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# REPLY TO WASSON AND KYTE

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Wasson and Kyte (1987) repeat previously published criticisms of the large flux of heretofore undetected, small comets in the vicinity of the earth's orbit as proposed by Frank et al. (1986a). These criticisms concern the distributions of known cometary orbits and the low dust content of the small comets. Rejections of these criticisms as decisive arguments that preclude the existence of the small comets are given by Frank et al. (1986b,c,d). Thus we confine our discussion to a recapitulation of our previous responses and a simple suggestion for accounting for the differences in dust content between the large, known comets and these small comets.

Wasson and Kyte (1987) state that the proposed flux of small comets implies an influx of extraterrestrial chondritic matter into the earth's atmosphere that exceeds the measured values by a factor of ~ $3 \times 10^9$. This large discrepancy is derived from the composite of three assumed factors: (1) the dust content of the small comets is similar to that for the large comets, (2) the amount of chondritic material should be limited to that received by the earth in the form of $10^8$- to $10^9$-gm stony meteoroids and (3) the small comets are confined to short-period orbits. The order-of-magnitude of factor (1) is easily estimated. The total influx of mass due to the small comets, ~ $10^7$/year at ~ $10^8$/gm per comet, is ~ $10^{15}$ gm/ year. If the dust content is similar to that for the large comets, ~ 20%, and the dust is chondritic matter, then this dust influx to the earth is ~ $2 \times 10^{14}$ gm/year. From measurements of iridium concentrations in ocean sediments, the upper limit for this influx of extraterrestrial chondritic material is ~ $10^{11}$ gm/year (cf. Barker and Anders, 1968). Thus the discrepancy is a factor of ~ $2 \times 10^{14}/10^{11}$, or ~ $2 \times 10^3$.

Factor (2) above is based on the assumption by Wasson and Kyte (1987) that the small comets comprising primarily volatiles such as water and methane should be identified with stony meteoroids with about the same mass, i.e., $10^8$ to $10^9$ gm. This limitation on the mass range for chondritic material provides another factor of ~ $10^3$. We eliminate this second factor on the basis that we are unable to directly associate the physical properties of a small comet with a stone of the same mass. Factor (3) is derived by Wasson and Kyte (1987) from the assumption that the small comets are in short-period orbits and that a large fraction of these small comets are rapidly devolatized. No mechanism for injecting these small comets into the planetary system with short-period orbits is given. This effect is proposed by Wasson and Kyte (1987) to provide an additional discrepancy of a factor of $1.6 \times 10^3$.



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These latter assumptions for (3) above by Wasson and Kyte (1987) are in direct contradiction to the inferences by Frank et al. (1986b,c,d) that the small comets are in long-period orbits with initial aphelia in the disk of such comets beyond the planetary system and that their vaporization rates may be suppressed by a carbon crust due perhaps to irradiation by charged particles and ultraviolet radiations (cf. Johnson et al., 1986, and references therein). Thus there is no substantial justification for the factor (3) assumed by Wasson and Kyte (1987). The discrepancy of dust content between large and small comets is most likely a factor of ~ $2 \times 10^3$ from assumption (1), and not the factor of ~ $3 \times 10^9$ claimed by Wasson and Kyte (1987). This factor of ~ $2 \times 10^3$ for the lesser dust content of the small comets and its possible significance are previously discussed in detail (Frank et al., 1986b,c,d).

The meteoroid mass fluxes in the mass range labeled 'meteors' and 'fireballs' in Figure 1 of Wasson and Kyte (1987) are derived principally from observations of the luminosities of meteors. Thus the inferred mass of the object is dependent upon the fundamental assumption that the meteoroid is a stony or iron object (cf. Bronshten, 1983). The position of the small comet flux at the top of Figure 1 is given by the assumption that 20% of the small comet's mass is dust and thus the comet should produce a luminosity equivalent to a stony meteoroid with mass ~ $2 \times 10^7$ gm. This assumption is in direct contradiction to the composition of water and other volatiles with traces of chondritic material as inferred by Frank et al. (1986b,d). Because the mass-luminosity relation that is used to derive meteoroid masses in Figure 1 of Wasson and Kyte (1987) is invalid for the proposed small comets, an alternative relationship for the impact of water-snow objects into the atmosphere must be applied. Coarse estimates of the luminosities for the impact of these water-snow objects into the atmosphere show that the observed meteor luminosities and rates are consistent with the proposed influx of small comets (Frank et al., 1987a). If the small comets exist, then the total global mass influx of extraterrestrial matter as represented by Figure 1 of Wasson and Kyte (1987) is an underestimate by a factor of ~ $10^4$.

Wasson and Kyte (1987) insist that the composition and orbital distributions of the small comets should be similar to those of the large, well-known comets. This criticism by Wasson and Kyte (1987) is reasonable: what mechanism is responsible for the disparate composition and orbital distributions of the large and small comets? We provide a simple model for comet formation that can reasonably explain the relationship between these two classes of comets.

Frank et al. (1986d) propose that the small comets are distributed in a disk centered on the sun and aligned approximately parallel to the orbital planes of the planets. The disk lies beyond the planetary system. The passage of a large mass, e.g., an undetected planet or a star, nearby this disk provides a shower of small comets in the planetary system (Frank et al., 1986d). The large variations of the frequency of atmospheric 'holes' along the earth's orbit reported by Frank et al. (1987b) are interpreted in terms of such comet showers. For a description of the relationship of this inner Oort disk with the spherical Oort cloud of comets, the reader is referred to Hills (1981). The more massive inner disk is interpreted in terms of the source for comets in the Oort cloud. Consider a simple model of the early solar nebular disk. Without gravitational perturbations due to the galactic tidal field, closely passing stars, smaller dark bodies, etc., collisions of the dust particles and icy grains in the nebular disk can be expected to force these particles into nearly circular orbits. With the gravitational perturbations an average relative velocity of the particles, $V_1$, can be expected. If it is assumed that the particles coalesce upon collision, it is a simple exercise to show that the mass of the forming comet at time t, M(t), is given approximately by $M(t) \approx (\pi/48)(\rho_s V_1 t)^3/\rho_c^2$, where $\rho_s$ and $\rho_c$ are the mass densities of the nebular disk and comet, respectively, and t is in units of seconds elapsed since the formation of the nebular disk. Thus the early nebular disk of dust and icy grains evolves into a disk of comets by collisional accretion.

Consider a numerical example for the simple model for comet formation given above. For $V_1$, we assume that the pressure during collisions of the comets in the disk is equal to their strength inferred from considerations of thermal stability at 1 AU, i.e., $\sim 10^4$ dynes/cm$^2$ (Frank et al., 1986c). For comets with densities of 0.1 gm/cm$^3$, $V_1$ is ~ 300 cm/sec. The corresponding orbits depart from circular orbits at 500 AU by several AU. We assume no significant mass loss from the nebular disk during the accretion process. However the early nebular disk can be reasonably expected to decrease in density with increasing heliocentric radial distance. In addition the composition of the disk can be such that the density of dust is higher at the inner edge of the disk with the ices of volatiles as dominant constituents in the outer regions of the disk. Thus if the nebular density is $\sim 10^{-14}$ gm/cm$^3$ at the inner edge of the disk, at 100 AU, for example, then the current size of the comets at this location is $\sim 3 \times 10^{17}$ gm, with the above values for $V_1$ and $\rho_c$ and $t = 4 \times 10^9$ years. This mass is in the range of the well-known, large comets. The large dust content reflects the composition of the early solar nebular disk at this position. On the other hand, if the disk density is $\sim 5 \times 10^{-18}$ gm/cm$^3$ at ~ 1,000 AU, then the present comet size is $\sim 4 \times 10^7$ gm. For reference the total mass of a disk with radius 2,000 AU and thickness 100 AU, and with uniform density $5 \times 10^{-18}$ gm/cm$^3$, is about 0.01 solar mass. Thus this simple model predicts that the inner Oort disk is populated with large, dusty comets at its sunward edge and with small comets comprising almost exclusively volatiles at larger distances.

The above distributions of comets in the inner disk can be expected to provide different orbital distributions for the large and small comets that are scattered from this disk by external gravitational perturbations. The large comets are tightly bound in their orbits closer to the sun. With the exception of very infrequent gravitational perturbations due to closely passing stars that produce showers of large comets at the earth, the orbits of these large comets outside of the disk can be expected to be distributed randomly due to the long-term gravitational actions of more distant stars, galactic tidal fields, and Jupiter (cf. Hills, 1981). The comets in the outer regions of the disk are less tightly bound and thus showers of these smaller comets at the earth are expected with greater frequency. Their orbital distributions may not be in a state of statistical equilibrium. The variations of the frequency of atmospheric holes as observed during a portion of the earth's orbit are interpreted in terms of presently occurring showers of small comets from the cometary disk (Frank et al., 1987b).

We find that the criticisms offered by Wasson and Kyte (1987) are insufficient to preclude the existence of a large flux of small comets in the vicinity of the earth as proposed by Frank et al. (1986a).

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