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REPLY TO MORRIS

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The various criticisms offered by Morris (1986) can be organized into two general categories: (1) the influx of small comets into the atmosphere as proposed by Frank et al. (1986a) is incompatible with the observed depositions of iridium and carbon onto the earth's surface and (2) the distribution of orbits for the large, well-known comets is inconsistent with that proposed for the small comets. We find that none of the criticisms given by Morris (1986) preclude the existence of these small comets.

Frank et al. (1986b) previously deduce an upper limit for the vaporization rate of the small comets from solar wind ion measurements. This upper limit is in the range of 10^{11} to 10^{12} H_2O molecules/cm^2-sec in the vicinity of the earth's orbit. This low vaporization rate requires a mantle. Morris (1986) states that such a mantle yields depositions of cosmic dust into the atmosphere that exceed the upper limits given by Barker and Anders (1968) from the iridium content of ocean sediments. This upper limit for Type I carbonaceous chondritic material is $6(\pm 3) \times 10^{10}$ gm/year. This same conclusion is given previously by Rubincam (1986) and Frank et al. (1986b). Implicit in this conclusion is the assumption that the iridium concentration in the dust of a comet is identical to that of the above chondrites. Frank et al. (1986a,b) suggest that the dust content of the small comets is fractionally much less than that of the large, well-known comets. Such a departure of composition between these two classes of objects does not seem wholly objectionable in consideration of the fact that the ratio of the small comet's mass to that of known comets is ~ 10^{-10}, or similar to the ratio of the known comets' masses to that of the earth. The source of the small comets is presumably at distances beyond the planetary system where volatile material condensed in the early solar nebular disk (cf. Reeves, 1978). Frank et al. (1986b) suggest that an alternative mantle composition may be carbon that is produced by exposure of methane clathrate to ultraviolet light or charged particle bombardment at distances from the sun where vaporization by solar insolation is negligible (cf. Cheng and Lanzerotti, 1978; Lanzerotti et al., 1985). This process of carbon-mantle formation may require periods of time comparable to the age of the solar system. For the purposes of an example, Frank et al. (1986b) use a mantle thickness of 1 cm and density 0.1 gm/cm^3 of carbon for a typical small comet with total mass 10^8 gm, average H_2O density 0.1 gm/cm^3, and thus a radius of 6 m. The corresponding total mass of carbon is ~ 4.5×10^5 gm, or ~ 5×10^{-3} of the total comet's mass.

The influx of carbon from these small comet mantles can be examined relative to the carbon budget for the earth. The influx rate given by Frank et al. (1986a) is ~ 10^7 comets/year, and, if the above carbon content is adopted, the total carbon influx is ~ 4.5×10^{12} gm/year. If we first assume the unlikely situation that none of the carbon is oxidized in the upper atmosphere, then the carbon could be deposited in the form of soot onto the earth's surface. A value for the deposition of soot in recent times onto the floor of the North Pacific is $1.8(\pm 1.9)$ μg/cm^2-year as given by Wolbach et al. (1985). The corresponding global deposition rate is $9(\pm 10) \times 10^{12}$ gm/year. This rate does not preclude the proposed carbon influx from the small comets. On the other hand, it is more likely that the carbon mantles are also consumed by atmospheric oxygen and dissociated water molecules during comet entry into the atmosphere and form CO, CO_2 and other carbon compounds. We use the summary of terrestrial carbon cycling given by Holland (1984) in the following discussion. Terrestrial carbon is found in the atmosphere (6.9×10^{17} gm), biosphere (1.1×10^{18} gm), hydrosphere (4.0×10^{19}) and crust (9.0×10^{22} gm). The ultimate reservoir of the cometary carbon is presumably in the crust. The carbon buried with new sediments is ~ 3.4×10^{14} gm/year. Approximately 75% of recent sediments are provided by the weathering of the old sedimentary rocks. The remainder, ~ $8(\pm 3) \times 10^{13}$ gm/year, is believed to be accounted for by the carbon released from the metamorphism of sedimentary rocks and by juvenile carbon from the mantle. The benchmark estimate of the carbon influx from small comets as given above is ~ 4.5×10^{12} gm/year, or about 5% of the terrestrial budget for new carbon in sedimentary rock. Thus the proposed influx of carbon from the small comets is not inconsistent with current knowledge of the inventory of terrestrial carbon.

The possibility that the small comets are mantled with a thin carbon crust is further supported by the remarkable Giotto findings of an extremely dark crust on a large fraction of the surface of Comet Halley (Keller et al., 1986) and of the large abundance of carbon ions in the cometary plasmas (Balsiger et al., 1986). In summary there appears to be no firm observational evidence that the proposed small comets cannot be mantled with a thin carbon crust. Other scenarios than that suggested above for mantle formation and composition also may be possible.

Morris (1986) comments that the orbital distribution of small comets inferred by Frank et al. (1986a) for heliocentric distances ~ 1 A.U. is dissimilar to that observed for well-known, large comets. The motion of small comets at the earth's orbit is assumed to be dominantly prograde and with low inclination. On the other hand, both retrograde and prograde motions of the large comets at low and high inclinations are observed (cf. Marsden, 1982). We offer a plausible, and probably not unique suggestion as to the

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origins of such an organized motion of small comets at the earth's orbit. It is unlikely that the primary source of the small comets in the vicinity of the earth is the distant Oort cloud. The corresponding orbits with aphelia beyond $\sim$ 20,000 A.U. are thought to be in statistical equilibrium from orbital perturbations by stellar encounters and the galactic tidal field (Hills, 1981; Morris and Muller, 1986; Morris, 1986). That is, the number of comets with trajectories entering the planetary system from this Oort cloud should be approximately uniform with respect to orbital inclination and motion. This conclusion is further strengthened by the findings of large variations of the fluxes of small comets along at least a fraction of the earth's orbit around the sun (Frank et al., 1986c). The scale lengths of the orbital perturbations of members of the distant Oort cloud are such that a passing star, for example, should produce a more-or-less uniform distribution of comets at the earth's orbit. The source of the comets in the Oort cloud is believed to be an inner cloud of comets at heliocentric distances $\lesssim$ 20,000 A.U. that formed during the condensation of the protosolar nebula (Oort, 1950; Hills, 1981). The total mass of this inner cloud is estimated by Hills to be a factor of $\sim$ 100 larger than that of the Oort cloud. Occasional perturbation of the cometary orbits in this inner cloud by massive objects and subsequent deflection of those comets in orbits penetrating the planetary system is a possible source for the Oort cloud. Jupiter is most effective in implementing this latter deflection. It is this massive, inner cloud of comets that may be pertinent to the swarm of small comets at the earth's orbit as inferred by Frank et al. (1986a).

For the purpose of an example, consider a disk of small comets that extends over heliocentric distances $\sim$ 100 A.U. to 5,000 A.U. and that generally lies near the plane of the planetary orbits. Initially assume that the perihelia for these small comets lie beyond the planetary system. A sufficiently massive object, e.g., an undetected planet or a passing, planet-sized body may traverse the inner cloud at distances $\sim$ 500 A.U. Then sufficient angular momentum and total energy could be lost by some of the small comets that they enter the planetary system. The current upper limits on the masses of such intruding objects are not stringent. Hills (1981) gives these limiting masses as 5×10^{-3} M_S at 100 A.U., 5×10^{-2} M_S at 1,000 A.U., and 0.5 M_S at 10,000 A.U., where M_S is the mass of the sun, 2.0×10^{33} gm. The initial shower of small comets at the earth's orbit is expected to be characterized by prograde and retrograde orbits and to exhibit a substantial intensity fluctuation along the earth's orbit. Because of the thermal instability of these small comets at distances $\lesssim$ 1 A.U. (cf. Frank et al., 1986d; McKay, 1986), few with perihelia inside the earth's orbit survive to execute a second orbit. In this regard, the large, well-known comets survive much closer penetration toward the sun, presumably due to their greater masses, e.g., the Kreutz family of sun-grazing comets. This feature may be responsible in part for the difference in the orbital distributions of these two classes of objects.

For small comets with perihelia within the planetary system and beyond $\sim$ 1 A.U., at least two important effects occur due to the presence of the planets, and largely due to Jupiter. First the number of comets in a shower declines roughly as $1/N^{1/2}$, where N is the number of perihelion passages (Hills, 1981). The losses are due to ejection from the solar system or injection into the distant Oort cloud. Because the comet orbital periods for the above example are $\sim 4 \times 10^3$ years, the shower lifetime for a decrease to 10% of initial intensities, N = 100, is $\sim 4 \times 10^5$ years.

The second major effect on the orbits of the small comets is a diffusion of the magnitudes of the semi-major axes, a. As noted by Morris (1986) the orbital perturbation for a single passage through the planetary system is large, $\Delta E = \Delta(1/a) \approx 4.5 \times 10^{-4}$ (A.U.)$^{-1}$, where E is the total specific energy of the comet (Everhart, 1968). It is this diffusion of semi-major axes, along with the thermal stability barrier at $\lesssim$ 1 A.U., that appears capable of yielding a dominant proportion of prograde orbits at the earth. The velocity change, Δv, for a comet due to the gravitational perturbation from an object with mass M, relative velocity V and closest approach distance R is given by the proportionality $\Delta v \propto M/RV$ (cf. Hills, 1981). Of interest here is the dependence on 1/V that greatly favors prograde orbits in the vicinity of the outer planets. For example, for a comet orbit with perihelion at Jupiter's orbit and aphelion at 500 A.U., V for retrograde orbits is a factor of $\sim$ 6 greater than that for prograde orbits. If the aphelion position decreases to 10 A.U. during the shower then this factor increases to $\sim$ 15. Thus during the declining phase of a cometary shower, the significantly more rapid diffusion of prograde orbits in the planetary system should be reflected in a corresponding dominance of prograde orbits at the earth.

An undetermined, smaller fraction of the comets can be expected to be in retrograde and high-inclination orbits during the decline of the comet shower. An upper limit on this fraction from ground-based observations of the absolute visual magnitudes of meteors cannot be usefully pursued until completion of the difficult task of modeling the luminosity of a small comet in its interaction with the atmosphere.

In summary the presence of the proposed small comets by Frank et al. (1986a) is not inconsistent with (1) the deposition of iridium onto the earth's surface, (2) the carbon budget for our planet, (3) the known properties of cometary crusts, and (4) the spatial distributions and orbital motions of cometary objects.

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