismic stations, but instead rattle around inside the Moon for about an hour, contributing to a general steady-state reverberation. Davis points out that the Moon is a high-$Q$ object ($Q \approx 5000$). ($Q$ is a measure of the storage time of vibrational energy. The high value of $Q$ for the Moon means that it can store vibrational energy for about an hour.) Seismic pulses, generated approximately once per minute by small-comet impacts, "would cause the moon to be in a permanent state of reverberation, appearing to ring like a bell" [*Davis*, 1986, 1181]. Whenever an S-IVB stage struck the Moon (Table 2), reverberations were detected at all the seismic stations for an hour following each impact.

Even if we accept the *FSC* [1986*g*] postulate that small-comet lunar impacts are essentially elastic (i.e., "tink") impacts, the impacts should still have been easily detectable. To show this, we simply correct the FSC estimate for (1) their excessively steep falloff of seismic transmission (point 2 above) and (2) their underestimate of the small-comet impact rate on the Moon. *Davis* [1986] and *Nakamura et al.* [1986], as well as *Morgan and Shemansky* [1991], conclude that the lunar impact rate that is consistent with a terrestrial rate of 20/min is 0.86 ≈ 1 small-comet impact with the Moon each minute; this is approximately 5 times greater than the FSC value. (FSC use an impact rate of $3.4 \times 10^{-3}$ comets/s = ~1 impact every 5 min.) Changing the seismic-attenuation function from $1/r^{2.15}$ to $1/r$ for the first 180 km and then using $1/r^{2.15}$ beyond that distance, we find the 15-km range calculated by FSC is increased to 250 km. The sensitive area for a given seismic station (according to the FSC seismic spectrum) is thus increased by a factor of $(250/15)^2 \approx 270$, and with the factor of 5 correction to the impact rate, there is an overall increase in detectable impacts to approximately 2700/yr. The observed rate is only ~200 events/yr, so the discrepancy, even using the elastic-impact model of FSC, is significant.

The reason Davis and Nakamura et al. concluded the discrepancy is even larger is because of the difference in seismic spectrum they expect from a large impact. To understand why an almost instantaneous impulse (1 ms for a small-comet impact) gives a relatively low-frequency (~1 Hz) seismic spectrum, we need to ask why a small explosion goes "pop" while a large explosion goes "boom," as, for example, the difference in sound produced by a firecracker and a bomb. The chemical action supplying a hot ball of gas for each device goes to completion in about the same time. Yet, from the firecracker we hear a high-frequency pop, and from the bomb, a low-frequency boom. Both devices produce hot gases so quickly that the ambient air does not have time to get out of the way, and each produces an acoustic shock wave. If the event proceeded slowly enough that no shock wave were produced, as in the sudden ignition of a puddle of gasoline, we would hear a "woomp" instead of an explosive sound.

TABLE 2. Dynamical Properties of Small-Comet and S-IVB Lunar Impacts

| *Property* | *Small Comet* | *S-IVB* |
|---|---|---|
| Overall dimensions of impacting body, m | 12 (diameter) | 6.6 (diameter) × 17.8 (length) |
| Mass, tons | ≥100 | 13.4 (+ 1.6 for J-2 rocket engine) |
| Density, g/cm$^3$ | $1 \times 10^{-1}$ | $2.5 \times 10^{-2}$ |
| Impact speed, km/s | 12–17 | 2.5 |
| Impact Mach number (relative to lunar regolith) | 15–21 | 3.1 |
| Momentum, (kg m)/s | $1.2–1.7 \times 10^9$ | $3.7 \times 10^7$ |
| Kinetic energy, J | $7–14 \times 10^{12}$ | $4.7 \times 10^{10}$ |

Shock waves expand until their amplitudes decrease to the point that they reach a relaxation radius, after which they propagate as ordinary acoustic waves. The acoustic spectrum produced by an explosion is broad, but the spectral peak occurs at a wavelength commensurate with the maximum diameter of the shock. A firecracker, with its small-diameter shock, has a corresponding short-wavelength acoustic spectrum which produces its high-frequency "pop." The bomb, with its larger shock diameter, supports a low-frequency spectrum, which is consistent with its "boom" [*Taylor*, 1950; *Few*, 1969]. The above concepts explain seismic data obtained in tests of nuclear weapons on and under the Earth's surface. Application of these data and concepts to small-comet impacts with the Moon yields an acoustic spectrum peaking near 1 Hz (M. Denny, personal communication, 1990). These ideas are summarized in Figure 11. For a quantitative treatment of phenomena associated with impact cratering, see the monograph by *Melosh* [1989].

The Moon has been calibrated for high-speed impacts of low-density objects, which verify the theoretical arguments involving energies, temperatures, pressures, and equations of state, etc. As mentioned earlier (section 2.2.1), during the Apollo program, several S-IVB stages from the Saturn V launch vehicles were deliberately crashed into the Moon to provide impacts of known momentum and energy. Table 2 (adapted from *Davis* [1986, Table 1]) compares the impact properties of small comets and the S-IVBs. Lunar Excursion Modules (LM) were also deorbited to make grazing impacts with the lunar surface. Even LM impacts, although delivering significantly less energy and momentum than the S-IVBs, produced easily detectable seismic signatures. The S-IVB is a low-density object, being, overall, less than half the density of small comets. Also, an S-IVB stage hits the Moon softly in the same sense as does a small comet. The fragile structure crumples on impact, giving a ~7-ms deceleration time. (I ignore the crater produced by the rocket engine because its mass is only ~10% that of the tank.) In an impacting S-IVB stage, the kinetic energy is 3.4 eV for an aluminum atom and 7.0 eV for an iron atom. As for a small-comet impact, the kinetic energy of each molecule in the impacting structure is greater than the atomic or molecular binding energies, so the consequence of the impact is largely independent of the strength of the projectile. The craters produced by the first three S-IVB impacts were photographed from the Apollo 16 Command Module. Though the S-IVBs are low-density, fragile objects, with less mass and kinetic energy than small comets, the S-IVB craters were measured to be 40 m in diameter, which matches predicted crater sizes [*Whitaker*, 1972]. These same scaling relationships predict ~100-m craters for small comets [*Baldwin*, 1987; R. G. Strom, personal communication, 1990].

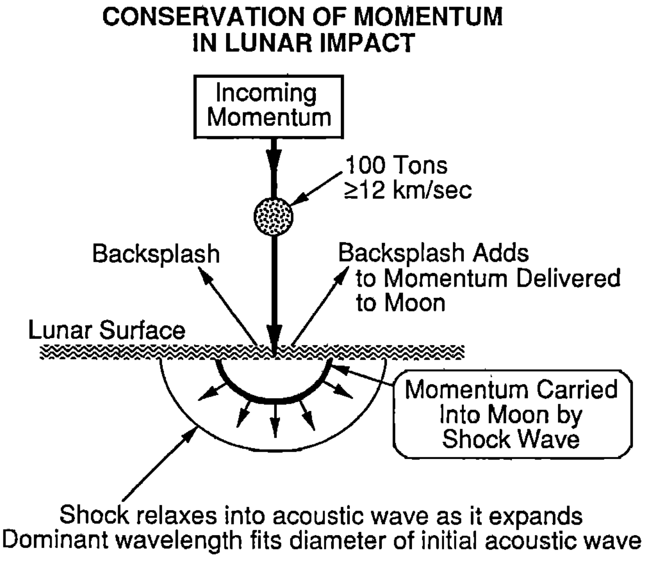


**Figure 11.** Momentum conservation in a small-comet impact with the Moon affects the resulting seismic spectrum. The speed of the comet is hypersonic (Mach 16–21) relative to seismic speed in the lunar regolith. The entire momentum of the comet, plus the momentum of any backsplash, is carried into the Moon by a shock wave. As the shock expands, its amplitude declines until it becomes a nonshock seismic wave. This earliest nonshock wave front is the seismic source region, and the dominant seismic wavelength corresponds to the dimension of the source region. The dominant seismic frequency of a small-comet impact is ~1 Hz and is within the sensitive band pass of seismometers placed on the Moon during the Apollo program.

*Davis* [1986] points out that in scaling the amplitude of impact-generated seismic waves, either energy or momentum can be used, with the momentum scaling being preferable. Because small comets strike the Moon with at least 30 times the momentum (and 150 times the energy) of an S-IVB stage, Davis argues that the seismic signals should have been easily detectable. *Nakamura et al.* [1986] conclude that the mass of the small comets would have to be reduced to 0.1 kg to avoid detection. Both Davis and Nakamura et al. contend that seismic signals would be generated by small comets in the same way as for the Apollo S-IVB impacts, and the discrepancy between observed and predicted small-comet impact rate on the Moon is $10^5$–$10^6$. This discrepancy is not based on the amplitude of the prompt signal from an impact. As indicated above, each impact causes the Moon to "ring like a bell" with a cumulative amplitude $10^5$–$10^6$ greater than that observed. While large, this discrepancy is not as large as that claimed by *Baldwin* [1987], who infers from analysis of lunar-crating records that there is a difference of a factor of about $3.3 \times 10^8$ between the expected impact rate of one small-comet per minute and the presently accepted rate of one small-comet-produced crater (diameter ≈ 100 m) every 630 years.

**4.1.1. Small-Comet Lunar Atmosphere.** *Morgan and Shemansky* [1991] have investigated the limits to a lunar atmosphere from various sources, including a small-comet source. They note that the comet-impact model of *O'Keefe and Ahrens* [1982] predicts that the Moon retains 25% of the comet material. With an impact rate of 0.86/min a substantial lunar atmosphere is formed. They point out that because the kinetic energy partitioned into the impacting water molecules is ~38% of the minimum of 14 eV = 5 eV (which is equal to the dissociation energy of water molecules), much of the impacting water is immediately converted into OH and H with the OH being of sufficiently low energy to be gravitationally retained by the Moon. At the more typical impacting energy of 21 eV it is doubtful that any of the water survives. Any water in the lunar atmosphere is broken up by solar photons within ~15 hours, adding to the OH atmosphere. For this scenario, *Morgan and Shemansky* [1991] calculate that the OH atmosphere produces a UV signal at the lunar limb of brightness 750 kR for the OH ($A - X$) transition near 3085 Å. They also show that a detectable signal results even for the lower limit obtained by adopting *FSC*'s [1986*g*] model of a near-elastic lunar impact in which small-comet water bounces back into space, leaving no residual lunar atmosphere. *FSC* [1986*g*] expect an outflow speed between ~5 and 10 km/s; they use 7 km/s as a midrange value to calculate the detectability of an outflowing atmosphere. Using these values, *Morgan and Shemansky* [1991] estimate the limb brightness is a still easily observable 50 kR. They conclude that "calculated emissions far exceed observed limits. . . . This estimate excludes a possible contribution [to the lunar atmosphere] from a small-comet source described by *Frank et al.* [1986*b*]" [*Morgan and Shemansky*, 1991, pp. 1358, 1364]. However, the search for small comets is an official mission objective for the Galileo spacecraft that passed the Earth in early December 1990. *Dessler et al.* [1990] have noted out that if such a lunar corona exists, it is detectable by the UV spectrometer on Galileo.

The analysis of *O'Keefe and Ahrens* [1982], who consider specifically the impact of low-density comets with airless planetary bodies, shows (in their section on energy partitioning [*O'Keefe and Ahrens*, 1982, p. 6676, Figure 19]) that, for a lunar impact, escaping ejecta (rock and dust as well as water) receives approximately 75% of the incoming energy of a fluffy 0.01 g/cm$^3$ comet. Their Figure 22 (which has its legend interchanged with their Figure 23) indicates that the mass of the ejecta from the Moon exceeds that of the incoming comet so, according to their analysis, small-comet impacts erode the Moon. My scaling from their Figure 22 gives an ejecta mass 6 times the comet mass for a 0.1-g/cm$^3$ comet, so 600 tons/min of lunar and cometary material should be injected into lunarlike orbits about the Earth, which creates an additional problem for the small-comet hypothesis.

### 4.2. Interplanetary Water Vapor and Insulation of Small Comets

In discussing injection of water vapor into the interplanetary medium by small comets, a range of evaporation rates and lifetimes has been used. Starting with their first interpretation paper, *FSC* [1986*b*] address the problem of evaporation of water from the small comets. They note that if evaporation proceeds as for ordinary comets, the solar-wind concentration would rise unacceptably. They therefore propose [*FSC*, 1986*b*, p. 309] that "the vaporization rate must be much less than that [of ordinary comets] and is presumably suppressed with dust mantles encompassing the small comets." Suppression by a factor of $10^3$ over ordinary comets then appeared adequate. But, following a Comment by *Rubincam* [1986], *FSC* [1986*e*] propose to reduce the vaporization rate by an additional factor of $10^3$, to $10^{11\pm0.5}/(\text{cm}^2\ \text{s})$, to keep below a limit derived from measurements of solar-wind-ion spectra. FSC arrive at this vaporization rate using a small-comet concentration of ~$3 \times 10^{-21}/\text{m}^3$, a factor of 40 times smaller than the value of $1.2 \times 10^{-19}/\text{m}^3$ in Table 1. The vaporization rate must be reduced proportionally (to ~$3 \times 10^9/(\text{cm}^2\ \text{s})$ to stay within the total mass-loading limit. *Donahue* [1987] places a more stringent upper limit on water-vapor injection by considering the effect of dissociation of $H_2O$ molecules in interplanetary space to produce H atoms, which are effective scatterers of solar Lyman-α, so even this vaporization rate is not low enough.

*Donahue* [1987] concludes that to be consistent with observations of interplanetary Lyman-α and with a small-comet concentration of $3 \times 10^{-20}/\text{m}^3$, the water-vapor production would have to be decreased from that of ordinary comets by a factor of $3 \times 10^8$. The suppression would have to be a bit more than that. The number density of small comets is 4 times larger than the number used by Donahue (Table 1). Both Donahue's criterion, derived from observations of interplanetary Lyman-α, and the FSC solar-wind limit would be satisfied if the vaporization rate were reduced to ~$10^9$ (cm$^2$ s). Such vaporization rates can, according to *FSC* [1986*e*], be achieved with an insulating mantle of only a few centimeters thickness.

As is often the case, when a parameter is changed to solve one problem, new problems are created. We review two such problems:

1. The insulation FSC postulate for small comets is so effective that planetary encounters, not evaporation, limit the lifetime of small comets. At a constant water-loss rate $R$, a small comet loses a mass equal to its initial mass in a time $M_0/(4\pi a^2 R m_w)$, where $M_0$ is the initial mass of the small comet, $a$ is its radius, and $m_w$ is the mass of a water molecule. In his Comment, *Morris* [1986] points out that the vaporization time must be accumulated near perihelion passage because, beyond a few astronomical units, the comet cools so its outgassing rate becomes negligible. A small comet with an aphelion of 500 AU has a period of 4000 years. If one third of a year of each 4000 years is spent vaporizing near perihelion and if $R = 10^9/(\text{cm}^2\ \text{s})$, the lifetime of a small comet by vaporization is $3 \times 10^{11}$ years, or 60 times the age of the solar system. Because neither the size of the small-comet reservoir in the Oort disc nor the rate of injection into the inner solar system is known, *FSC* [1986*h*] are not concerned by this limit to the lifetime. However, the long lifetime does create a new problem: *Morris* [1986, p. 1482] states that "interactions with Jupiter

would spread [small-comet] energies and orbital inclinations over a wide range." In these encounters with Jupiter, some small comets are thrown out of the solar system (thus terminating their lives as solar-system objects), but other small comets are perturbed into high-inclination or into retrograde orbits. A small comet in a retrograde orbit (inclination 180°) impacts Earth's atmosphere at an unacceptably high speed of more than 72 km/s, which would reveal their presence by emitting bright optical flashes.

The Comments of *Donahue* [1987], *Morris* [1986], and *Rubincam* [1986] thus combine to produce a logical dilemma for the small-comet hypothesis. To keep vaporization rates low so as to not violate solar-wind and interplanetary-Lyman-α observations, the comets must be insulated $10^9$ times better than ordinary comets. (One might wonder why the crusts on ordinary comets are not such good insulators as the covers on small comets, but it is clear they are inferior because Halley was observed to be outgassing while it was more than 5 AU from the Sun.) It is this excellent insulation covering small comets that creates the dilemma. A low outgassing rate implies a lifetime ultimately limited by planetary encounters that throw some small comets out of the solar system but put others into inclined or even retrograde orbits. The bright flash calculated by *FSC* [1986*b*] to be produced by such inclined small-comet orbits must be exceedingly rare because an area 50 km across, radiating a $2 \times 10^7$ rayleigh flash is akin to a nuclear explosion; it would not go unnoticed. To put this discrepancy into perspective, *Hanson* [1986] estimates that a small comet would strike the upper atmosphere within view of a ground-based observer approximately once per hour. Even if, as argued by *FSC* [1986*h*] in their Reply to *Morris* [1986], only one sixth of the small comets are in retrograde orbits, the bright flashes ought to be seen by a given ground-based observer, on average, twice per night.

2. Disposal of the insulating cover is a bothersome point. *McKay* [1986], *Morris* [1986], *Rubincam* [1986], and *Wasson and Kyte* [1987] published Comments on this point. The theme of these Comments is that the flux of insulating material, broken into pieces at the small-comet breakup radius, enters the atmosphere (where the carbon ought to burn and be seen as meteors). The carbon and other material that does not burn descends through the atmosphere to the surface where much of the material contributes to sediments on the ocean bottom. The Comment by *Wasson and Kyte* [1987] is perhaps the most comprehensive on this point; the reader is referred to both that paper and the accompanying Reply by *FSC* [1987*b*], which, written at the end of the series of Comments and Replies, contains the best defense of the small-comet hypothesis with regard to this topic. According to *Wasson and Kyte* [1987], while ordinary comets contain 20–40% chondritic rocky matter by weight, small comets must contain $3 \times 10^9$ times less rocky matter. This limit means that the interior and the insulating layer of each small comet cannot contain more than about 0.3 g of rocky material. Why then are these comets, which are held to consist of almost pure water, so well insulated? Is the progenitor of the insulating material contained within each small comet? Wasson and Kyte argue that there is less material and less gravity to work with in small comets, so they should have thinner insulating mantles than ordinary comets. The insulating mantle proposed by FSC constitutes a disposal problem because it must be gotten rid of without producing an overt signal. A layer 4 cm thick, of mass density of 0.1 g/cm$^3$, covering a 6-m-radius sphere, has a mass of nearly 2 tons. As pointed out in section 2.1, the insulating material must be as fragile as the small-comet itself so it can be broken up in a few seconds at altitudes near 3000 km. Do the tons of insulation break into a few large chunks or many small pieces? FSC propose the insulator to be largely carbon or carbon polymer compounds. Can tons of carbon or carbon polymer enter the atmosphere at 20 km/s and not produce a visual display? In their Reply, *FSC* [1987*b*] review their earlier proposal of a special formation mechanism for small comets from water and other volatiles, avoiding contamination by silicates and chondritic matter. They do not discuss the possibility of visual displays from atmospheric entry of pieces of carbon insulation.

**4.2.1. Hydrogen Torus at 1 AU.** In his first paper on interplanetary Lyman-α from small comets, *Donahue* [1987, p. 213] states, "A contribution to the interplanetary Lyman-α radiation at 1 AU of as much as 25 R by the hydrogen associated with small comets would have been detected as a signal rapidly decreasing with heliocentric distance by the ultraviolet spectrometers on Voyager 1 and 2." To test for the existence of such a signal, *Donahue et al.* [1987] analyzed Voyager ultraviolet spectrometer (UVS) data from Voyager 2. They reported that a Lyman-α signature near 1 AU was indeed present; an extra 168 rayleighs had appeared, "decreasing rapidly (between $r^{-3}$ and $r^{-4}$) with heliocentric distance" [*Donahue et al.*, 1987, p. 548]. They proposed that the hydrogen causing this signature comes from "a very large number of 'cometesimals' with radii between a few metres and a few tens of metres in the neighborhood of the Earth" and further proposed "that these cometesimals are ice-coated, porous, low-density refractory boulders" [*Donahue et al.*, 1987, p. 548]. In some ways, these sounded a lot like the small comets of FSC. But, Donahue et al., by proposing a low concentration of cometesimals, distanced themselves from the many problems with the small-comet hypothesis that had become evident by the time the Donahue et al. paper was being submitted (mid-1987). They reduced the small-comet concentration by having clean ice coating a rocky core. With the assumption of no insulation the vaporization rate rose to $3.9 \times 10^{17}/(\text{cm}^2\ \text{s})$, which was approximately 7 orders of magnitude greater than the vaporization rate of $\sim 10^{11}/(\text{cm}^2\ \text{s})$ that FSC were then using, so the concentration of the cometesimals was a factor of $10^7$ smaller than the FSC concentration of small comets.

This was a high point for the small-comet hypothesis. Donahue et al. were independent observers coming forth with new evidence that this class of object (icy, ~12 m, and in small-comet-like orbits) actually existed. At this point, as the punch line in the allegorical joke goes, they were only "haggling over the price." One might imagine FSC perhaps giving up on ocean formation and reducing their small-comet concentration by $10^{3.5}$, and Donahue et al. adding some insulation to their cometesimals and increasing their concentration by $10^{3.5}$.

Even before the Donahue et al. paper appeared in print, *FSC* [1987*c*] had submitted a paper to *Nature* referencing the Donahue et al. preprint and showing how the new Lyman-α observations "support the controversial hypothesis by *Frank et al.* [1986*b*] that a large flux of small comets is presently impacting Earth's atmosphere" [*FSC*, 1987*c*, p. 1]. Unfortunately for the small-comet hypothesis, the support by Donahue et al. was short-lived. Less than 1 year later, a paper by *Hall and Shemansky* [1988] showed that there was an error in the Donahue et al. analysis. According to *Hall and Shemansky* [1988, p. 419] "there is no systematic evidence for a local source of atomic hydrogen in the Voyager data." They also lowered the earlier limit of 25 R used by *Donahue* [1987] to 20 R. The UV spectrometer on the Galileo spacecraft will test this limit in its two flights past Earth (via Venus to Jupiter) [*Frank and Sigwarth*, 1989].

**4.2.2. Earth as a Comet.** *Dessler et al.* [1990] note that a small comet crossing the breakup radius has no knowledge of whether it is going to hit the Earth, trajectories 1 or 2, or miss it, trajectories 3 or 4. Unless the breakup mechanism is, somehow, able to discriminate between hits and near-misses, a cometlike tail consisting of water and pieces of thermal insulation will extend from Earth. Small comets on trajectories such as trajectory 3 in Figure 7 will, following the standard properties of small comets, breakup and vaporize within, say, 30 s, but then the water vapor returns to interplanetary space. (The same process may occur at other planets that can support the same breakup mechanism as does Earth.) The result is a 60° half angle, cone-shaped spray of water vapor extending in the Earth's orbital direction [see *Dessler et al.*, 1990, Figure 2].

Using the ratio of trajectory areas in Figure 7, Dessler et al. argue that the flux of small comets that disintegrate near Earth but then miss it is comparable to the impacting flux. They obtain 14 small comets/min breaking up but missing Earth's atmosphere. This corresponds to ~24 tons/s of water vapor (nearly $10^{30}$ $H_2O$ molecules) streaming from the Earth at a relative speed of just over 12 km/s, somewhat like a comet tail. Such a water flux is significant as can be judged by the direct measurements of comet Halley that show approximately 20 tons/s of gas issuing from it at 1 AU, and 80% of this gas (16 tons/s) is water vapor [*Krankowsky et al.*, 1986]. The water dissociates into H and OH within about $10^5$ s, to form a cometlike tail of Earth that would be detected by virtually any ground-based or space instrument that could see atomic and molecular spectra of H and OH from comet Halley. The DE imager is among such instruments, having made valuable measurements of the hydrogen created by photodissociation of water issuing from Halley [*Craven and Frank*, 1987; *Frank and Craven*, 1988]. *Dessler et al.* [1990] point out that it is probably significant that such an induced cometlike tail has not already been detected by, say, the IUE spacecraft that should have noted an anomalous increase in UV sky brightness when looking in the direction of the Earth's velocity vector. On its two Earth flybys the UV instrument on Galileo will scan in directions appropriate to detect such a cometlike tail of Earth.

## 5. OTHER EVIDENCE

An interesting new discovery is typically swamped by independent verification (e.g., high-temperature superconductivity) or denial (e.g., cold fusion). As of this writing (March 19, 1991), seven separate verification tests of the small-comet hypothesis have been published, five of which have already been discussed: (1) search for direct ionospheric effects of water-vapor-cloud passage (section 3); (2) lunar-seismometer survey for small-comet impacts (section 4.1); (3) a lunar atmosphere induced by small comet impacts (section 4.1.1); (4) search for a hydrogen torus at 1 AU (section 4.2.1); (5) a cometlike tail of Earth (section 4.2.2); and two others to be discussed below: (6) detection of atmospheric dark spots by other satellite UV imagers; and (7) telescopic or visual sightings of small comets, either before or after breakup.

### 5.1. Atmospheric Holes: Viking Results

A classic test of an experimental finding is its reproducibility. An obvious thought is that the impact of 50-km-diameter, 100-ton clouds of water vapor nearly 30,000 times per day ought to be visible to some instrument other than the imager on DE 1. For example, *Banks* [1989] has shown quantitatively that small-comet impacts should create bright IR signatures. Similarly, *Anger et al.* [1987*a*] examined data from their UV imager on the Viking satellite and reported that they did not find any cometary "holes" in an initial inspection of their relevant UV images. "However," they say [*Anger et al.*, 1987*a*, p. 386], "based on their reported optical characteristics, extensive analysis will need be done to determine whether the Viking UV data can support or deny the existence of this phenomenon." In an analysis of this finding of *Anger et al.* [1987*a*], *Frank and Craven* [1988, p. 268] write that because of the wide band pass of the instrument, "the detection of atmospheric holes is not possible with Viking unless there is some small portion of the field of view that is not overwhelmed with long-wavelength radiation or auroral emissions as determined with the Viking imaging instrumentation." However, in their paper describing the Viking imager, *Anger et al.* [1987*b*] provide band-pass information (see their Table 1) showing that, while the criticism by *Frank and Craven* [1988] is valid for "Camera 0," it is not valid for "Camera 1." This must indeed be the case because, shortly after writing the review paper [*Frank and Craven*, 1988], *Frank et al.* [1988*a*], using Viking imager data from camera 1, with S. J. Murphree (the Principal Investigator for the Viking UV imager) and his colleague L. L. Cogger listed as coauthors, report confirmation of the atmospheric dark spots at the AGU 1988 Spring Meeting. Murphee and Cogger's names on the abstract gave added credibility to the claimed finding; but, their names do not appear on the subsequently published paper [*FSC*, 1989].

In a personal communication, S. J. Murphree (the Principal Investigator for the Viking UV imager) disagrees with FSC on the statistical significance of the dark spots and because a few dark spots are present in calibration images in which an electron flux generated an essentially uniform background. Murphree writes, "the fact that depressed pixels could be found in the few such [calibration] examples we have is I think strong evidence against a geophysical source for the pixel depression [i.e., dark spots]." *Cragin* [1990] presents detailed criticisms in which he too argues that the Viking results of *FSC* [1989] are statistical fluctuations, and he reports on the statement by Murphree that dark spots appear in the calibration data, which shows they are instrument artifacts and not real geophysical effects. The Reply to Cragin by *FSC* [1990*a*] does not directly address the arguments raised but restates the points originally made *FSC* [1989]. The idea that the dark spots from the DE imager (as shown in Plate 1) may also be a form of instrument artifact is discussed in section 6 of this review. In the future, other satellites, such as the recently launched Japanese satellite Exos-D, may be able to test the reproducibility of the atmospheric dark-spot phenomenon.

### 5.2. Direct Detection

With the number of small comets near Earth being large (see Table 1), should they be visible using telescopes, or even the naked eye? Telescopic observations are difficult because small comets are small and dark, and, except for certain favorable viewing directions, they move at an angular rate that is large for astronomical objects. Still, small comets should be seen by telescopes designed to search for satellites, satellite debris, and asteroids. Also, small comets should be visible following breakup when a cloud of ice crystals expands outward from the disrupted comet.

**5.2.1. Optical Detection.** Can the small comets be detected with optical telescopes? Two such searches having roughly comparable sensitivities have been reported. One search was a retrospective analysis of data obtained in a search for asteroids and small space debris orbiting Earth. The retrospective analysis is reported in a comment by *Soter* [1987]. He begins by reasoning that with nearly $3 \times 10^7$ small comets within a spherical volume bounded by the Moon's orbit, "many of them should have been observed by instruments used to survey artificial satellites and debris" [*Soter*, 1987, p. 162]. The angular velocity of small comets is a predictable function of the viewing direction. A maximum angular velocity occurs for small comets passing through the plane containing Earth and perpendicular to the Earth's orbital velocity vector (e.g., passing through the Earth's shadow). The angular velocity is a minimum for small comets approaching Earth with an impact parameter less than about 2 $R_E$ (see Figure 7).

Soter performs a retrospective analysis of telescopic data acquired by *Taff* [1986] before the small-comet hypothesis was advanced. One specific purpose of these data was to find faint, slow-moving objects [*Taff*, 1986] for which the limiting magnitude is $m_v$ = 17.7. The reason for the requirement of small angular movement is to keep a spot of light on a single charged-coupled-device pixel long enough to overcome background noise. Soter assumes that the small comets have an albedo of 0.02 and concludes that, for the cases of small angular motion, they should be visible out to distances ~16 $R_E$. Near the breakup distance the small comet should be ~$10^3$ times brighter, which implies $m_v \approx 10$. The search covered more than 200 hours of observing time at all hours of the night during 1977–1981, mostly in September–October and February–March. Soter concludes that the detection rate should have been ≈250/h when looking in the most favorable directions, i.e., those in which small comets have minimum angular velocity as viewed from Earth. The sensitivity of this search is indicated by the claim that even if the radii of the small comets were halved and their albedo reduced by a factor of 10, the detection rate still should have been several per hour. The observed detection rate was only 1/h, and these streaks were claimed to be consistent with those of distant artificial satellites.

In their Reply, *FSC* [1987*d*, p. 164] argue that "Soter grossly overestimates this detection rate by not recognizing the importance of (1) the minimum of cometary fluxes during the observing period with the telescope and (2) the broad range of possible physical properties of these small comets." With regard to point 1, FSC show in Figure 1 of their Reply that the rate of occurrence of atmospheric dark spots declines from near normal in early November to about one-tenth the normal rate by mid-January. They calculate an early-November flux of small comets of ~$7.2 \times 10^{-10}/(\text{km}^2\ \text{s})$, declining by a factor of 10 by mid-January. (The reality of this claimed annual variation is discussed briefly in section 6.) *FSC* [1987*d*, p. 166] further state that all the observations used by Soter were taken in the months of January and February, although Soter states that the observations were made in September–October and February–March. With regard to point 2, FSC argue that the phase function for the small comets is different from the value assumed by Soter, although their minimum value of phase function (which gives the highest anticipated detection rate) agrees with Soter's value.

The observed rate of faint, moving objects is given as 1–5/h by *FSC* [1987*d*] and 1/h by *Soter* [1987]; Soter quotes *Taff* [1986] and FSC quote a personal communication from L. G. Taff (1986) as their sources. FSC indicate that some of Taff's sightings may be of small comets. FSC and Soter agree on the formula for calculating the brightness of the small comets, yet, according to *FSC* [1987*d*, p. 167], "Soter overestimates the detection rates of the proposed small comets . . . by factors ~$10^2$ to $10^3$." Reasons for this difference are as follows: First, Soter uses a higher space density (and hence flux) for small comets. (Soter uses the space density listed in Table 1.) Second, FSC hold that Soter's observations were made in January and February while Soter claims they were made in September–October and in February–March. Third, FSC reduce the detection threshold of the telescope to $m_v$ ~16 (instead of the value of 17.7 used by Soter). The reason for this reduction in sensitivity by FSC is because in routine surveys the telescope has a limiting magnitude of 16.5, and in twilight conditions the high sensitivity of 17.7 is degraded by 1–2 magnitudes. Soter argues that observations were made at all hours of the night, and the maximum sensitivity of the telescope (avoiding twilight) is applicable.

If we accept Soter's statements that (1) observations were made in September–October, (2) the telescope was operated at maximum sensitivity at times removed from twilight, and if we use the small-comet flux of $1.5 \times 10^{-9}$ /(km$^2$ s), then the "early November" numbers in the columns $M_v$ = 17 or 18 of FSC's Table I (multiplied by a factor of 2 to correct for the lower flux used by FSC) bring the two papers into agreement. Even with the largest value for phase function proposed by FSC, and at a threshold of $M_v$ = 17, the September–October anticipated detection rate is 19/h for 8-m-diameter small comets with albedos of $5 \times 10^{-3}$. This is a minimum anticipated rate, and it is an order of magnitude greater than the observed rate. If we return to the standard 12-m small comet, an albedo of 0.02, and a phase function like that observed for dark interplanetary objects, the discrepancy between anticipated and observed rates rises to ~$10^3$.

A second telescopic search for the express purpose of looking for small comets was carried out by *Yeates* [1989], who introduced a clever idea to improve the sensitivity of satellite-asteroid search telescopes when viewing fast-moving objects. As remarked earlier, the sensitivity of the search is increased if the spot of light from a faint object can be kept on a single CCD pixel long enough to build up a sizeable signal. Thus Soter's data have maximum sensitivity when the telescope is pointed in the plane of the ecliptic and perpendicular to the Sun-Earth line and is driven to cancel the Earth's rotation. This viewing direction has the disadvantage of involving 90° phase illumination, which lowers the effective albedo of the already dark small comets. Yeates reasoned that the sensitivity could be improved if the telescope could track small comets as they pass near Earth. Because the orbits of small comets are reasonably well defined, their angular velocities as a function of distance and viewing direction are equally well defined. Yeates originated a simple but effective idea of looking near the anti-Sun direction, but outside the Earth's shadow, in which case the phase-function value (the albedo) should be a maximum, and shutting off the telescope's sidereal drive to let the rotation of the Earth turn the telescope to track small comets that are a distance $r = V_{CE} \cos \alpha / \Omega_E$, where $V_{CE}$ is the velocity of a small comet relative to Earth, $\alpha$ is the angle in the ecliptic plane measured from the anti-Sun direction, and $\Omega_E$ is the angular velocity of Earth's rotation. Yeates obtains a nominal detection distance of 22 $R_E$ for an object with $m_v$ = 18. A specifically designed experiment such as this has advantages over retrospective analyses such as the one carried out by *Soter* [1987]. The results of the search by Yeates was reported at the same 1988 AGU meeting as the *Frank et al.* [1988*a*] presentation of Viking imager corroboration of the DE dark-spot phenomenon. The AGU report was apparently prepared too late to allow publication of an abstract in the meeting issue of *Eos Transactions AGU*. This paper was subsequently published [*Yeates*, 1989]. Yeates' AGU report, coupled with the *Frank et al.* [1988*a*] report of apparent replication of the DE dark spot by the Viking imager, momentarily gave the small-comet hypothesis significant standing. Recall that at this time, the paper announcing the discovery of a hydrogen torus at 1 AU produced by (only a few) cometesimals [*Donahue et al.*, 1987] had been published, but the paper showing that this was not so [*Hall and Shemansky*, 1988] had not yet been submitted for publication. This report by Yeates fit into a developing pattern of support for the existence of a previously unsuspected population of small comets.

Yeates varied his look directions and argued that faint short streaks in the CCD images were consistent with predicted rates and motions of the small comets. Analysis of pictures of the claimed small-comet detections [*Yeates*, 1989] supports the occurrence rates and motions predicted by the small-comet hypothesis. Moreover, Yeates reported that the streaks disappeared, as expected, when the sidereal drive was turned on so the telescope tracked stars instead of the small comets. But, the small-comet streaks are faint, near the background noise level, and the noise level depends on whether or not the sidereal drive is on or off (T. Gehrels, personal communication, 1990). None of the small-comet streaks are brighter than threshold level, i.e., there is little variability in brightness. The traditional requirement for positive identification of a faint object is to see it twice. An extension of the above work of *Yeates* [1989] was presented at the 1988 Fall AGU meeting by *Frank et al.* [1988*b*] in which the requirement for two consecutive sightings of the same small comet was apparently met. *Frank et al.* [1990*b*] subsequently published these data. The paper by *Yeates* [1989] shows one such pair of images.

A problem with this claimed detection is that the images look to many experienced observers to be much like noise. In spite of the ordinarily convincing agreement with theoretical predictions based on the small-comet hypothesis, most members of the community of observers are not convinced that Yeates has seen the small comets. E. Shoemaker, an active and successful hunter of comets and asteroids, is quoted as saying "He [i.e., FSC] is pushing right against the noise limit. When you look for rare things, you can find all kinds of flukes. They don't look convincing to me. I would want three [consecutive] images, and then I would be convinced. If they were strong images, two would suffice" [*Kerr,* 1989]. The images displayed by *Frank et al.* [1988*b*] were obtained with the Spacewatch camera, of which T. Gehrels is the Principal Investigator. Although Gehrels is included in the author list of the *Frank et al.* [1988*b*] abstract, he did not agree with the identification of these images as small comets. (His name does not appear in the *Frank et al.* [1990*b*] publication.) Immediately on learning he was listed on the abstract as a coauthor, T. Gehrels (personal communication, 1990) asked that a statement giving the reasons for his disagreement be posted alongside the Frank et al. poster display. The statement is reproduced here because it is indicative of why the small-comet images published by Frank et al. and by Yeates are not accepted as such by most experienced observers. The entire statement reads as follows: "Evaluation of Cometesimals, November 1988, Tom Gehrels. If there indeed were as many cometesimal events in the noise of our CCD frames as L. A. Frank and C. M. Yeates believe, I would expect a noticeable distribution in their size and distance such that occasionally we should see a convincingly bright event. The images that have been shown to us are unconvincing, and this includes the observation of 19 April 1988 for repeated events. Anyone can look at the pictures released by Yeates and Frank and decide for oneself. Before believing the discovery of cometesimals, a new type of population in the solar system, one would want to see a few good images. Independent observations are needed. (signed) Tom Gehrels, Spacewatch P.I."

Thus two complementary telescopic searches with similar sensitivities have failed to produce convincing evidence of the existence of small comets. It must be explicitly recognized that this conclusion is not shared by *Frank et al.* [1990*b*]. However, the consensus of other astronomers is that the purported sightings are CCD instrument noise.

**5.2.2. Visual Detection.** Both *Soter* [1987] and *FSC* [1987*d*] note that the brightness of the small comets should increase after fragmentation, with FSC estimating that the brightness should approach second magnitude for a few seconds. FSC do not say how they calculated the brightness increase, but we can guess that the primary reason is the increase in visible surface area after disintegration. For a dispersed cloud of 30-μm spherical particles the visible exposed area is 2.5 $\text{km}^2$ as compared to 113 $\text{m}^2$ for the intact small comet. The visible ice area increases linearly with decreasing size of the ice particles. For this surface area calculation I assumed the ice particles were spherical, which gives the minimum area per unit mass. The crystal shapes are almost certainly dendritic, so the visible area, and therefore the brightness, are greater than indicated by the above increase in surface area. The ice crystals can be considered to be relatively clean because, to make much difference in single-particle albedo, addition of a significant mass of dark material to the small comet would be required. This would compound the problems of disposition of nonwater components, for example, the darkening agent in addition to the surface insulation (see sections 4.2 and 2.2.2).

The expected frequency of visibility of the small-comet ice clouds depends on the latitude and season of the observer. A few freehand sketches should convince the reader that high latitudes provide the most favorable viewing locations and equatorial latitudes the worst. Estimating the time interval of visibility of these ice clouds depends on whether or not you take the experiments reported in sections 2.2.1 and 2.2.2 as applicable to small-comet ice. If they are applicable, the ice clouds would be visible for ~1 hour; otherwise, they could be seen for the assumed sublimation time of about 10 s. As yet, there are no confirmed sightings of small-comet clouds after breakup.

We have reached a point in this review where it is no longer necessary to suspend disbelief in order to continue. We now deal with a different hypothesis.

## 6. THE INSTRUMENT-ARTIFACT HYPOTHESIS

The senior member of the FSC group is one of the world's most experienced space experimentalists for whom the pitfalls of data artifacts are well known. The idea that the dark spots might be some sort of instrument artifact was considered by FSC at the outset. In their initial observation paper, *FSC* [1986*a*, p. 303] state, "Considerable scrutiny of the measurements is used to demonstrate that these atmospheric holes are not due to telemetry noise or other spurious effects." No other possible sources of noise are discussed.

One of the earliest Comments advanced the thesis that the dark spots are instrument artifacts [*Chubb,* 1986]. The Comment opens with arguments that the DE instrument might produce random dark pixels, "probably the result of cosmic ray interactions with photometer or electronics" [*Chubb,* 1986, p. 1075]. These arguments, while perhaps plausible, are not testable without retrieving the instrument to run appropriate laboratory experiments. However, Chubb advances some simple, testable ideas that argue against the dark pixels being a geophysical phenomenon. Chubb points out that a geophysical interpretation of the dark pixels requires that at intermediate and low altitudes, strings of darkened pixels should be the rule. This effect is illustrated in Figures 12*a* and 12*b*. Figure 12*a* shows a cloud with angular diameter 0.29° as seen from apogee (altitude 3.6 $R_E$). In Figure 12*b*, DE is about 3 times closer to the same cloud. DE is 1 $R_E$ above the cloud (spacecraft

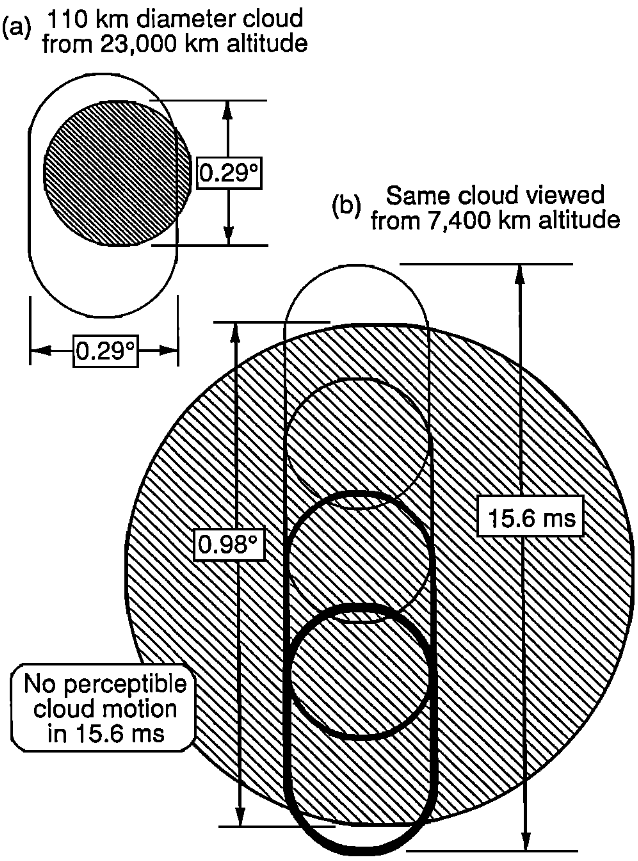


**Figure 12.** Pixel-darkening pattern caused by a small-comet water-vapor cloud as seen at different spacecraft altitudes. The cloud in this example has a diameter of 110 km and is at an altitude of 1000 km (400 km above the dayglow layer). (*a*) The cloud is shown within the field of view of a single pixel of the DE imager while the spacecraft is near apogee (3.6 $R_E$ altitude and 3.45 $R_E$ from the cloud). The angular diameter of the cloud, which in this example is 0.29°, darkens the pixel by 50–80%. (*b*) The same cloud as in Figure 12*a* but with DE closer is also shown, so the cloud has an angular diameter of 0.98°. In this case, six dark pixels in a row are expected, the four that are shown plus two overlapping each end. Contrary to this expectation, dark pixels occur invariably as single-pixel events, independent of spacecraft altitude [*Cragin et al.*, 1987]. Two-pixel events are seen occasionally, three-pixel events only two or three times, and four- to six-pixel events, never. This finding is not consistent with the small-comet hypothesis, but it fits the instrument-artifact hypothesis. To avoid this problem, *FSC* [1987*e*] have proposed a dark spot of constant angular extent (see Figure 13).

altitude 1.05 $R_E$), and the cloud subtends 1° angular diameter. A cloud of this angular size can darken six sequential pixels, the four shown plus one additional pixel at each end. The four shown will be darker than the single pixel near apogee (Figure 12*a*). We focus on the four central pixels. The time to acquire data for these pixels is 4 × 3.9 ms = 15.6 ms. The cloud cannot move noticeably during this interval. There should be an altitude-dependent progression of sequential pixels, starting with mainly single-pixel events at apogee but increasing numbers of dark pixels in a string as altitude decreases. The example of Figures 12*a* and 12*b* shows that four to six pixel strings in a single line scan should be the rule at altitudes around 1 $R_E$.

*Chubb* [1986, p. 1076] raises a second point, namely that because there is significant overlap between consecutive pixels, if one pixel is darkened by the usual 80%, the preceding and following pixels should be also, although not as much. This "should create an asymmetry in the recorded images that makes the [roughly north-south] roll scan direction obvious." This effect is illustrated in Figure 12*b*.

*FSC* [1986*c*, p. 1079] respond, "It is not possible for the present authors [FSC] to reasonably attribute these observations to an instrumental artifact." The reasons given are (1) their several years of effort in investigating and discarding this possibility and (2) similarities in time variations between small-comet and radar-meteor rates. On the occurrence of multiple darkened pixels, they return to a point made earlier [*Frank et al.*, 1986*a*, p. 304]; darkened pixels sometimes appear next to each other on adjacent scan lines, but seldom on the same scan line. (Recall that pixels on adjacent lines are separated by 6 s while adjacent pixels on the same line are separated by 3.9 ms.) They use these observations of dark-pixel pairs to show in their Reply [*FSC*, 1986*i*, p. 1080, Figure 3] that most (but not all) of the dark spots move east to west, as called for by the prograde orbits of small comets. FSC call on an orbital inclination of 35° to fit these observations of (backward) west-east motion. I have not been able to reproduce the backward motion with such a small inclination angle.

*FSC* [1986*i*, p. 1081] agree that at lower altitudes, "consecutive pixels with decreases of responses [i.e., darkened pixels] due to the occluding water vapor are expected for a single scan line." But, they restrict their search for consecutive pixels to a DE altitude range of 1000–2000 km where the spacecraft spends little time and has a small view of the Earth; few clouds are therefore expected. They report that in 130 orbits, during "$4.8 \times 10^4$ seconds, two atmospheric hole sightings with three consecutive darkened pixels in a single scan line are found" [*FSC*, 1986*i*, p. 1082]. FSC do not discuss the lack of the expected asymmetry in the spacecraft roll (i.e., scan line) direction. Their finding of only two darkened pixel strings is consistent with neither simple expectation nor their own Figure 4, which shows a 50-km cloud subtending an angle of 1.9° at these altitudes. The pixels are 0.23° apart, so a string of 1.9°/0.23° ≈ 8 darkened pixels should have been seen (or ~18 pixels for the larger cloud shown in Figure 12*b*). FSC do not discuss observations from intermediate altitudes (~1 $R_E$) where more observing time is available and where three to five dark-pixel strings should be commonplace.

The instrument-artifact hypothesis allows us to understand an otherwise odd claim by *FSC* [1987*d*] of a long-term correlation between small comets and backscatter observations of radar meteors. (I regard the claim as odd because forward-scatter radio or telescopic observations of meteors show qualitatively different time dependences [e.g., *McKinley*, 1961, p. 114, Figure 5-5]. Also, the diurnal variations in small-comet event rate shown by *FSC* [1986*a*, Figure 5] are unlike any of the radio-meteor observations [*Chubb*, 1986].) FSC report a factor of 10 decline in small-comet event rate between early November and mid-February 1981–1982. W. B. Hanson (personal communication, 1989) has pointed out that they deduce this time dependence by examining dark-pixel occurrence over a fixed area. *FSC* [1987*d*] do not claim that the dark-pixel rate of one in 800 changes with time, only that the event rate per unit area changes with time. (In such analyses a multiple-pixel string, illustrated in Figure 12*b*, is taken to be a single event.) With a fixed dark-pixel rate the rate per unit area varies inversely with the square of the distance between the imager and the area and directly with the cosine of the angle between the viewing direction and the normal to the area, i.e., it would be a sensitive function of altitude and location in solar ecliptic coordinates. One cannot tell from the evidence presented by *FSC* [1987*d*] whether the change with time is a geometric or a temporal phenomenon. Until we have more information, it is unproductive to examine this point further.

*Cragin et al.* [1987] extend the instrument-artifact hypothesis and make it quantitative using UV-imager data obtained from the FSC team. Specifically, they studied 182 mission analysis files covering altitudes from about 1100 to 23,300 km (0.17–3.66 $R_E$) during an 11-day period starting September 23, 1981. They performed extensive statistical analyses and made two principal findings. (1) The expected darkening of adjacent pixels does not occur. (2) More importantly, dark-pixel events are predominantly single-pixel events, independent of spacecraft altitude, and their occurrence rate is one in 800, also independent of altitude. This finding argues persuasively against any geophysical cause of the atmospheric dark spots.

*FSC* [1987*e*] devote most of their response to Cragin et al. to explaining why, at large distances, pixels adjacent to a dark pixel in a scan line are not darkened somewhat by pixel overlap. To do this, they introduce two new features for their small comets: (1) a large, bright, semiannulus surrounding each dark spot; and (2) a constant dark spot diameter of 0.33°, apparently independent of altitude. The arrangement, shown in Figure 13, is adapted from *FSC* [1987*e*, Figure 3]. The semiannulus is 1.8 times brighter than the average dayglow. According to *FSC* [1987*e*, p. 579], "The luminosity can be due to the impact of exospheric neutral gas and of ionospheric ions onto the cometary gases facing the direction of motion." Calling on the impact of "ionospheric ions onto the cometary gases" would appear to be inconsistent with their earlier Reply to Hanson [*Frank et al.*, 1986*d*] in which the passage of a small comet left the ions in the ionosphere relatively undisturbed (see Figure 4). The bright cap or semiannulus is a subject of ongoing investigation [*Sigwarth et al.*, 1988] and is not yet available for study in a refereed journal. Their abstract describes a model that involves either "the direct impact of atmospheric O atoms on cometary $H_2O$" or "charge exchange of cometary $H_2O$ with ambient O+ ions." Because atmospheric O or O+ is involved, this model for creating the bright semiannulus (or hemispherical cap) will not work above 1000 km where the O and O+ concentrations are negligible. Thus it appears that the bright semiannulus will not work where it is needed, i.e., when the small comet is at higher altitude. Also, *FSC* [1989] do not report confirming evidence for existence of the semiannulus in the Viking images (section 5.1).

The bright feature solves one aspect of the overlap problem by putting compensating light into adjacent pixels that would otherwise be darkened by a dark spot. *FSC* [1987*e*] show that with the dark and bright areas of fixed angular size shown in Figure 13, they can reproduce their observations. But, by fixing the angular diameter, a new problem appears. Their fixed-angle dark spot has a linear diameter that is a function of viewing altitude. When DE is at 3.15 $R_E$, the dark spot has a diameter of 110 km. This same linear size cloud and bright semiannulus do not solve the pixel overlap problem if the spacecraft altitude is reduced to, say, 1.25 ± 0.25 $R_E$ (where the spot and semiannulus would be ~3 times the angular size at apogee) because one would then expect several dark pixels in a row followed by several bright pixels in a row. There is no compensation for overlap by the bright area if the spot angular size is larger than that of a pixel. Thus when DE is near 1.25 $R_E$, the cloud linear diameter must be reduced to ~35 km.

*FSC* [1987*e*, p. 580], at the end of their Reply, address the altitude dependence of multiple darkened pixels. They

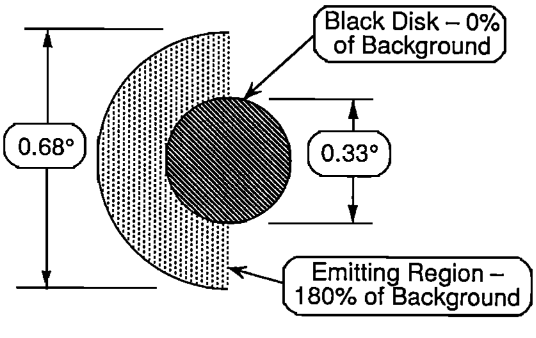


Figure 13. A feature of small-comet atmospheric entry introduced by FSC to avoid one of the problems caused by pixel overlap (section 6). *FSC* [1987*e*, Figure 3] propose that a bright semiannulus is attached to each dark spot. By adding this bright semiannulus (80% brighter than the dayglow), FSC leave the dark spot unaltered but place compensating light in adjacent pixels. This avoids the contiguous dark-pixel problem, but only for the fixed angular (not physical) dimension shown. Because they specify only the angular dimension of this object, its physical size must vary with spacecraft altitude. The bright semiannulus was not reproduced by the Viking satellite pictures [*FSC*, 1989].

note that "some increase in the number of consecutively darkened pixels, or double pixels, is expected with decreasing altitude." For the data set used in the analysis for their Reply, FSC report four double pixels at 3.15 ± 0.15 $R_E$, 12 double pixels at 1.8 ± 0.3 $R_E$, and 12 at 0.75 ± 0.25 $R_E$. This data set produced only one event with three consecutive darkened pixels, which they say is "expected at the lowest altitude." No string of four or more darkened pixels is reported.

It might appear that FSC, by adopting a fixed angular size for the small-comet water-vapor cloud, have come to an unspoken agreement with some of their critics to the effect that dark pixels appear predominantly as single-pixel events, independent of altitude. But, *FSC* [1987*e*, p. 580] state that they disagree with the findings of *Cragin et al.* [1987] and claim that their differences are due to "an incomplete theoretical treatment and an insufficiently large set of data" used by Cragin et al. Although the statistical analysis contained in the Comment by *Cragin et al.* [1987] undoubtedly makes for tedious reading, I found their theoretical treatment to be sound. An increase in multiple pixels with decreasing altitude, as called for by *Chubb* [1986] and by Cragin et al., is such a powerful first-order effect that it must be seen in just a few pictures taken at different altitudes, or the small-comet hypothesis fails in a fundamental way. At low altitudes, events consisting of six to 18 dark-pixel strings should be the rule. One would infer from their newest model (Figure 13) that there should also be, on average, even longer strings (six to 35) of bright pixels caused by the bright semiannulus. Neither of these is seen in the DE data.

The instrument-artifact hypothesis offers simple explanations for otherwise puzzling dark-pixel data. For example, *FSC* [1986*a*, p. 306] report that dark pixels are seen above the Earth's limb when looking at the geocorona. *FSC* [1986*i*, p. 1082] state that the inferred altitude of the water-vapor cloud "is based upon the assumption that the comet disrupts and vaporizes at the lowest possible altitude, ~several thousand kilometers. . . . It is possible that the water vapor clouds . . . are positioned at altitudes of 5000–10,000 km." As pointed out in section 2.1, breakup at altitudes above 1000 km is unexplained. If small comets can disintegrate at virtually any altitude, problems such as water-vapor deposition in the ionosphere (section 3.1.1) and the addition of H and OH in a stream issuing from the Earth's vicinity (section 4.2.2) are compounded. According to the instrument-artifact hypothesis, dark pixels appear in images of the geocorona simply because one in 800 pixels is dark; the observation becomes an instrumental, not a geophysical, effect. With one pixel in 800 randomly turning dark, a statistical fluctuation yielding two adjacent dark pixels is a reasonable expectation [*Cragin et al.*, 1987]. However, a three-dark-pixel event is extremely rare, and four sequentially dark pixels is an almost impossible random coincidence.

## 7. SUMMARY

I believe it is fair to say that things look bleak for the small-comet hypothesis. On close inspection the FSC small-comet hypothesis papers (particularly the Replies) seem permeated with difficulties. The small-comet hypothesis does not solve any long-standing problems or unify dissociated fields of research. Rather, it creates problems. However, I believe all would agree that if compelling evidence made the small-comet hypothesis tenable, a way would be found to accommodate it. And, after modification and transformation of several fields of research were accomplished, the affected sciences would be healthier and infused with new vigor. But this is not what is happening.

We have examined the basic premise of the small-comet hypothesis and found physical problems and internal inconsistencies (section 2). Incompatibilities with the weight of years of accumulated geophysical knowledge indicate that the small-comet hypothesis is not valid (sections 3 and 4). So far, most of the efforts to verify the small-comet hypothesis have, instead, negated it (section 5). A divergent hypothesis, the instrument-artifact hypothesis, is able, neatly and economically, to accommodate all the known facts (section 6). There are internal inconsistencies; some, such as the size of the water-vapor cloud that produces a dark pixel, are minor. But, they lead to larger problems; for example, in their most recent modeling efforts, to answer their critics, *FSC* [1987*e*] chose a fixed dark-spot angular diameter, which implies that the size of the observed cloud (dark spot) and its water content are somehow controlled by the altitude of the DE spacecraft.

A careful reading of just a few of the Comments and Replies on the small-comet hypothesis can raise a sense of incredulity. For example, I regard the Comments on the lunar seismometer observations (section 4.1) as fatal to the small-comet hypothesis. And, I find convincing the explanation of the dark spots as instrumental artifacts (section 6). Depending on one's background, other of the Comments might seem more compelling. FSC obviously do not agree. In their review, *Frank and Craven* [1988, p. 270] state, "If [the small-comet hypothesis] is correct, a greatly revised perspective of Earth's geological history must be initiated. Similarly revisions of currently accepted conclusions concerning other bodies in the solar system are necessary. Major reinterpretations [are needed for] . . . lunar seismic waves . . ., the relationship of mass and luminosity for meteors in Earth's atmosphere, and the enhanced D/H ratio in the atmosphere of Venus." They continue [*Frank and Craven*, 1988, p. 271], "Surprisingly, there is no observed phenomenon in the solar system that decisively eliminates the possibility that this large population of small comets is present in the planetary system." But this is not how the game is played. There is no confirming evidence that conventional wisdom in any of these separate fields needs substantial modification. It seems unlikely that the scientific community will expend much additional effort in investigating either the small-comet hypothesis or its consequences.

### 7.1. Some Personal Reflections

It has been my experience that writing a review paper rewards its author with new knowledge, insight, and inspiration. Yet, I found writing of this review a painful experience. In my judgment the small-comet hypothesis appears to me to be permeated with fatal flaws, and I must face the fact that the small-comet hypothesis and 55 pages of Comments and Replies were published in *GRL* while I was responsible for its content. I have been asked, if I had it to do over again, would I still publish the FSC small-comet papers? The answer is, if I didn't know more than I knew at the time they were submitted, I would certainly accept the original "discovery" papers again. However, I would dearly love a second chance with the Comments and Replies.

The rationale for publishing the first FSC papers is one I have consistently espoused: "Rigid attempts to publish only what is correct may result in the publication of only what is popular" [*Dessler*, 1972, p. 11]. The publication of the small-comet hypothesis provided a detailed disclosure to the scientific community of a potentially important new idea. While it is true that most new ideas that seek to overturn conventional wisdom are wrong, not all are. "The importance for scientific progress of the occasional new idea that proves correct is out of all proportion to their number" [*Dessler*, 1986*a*]. It would have been the highlight of my career as an AGU editor to have my decision (i.e., accepting the FSC papers for publication) vindicated by confirmation of the small-comet hypothesis. (Editors always wish to see their decisions vindicated.)

My policy for handling Comments and Replies evolved from my experience with *Journal of Geophysical Research (JGR)*. I believe that a journal should encourage debate in forefront fields where, by definition, there is insufficient knowledge to reach a consensus [*Dessler*, 1972]. Comments were subject only to editorial review for appropriateness of content; neither Comments nor Replies were refereed. I believe the policy worked splendidly. In *JGR*, during my last 2 years as editor, a cogent Comment and (usually) a Reply appeared almost every month. The interested reader may enjoy browsing through some 1968–1969 issues of *JGR-Space Physics* to form an independent judgment on their quality.

The Comments and Replies involving FSC did not fit the pattern, but, because of my earlier favorable experience, I was slow to react. Once the initial discovery papers of FSC were published, there was no need for unrestrained exchange between authors and critics. If small comets exist, their presence would be confirmed in due course. If FSC were correct, they would enjoy fame and glory; nothing their critics said would be remembered, except perhaps as quotations demonstrating the evils of scientific dogmatism. In retrospect, a smaller number of representative Comments should have been published, and the Replies should have been refereed so that *GRL* would not publish, under the guise of open debate, material that could not pass ordinary peer review. As *Feldman* [1987] points out, by allowing individual replies to each criticism, the debate was turned inside out with the burden of proof shifted to the critics. FSC close many of their later Replies with a statement to the effect that their critics had not proved that small comets did not exist.

What will happen next? The small-comet hypothesis has stirred up some healthy interest in related subjects and perhaps inspired some useful research. I do not believe that the small-comet hypothesis will soon disappear [e.g., *Frank*, 1990]. I expect it to pass through more interesting stages before a resolution is achieved.

## APPENDIX: LIFETIME OF ICE CRYSTALS IN SPACE (SECTION 2.2)

An approximate value for the lifetime of an ice crystal of radius $a$ is obtained by equating the energy it absorbs during its lifetime $\tau$ with its heat of sublimation. (Blackbody radiative losses from the ice crystal are explicitly ignored to yield a minimum lifetime.) Thus $S\pi r^2\varepsilon\, dt = 4\pi r^2\rho L_s\, dr$, where $S$ is the energy flux incident on the droplet, $\varepsilon$ is the absorptivity of the particle, $\rho$ is its mass density, and $L_s$ is the heat of sublimation. Integrating time from zero to $\tau$ and the radius from $a$ to zero, we obtain

$$\tau = 4a\rho L_s/S\varepsilon \tag{A1}$$

Ice is a poor absorber of visible sunlight. This follows intuitively from the high albedo and translucence of fresh snow, which has an albedo of 93%. *Chamberlain and Smith* [1970, p. 763, Table A1], provide a table of single-particle-scattering albedo as a function of total albedo. From their table, for a total albedo of 92.97% the single particle albedo is 99.90%, which means that in terrestrial snow, each scattering absorbs 0.001 of the incident light. The total albedo falls sharply for a small decline in single-scattering albedo. In snow that looks rather dingy, an individual snowflake absorbs little of the incident light (10% absorption for individual snowflakes in a snowbank with an albedo of less than 50%). For clean snow, in the visible part of the spectrum, $\varepsilon$ is 0.001, and only 1.4 W/m$^2$ of the $1.4 \times 10^3$ W/m$^2$ solar constant is absorbed. At infrared (IR) wavelengths, however, water and water-ice are absorbing. For small comets the strongest IR emitter is the Earth. The albedo of the Earth is 32.1%, so the Earth radiates in the IR 67.9% of the solar energy falling on an area $\pi R_E{}^2$, the radiation coming from an area $4\pi R_E{}^2$ [*Kondratyev*, 1969]. From *Kondratyev* [1969, p. 747, Table 10.21] the IR flux from Earth is $237/R^2$ W/m$^2$, where $R$ is the geocentric distance in $R_E$. In comparison, solar IR at 1 AU in the wavelength range of interest is only

8 W/m$^2$. Solar UV flux is less, and UV is not strongly absorbed by ice. Thus $S \approx 250$ W/m$^2$.

For the ice particles from the shuttle, $R = 1$, so $S = 250$ W/m$^2$. With $a = 100$ μm, (A1) indicates a particle lifetime $\tau \approx 4.5 \times 10^3$ s = 75 min. For small-comet ice crystals, with sublimation occurring near 3000 km altitude, the incident IR flux is reduced by a factor $1/R^2$. This decreases the terrestrial component of the IR flux to 110 W/m$^2$. For the total IR flux we use 125 W/m$^2$. For a crystal of radius $a = 30$ μm, which is a particle with about the same volume as cirrus-cloud ice crystals, (A1) indicates $\tau \approx 45$ min. To obtain the required sublimation time of $\tau < 20$ s (see section 2.2.2), the radius of the ice crystal must be less than 0.2 μm.

We also can apply (A1) to the oxygen and hydrogen ice clouds from Apollo 14, for which $L_s(O_2) = 2.3 \times 10^2$ J/g and $L_s(H_2) = 5.1 \times 10^2$ J/g. For ice particles with $a = 100$ μm, and $S\varepsilon \sim 10^{-2}$ W/m$^2$ (the value is small because gaseous and solid $O_2$ and $H_2$ are poor absorbers in the IR and visible but absorb well in the short-wavelength range of the UV portion of the solar spectrum [*Goody*, 1964, chapter 5]), the theoretical lifetime is hours. With this result we can claim a rudimentary understanding of the observed long life of ice in space.

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