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A PRELIMINARY MODEL OF THE COMA OF 2060 CHIRON

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Abstract. We have included gravity in our fluid dynamic model with chemical kinetics of dusty comet comae and applied it with two dust sizes to 2060 Chiron. A progress report on the model and preliminary results concerning gas/dust dynamics and chemistry is given.

1. INTRODUCTION

There has been much interest in 2060 Chiron since observations of comet-like activity and a resolved coma established it is a comet. Determinations of its radius range from 65 to 200 km, making Chiron unique among bodies with atmospheres in the Solar System. This unusually large size for a comet suggests that the atmosphere of Chiron is intermediate to the tightly bound, thin atmospheres typical of planets and satellites and the greatly extended atmospheres in free expansion typical of cometary comae. Under certain conditions (depending on molecular weight, temperature, heliocentric distance, and the size and mass of Chiron) it may gravitationally bind an atmosphere which is thick compared to its size while a significant amount of gas escapes to an extensive exosphere. These attributes coupled with reports of sporadic outbursts at large heliocentric distances ($\gtrsim$ 12 AU) (1,2) and the identification of CN in the coma (3) make Chiron a challenging object to model. Simple models of gas production and a dusty coma have been recently presented by several investigators (see, e.g., 4-6) but a general concensus on many basic features has not emerged. We have begun development of a more complete coma model of Chiron (7). The objectives of this paper are to report progress on this model and give preliminary results for understanding Chiron.

2. GAS PRODUCTION

Throughout its orbit, Chiron remains too far from the Sun for direct sublimation of water to be important, but CO, N_2, and CH_4 ices could be the cause of activity throughout its complete orbit (4,7). CO_2 production "turns on" only about 10 years prior to perihelion. At perihelion, on the order of a Mg/s of CO can be released even if only a small amount (a few %) of Chiron's surface is active. At these activity levels, the mean free path of a CO molecule at the surface is on the order of 100 m, much smaller than the flow scale length, so the sublimating gas is collisionally coupled and the fluid dynamic approach is required. The extent of the collision region can be determined only by detailed modeling or observations but an upper limit can be estimated assuming free expansion (R^{-2} density distribution) and isotropic emission. In this limit, its size is roughly $3 \cdot 10^3$ km, about the same as the collision zone of P/Halley at perihelion. Under the influence of Chiron's gravity (a few to 10 cm s^{-2}), fluid dynamic conditions near the surface are even more favorable.

The sublimation of a volatile, like CO, leads to a gas temperature close to 30 K throughout Chiron's orbit (5), far below that of a blackbody in radiative equilibrium. This results in a thermal velocity that is comparable to the escape velocity (7), given uncertainities in the size and mass of Chiron. This situation may lead to a bound atmosphere with extensive exosphere as slower molecules in the Maxwellian distribution cannot escape while those traveling faster than the escape velocity leave. The loss of these more energetic molecules results in substantial cooling of the remaining gas, making it more tightly bound. However, slightly higher thermal velocities lead to hydrodynamic escape or "blow-off" of the atmosphere (8). This situation is complex and sensitive to the actual bulk parameters.

Other processes can heat and cool the gas (7), including photo-reactions (heating), radiative cooling, collisions with grains that are hotter than the gas (heating), sublimation from icy grains, and expansion cooling of the gas. In the case of photo-destruction of CO, typical rates (9) at 10 AU yield a lifetime of 4.5 years, making this a minor source of energy and ions on smaller timescales. Charge exchange with the solar wind may be an important ion source at Chiron also. Each of these effects requires investigation with detailed modeling to assess its significance, as we are undertaking.

3. THE DUST COMA

The sublimating gas entrains dust particles as it leaves Chiron's surface. The dust dynamics is also influenced by the gravity and rotation of Chiron within a sphere of influence given by (10),

$$R_{GS} = r(M_{Chiron}/2M_{Sun})^{1/3}.$$

At r = 10 AU, adopting a radius of 120 km and a density of 1 g cm^{-3} for Chiron, $R_{GS} \approx$ 1500 R_{Chiron}. Outside of this region, both solar gravity and radiation pressure must be taken into account. The maximum particle size that can be lifted by gas drag has been estimated to be on the order of 100 μm for CO sublimation (5). In a typical comet, the gas density decreases as R^{-2}, and for large particles (with velocities much smaller than the gas) the ratio of the gas drag to gravity is constant (11). Once lifted off the nucleus, these particles will leave the comet. However, considering gas production from restricted active areas and the effects of gravity on the gas, the gas density will decrease more rapidly than R^{-2} and these larger particles may decouple from the gas drag before escape, traveling in bound orbits and may eventually fall back to the surface. The extent of the gas–dust interaction region depends on particle size and bulk density. Based on our preliminary model, we estimate the size of the acceleration region to be on the order of ten Chiron radii for 1 to 10 μm particles.

Beyond the gas–dust interaction region, the dust trajectories are increasingly influenced by radiation pressure and can be approximated by the fountain model (12). Micrometer-sized particles follow parabolic orbits confined within an envelope which is a paraboloid with focus in the nucleus and apex in the sunward direction. The standoff distance can be roughly estimated for these particles, using typical parameters for Chiron, to be on the order of 100 R_{Chiron}. At further distances, the solar gravity and the Poynting-Robertson effect influence the dust dynamics. Other effects that may need to be considered in a realistic model of the dust coma include grain-grain collisions and charging of particles by solar wind, secondary electron emission, or coma plasma.

4. PRELIMINARY MODEL OF 2060 CHIRON

One-dimensional, multi-fluid simulations of the coma of Chiron at perihelion have been performed. These simulations are based on our model that treats the physics and chemistry of the inner coma in great detail (9). Recent progress of the model includes incorporation of dust entrainment by the gas, dust size distributions, dust fragmentation, and distributed coma sources of gas-phase species related to the dust described in (13).

In this preliminary model of Chiron, CO is assumed to be the only volatile. Other model parameters include r = 8.51 AU, R_{Chiron} = 120 km, A = 0.03, ρ_{Chiron} = 1. The dust-to-gas mass production ratio (χ) is assumed to be 1. Two sizes of dust (a = 1 and 10μm) are considered and the dust mass distribution is approximated by a power law (exponent = 0.5). The model capabilities for dust fragmentation are not used in the present calculations. Being a diatomic molecule, CO is not an efficient emitter in the infrared so the radiative cooling term has been omitted in this first-order model. For comparison, a dust-free model (χ = 0) and a model with a modest amount of dust (χ = 0.1) were produced also.

In the simulations, gas and dust are rapidly accelerated upon leaving the nucleus as illustrated in Fig. 1. For standard dust densities, small particles are more efficiently entrained with the gas flow than large particles, resulting in higher terminal speeds. The acceleration zone for all particles is approximately within 10 R_{Chiron}. The inclusion of dust has two important effects on the gas flow. The first is an initial mass-loading of the gas, reducing the gas velocity to subsonic values close to the surface of the nucleus. The second effect is a strong coupling of the gas and dust temperatures near the nucleus as shown in Fig. 2. Upon release, the dust heats rapidly to its radiative equilibrium value of 95 K. Collisions of molecules with dust particles heat the gas (initially at 30 K) to 85 K within a Chiron radius. This results in a terminal gas velocity about 80% higher than that calculated from a pure gas model. Even with a modest amount of dust ($\chi = 0.1$), the gas is significantly heated in the near-nucleus region. A complete description of our model and more extensive results will be presented in a forthcoming publication.

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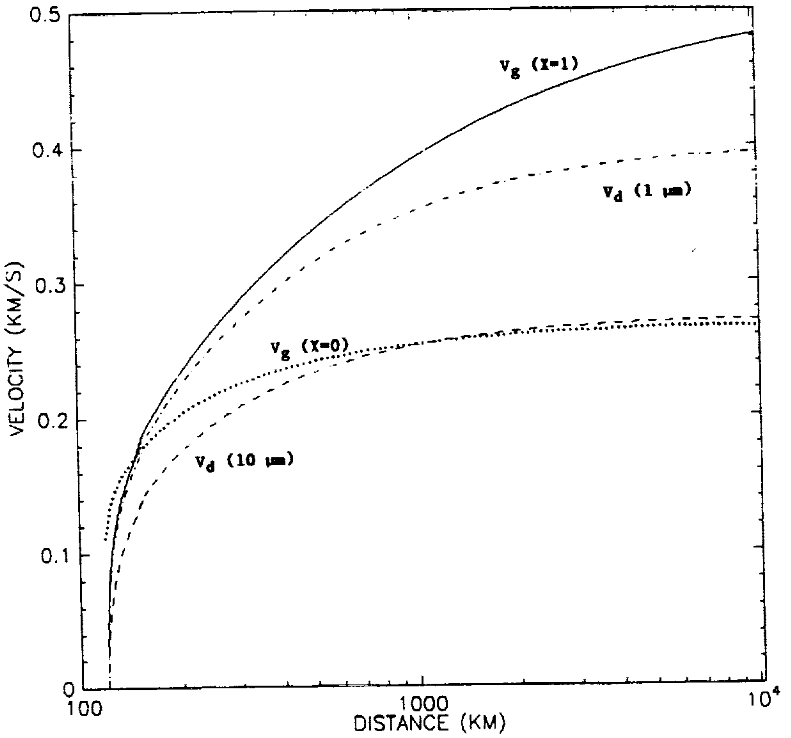

Figure 1. Gas and dust speeds for Chiron at perihelion. The dust acceleration region is within about 10 R_{Chiron}. For comparison, the dotted line is the gas speed for a dust-free model ($\chi = 0$).

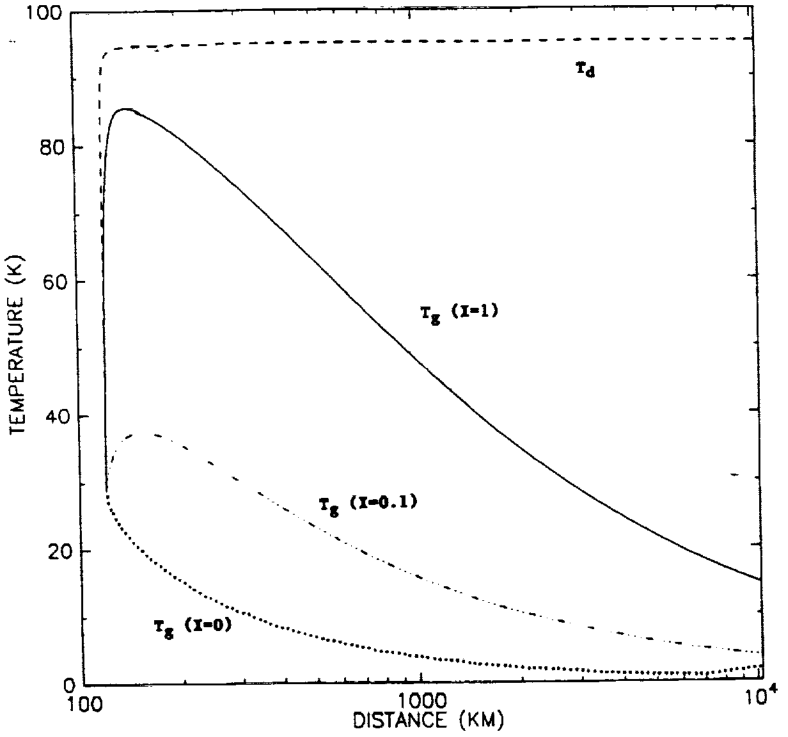

Figure 2. Temperature profiles of the gas and dust for Chiron at perihelion. Upon release from the nucleus, both sizes of dust quickly reach radiative equilibrium at 95 K. The gas is strongly heated by the dust in the near-nucleus region for the $\chi = 1$ case. Even with a modest dust-to-gas mass ratio ($\chi = 0.1$), the gas is heated significantly above the dust-free model ($\chi = 0$).