NASA-CR-204774

SwRI Proposal No. 15-7238
February 27, 1997

An Final Report for

STUDIES OF DISKS AROUND THE SUN AND OTHER STARS
NAGW-4468

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INTRODUCTION

This is the Final Report for NAGW-4468 (SwRI Project 15-7238), *Studies of Disks Around the Sun and Other Stars,* (S.A. Stern, PI). This is a NASA Origins of Solar Systems research program, and this NASA Headquarters grant has now been transferred to a new grant at NASA GSFC (NAG5-4082). Thus the need for this "Final Report" on a project that is not, in fact, complete.

We are conducting research designed to enhance our understanding of the evolution and detectability of comet clouds and disks. This area holds promise for also improving our understanding of outer solar system formation, the bombardment history of the planets, the transport of volatiles and organics from the outer solar system to the inner planets, and to the ultimate fate of comet clouds around the Sun and other stars. According to "standard" theory, both the Kuiper Belt and the Oort Cloud are (at least in part) natural products of the planetary accumulation stage of solar system formation. One expects such assemblages to be a common attribute of other solar systems.

Our program consists modeling collisions in the Kuiper Belt and the dust disks around other stars. The modeling effort focuses on moving from our simple, first-generation, Kuiper Belt collision rate model, to a time-dependent, second-generation model that incorporates physical collisions, velocity evolution, dynamical erosion, and various dust transport mechanisms. This second generation model is to be used to study the evolution of surface mass density and the object-size spectrum in the disk.

PROGRESS

1) We have now completed the first model of collision rates of the Kuiper Belt (KB). With this model we explored the rate of collisions among bodies in the present-day Kuiper Belt as a function of the total mass and population size structure of the Belt. We find that collisional evolution is an important evolutionary process in the KB as a whole, and indeed, that it is likely the dominant evolutionary process beyond $\approx$ 42 AU, where dynamical instability timescales exceed the age of the solar system. Two further findings we report from this modelling work are: (i) That unless the Belt's population structure is sharply truncated for radii smaller than ~1–2 km, collisions between comets and smaller debris are occurring so frequently in the Belt, and with high enough velocities, that the small body (i.e., km-class object) population in the disk has probably developed into a collisional cascade, thereby implying that the Kuiper Belt comets may not all be primordial, and (ii) that the rate of collisions of smaller bodies with larger $100 < R < 400$ km objects (like 1992QB$_1$ and its cohorts) is so low that there appears to be a dilemma in explaining how QB$_1$s could have grown by binary accretion in the disk as we know it. Given these findings, it appears that either the present-day paradigm for the formation of the KB is failed in some fundamental respect, or that the present-day disk is no longer representative of the ancient structure from which it evolved. In particular, it appears that the 30–50 AU region of the Kuiper Belt has very

likely experienced a strong decrease in its surface mass density over time. This in turn suggests the intriguing possibility that the present-day Kuiper Belt evolved through a more erosional stage reminiscent of the disks around the A-stars β Pictorus, α PsA, and α Lyr. These results were published in *The Astronomical Journal* in 1995 and 1996.

2) We have used our intial collision rate model and a second code to estimate the detectability of IR emission from debris created by collisions. We found that eccentricities in the Kuiper Belt are high enough to promote erosion on virtually all objects up to $\sim$ 30 km, independent of their impact strength. Larger objects, such as the 50–170 km radius "QB_1" population, will suffer net erosion if their orbital eccentricity is greater than ≈ 0.05 (≈ 0.1) if they are structurally weak (strong). The model predicts a net collisional erosion rate from all objects out to 50 AU ranging from 3×10^{16} to 10^{19} g yr,$^{-1}$ depending on the mass, population structure, and mechanical properties of the objects in the Belt. We find two kinds of collisional signatures that this debris should generate. First, there should be a relatively smooth, quasi-steady-state, longitudinally isotropic, far IR (i.e, $\sim 60\ \mu$m peak) emission near the ecliptic in the solar system's invariable plane ecliptic, caused by debris created by the ensemble of ancient collisions. The predicted optical depth of this emission could be as low as 7×10^{-8}, but is most likely between 3×10^{-7} and 5×10^{-6}. We find that this signature was most likely below IRAS detection limits, but that it should be detectable by both ISO and SIRTF. Secondly, recent impacts in the KB should produce short-lived, discrete clouds with significantly enhanced, localized IR emission signatures superimposed on the smooth, invariable plane emission. These discrete clouds should have angular diameters up to 0.2 deg, and annual parallaxes up to 2.6 deg. Individual expanding clouds (or trails) should show significant temporal evolution over timescales of a few years. As few as zero or as many as several 10^2 such clouds may be detectable in a complete ecliptic survey at ISO's sensitivity, depending on the population structure of the Kuiper Belt. This work was published in *Astronomy & Astrophysics* in 1996.

3) We then employed our model to study the collisional environment in the ancient Kuiper Belt. We explored the consequences of a massive, primordial Kuiper Belt using a collision rate model that assumes the dominant growth mechanism in the 35–50 AU region was pairwise accretion. We found that the growth of QB_1-class objects from seeds only kilometers in diameter required a very low eccentricity environment, with mean random eccentricities of order 1% or less. Duncan et al. (1995) have shown that the presence of Neptune induces characteristic eccentricities throughout the 30–50 AU region of a few percent or greater. We therefore concluded that growth of objects in the 30 to 50 AU zone to a least this size must have occurred before Neptune reached a fraction of its final mass. Once Neptune grew sufficiently to induce eccentricities exceeding $\approx$1%, we found that the disk environment became highly erosive for objects with radii smaller than $\sim$20–30 kilometers, which likely created a flattening in the disk's population power law slope between radius scales of $\approx$30 to $\approx$100 km, depending on the density and strength of such objects. This erosive environment could have resulted in sufficient mass depletion to evolve the disk to its present, low-mass state, independent of dynamical losses (which surely also played an important role). During the period

of rapid erosive mass loss, the disk probably exhibited optical depths of 10^{-4} to 10^{-5} (reminiscent of β Pictoris), for a timescale of $\sim 10^7$ to $\sim 10^8$ years. As a result of the evolution of the disk inside 50 AU, we suggested that (i) the present-day Solar System's surface mass density edge near 30 AU is actually only the inner edge of a surface mass density *trough*, and (ii) that the surface mass density of solids may rise back beyond ~50 AU, where the giant planets have never induced erosive high eccentricities. Indeed, the growth of objects in the region beyond 50 AU may be continuing to the present. This work was published in *The Astronomical Journal* in late 1996.

4) In collaboration with CoI Colwell, I have completed the main task of the proposed work in this grant effort, to construct a time-dependent code for modelling of Kuiper Belt collisional evolution. Two papers are now in press discussing key results obtained with this model (Stern & Colwell 1997a, b). Applying a time-dependent model of collisional evolution of the EKB, we found that under a wide range of assumptions, collisional evolution should have depleted the mass of the 30–50 AU zone by >90% early in the history of the solar system, thereby creating a deep scar or gap in the surface mass density across a wide region beyond Neptune, much like what is observed today. Dynamical erosion may have further accelerated the depletion process. Given the fact that Neptune has had far less dynamical influence beyond 50 AU, our results also suggest that unless the solar nebula was truncated near 50 AU, then surface mass density of solids beyond ~50 AU increases again, most likely dramatically. In paper II, we employed the new, time-dependent collisional evolution code to study the conditions under which the ≈50–200 km radius Edgeworth-Kuiper Objects (EKOs) in the region between 30 and 50 AU (now called the Edgeworth-Kuiper Belt, or EKB; Edgeworth 1943, 1949; Kuiper 1951) were formed. Assuming that these bodies were created by pairwise accretion from 1 to 10 km building blocks, we find that three conditions were required, namely: (i) at least 10 $M_\oplus$ and more likely 35 $M_\oplus$ of solids in the primordial 30 to 50 AU zone, (ii) mean random orbital eccentricities of order 0.002 or smaller, and (iii) mechanically strong building blocks. Furthermore, we find that the accretion of 100–200 km radius bodies in the 30 to 50 AU region from collisions among a starting population of 1 to 10 km building blocks required $\approx 10^8$–10^9 years, with the lower range only being reached for 30 to 50 AU zone masses approaching 100 $M_\oplus$ of solids or mean random orbital eccentricities <0.005 (which we do not believe is realistic after gas dissipation). Therefore, unless accretion had already produced many building blocks significantly larger than 10 km in diameter at the time the nebular gas was removed, our results also indicate that Neptune did not form on a timescale much shorter than ~70 Myr, and could well have required many hundreds of Myr to approach its final mass. We also explore the growth of Pluto-scale (i.e., radius 1000–1200 km) objects in the 30 to 50 AU region under a variety of assumptions. We further find that once ~300 hundred kilometer radius objects were formed, the growth of 1000 km radius and larger objects occurs relatively easily and comparatively quickly. The lack of many Plutos in the 30 to 50 AU zone therefore argues strongly that growth was terminated in that region rather abruptly at the time the presently observed population of 100–200 km radius EKOs were being completed. In the region beyond 50 AU where Neptune's dynamical influence was much reduced, model runs yield 100 km to 1000 km radius, and perhaps even larger

bodies which should be detectable with on-going or soon-to-be started surveys. We suggest that if dynamical conditions did not remain calm enough to allow Pluto itself to be grown in the 30 to 50 AU zone before perturbations from Neptune created a dynamically erosive, low-mass environment there, then it may be that Pluto was grown beyond the influence of Neptune's perturbations and later transported inward, perhaps in part via the Charon-forming collision.

5) These five papers were accompanied by an invited review, submitted to the *Planetary Ices* book, summarizing the present state of knowledge about the Kuiper Belt and Pluto, and another review, on the origin of Pluto, which is now in press for the UA Space Science serives volume, *Pluto & Charon.*.

6) We organized and sponsored a 2-day workshop on collisions in the Kuiper Belt. This workshop was attended by D. Davis (PSI), P. Farinella (Italy), R. Canup (U. Colorado), M. Festou (France), J. Colwell (U. Colorado), H. Levison (SwRI), and PI Stern (SwRI). The proceedings of this workshop were informally published and the distributed among the participants. A copy was also sent to Origins program scientist Trish Rogers.

7) We have also written a popular-level article on extra-solar comets for *Astronomy* magazine.

8) Additionally, PI Stern has given nine invited talks summarizing the collisional modelling results obtained under the Origins program. A list of these invited talks is attached.

9) For the remainder of this program we plan to (i) concentrate on improving our KB collisional evolution code to include coupled mass-velocity evolution, and (ii) to then begin exploiting the improved code to better understand the growth of objects in the Kuiper Belt.

RELEVANT PUBLICATIONS

Collision Rates in the Kuiper Disk and Their Implications. S.A. Stern, *The Astronomical Journal*, **110**, 856, 1995.

Signatures of Collisions in the Kuiper Disk. S.A. Stern. *Astronomy & Astrophysics*, **310**, 999, 1996.

Escapees from the Kuiper Disk: The Centaurs. S.A. Stern and H. Campins. *Nature*, **382**, 507, 1996.

The Collisional Environment, Timescales, and Architecture of the Ancient, Massive Kuiper Disk. Stern, S.A., **112**, 1203, 1996.

Interstellar Intruders. S.A. Stern, Astronomy Magazine, February, 47–51, 1997.

On the Origin of Pluto, Charon, and the Pluto-Charon Binary. S.A. Stern, W.B. McKinnon, and J.I. Lunine. Invited chapter for the UA Press Space Science Series volume, "Pluto & Charon," in press, 1997.

Pluto and the Kuiper Disk. S.A. Stern. "Ices in the Solar System." (C. DeBergh, B. Schmitt, M.C. Festou, eds.), in press, 1997.

Collisional Erosion in the Edgeworth-Kuiper Belt. Stern, S.A., and J.E. Colwell. *ApJ*, in press, 1997.

On the Accretion of 100–1000 km Radius Bodies in the Edgeworth-Kuiper Belt. S.A. Stern and J.E. Colwell. Astronomical Journal, in press, 1997.

SCIENTIFIC PRESENTATIONS & ABSTRACTS

Collisions in the Kuiper Disk. Astronomy Luncheon Seminar. Queen's University Department of Physics. Kingston, Ontario, 2 February 1995.

Pluto, Charon, and The Kuiper Disk. Ices in the Solar System Meeting. Toulouse, France, 25 March 1995.

The Kuiper Disk: Evidence for Arrested Planetary Accretion? Laboratory for Atmospheric and Space Physics Seminar, University of Colorado, Boulder, CO, 28 September 1995.

Collisions and the Architecture of the Kuiper Belt. Kuiper Belt Workshop. Canadian Institute for Theoretical Astrophysics. Toronto, Canada. 8 June 1996.

Collisions in the Massive, Ancient Kuiper Disk. ACM V, Versailles, France. 10 July 1996.

Collisions, Erosion, and Accretion in the Kuiper Disk. New Mexico State University, Department of Astronomy. Las Cruces, New Mexico. Departmental Seminar. 18 July 1996.

Accretion in the Kuiper Belt. Physics Department Seminar, Southern Methodist University, Dallas, TX, 10 February 1997.

Pluto: The Final Frontier? Invited Review. American Association for the Advancement of Science (AAAS), Annual Meeting, Seattle, WA, 14 February 1997.

The Kuiper Disk: Planetary Science's Newest Frontier. Origins Conference. Estes Park, CO, 20 May 1997.

COLLISIONAL TIME SCALES IN THE KUIPER DISK AND THEIR IMPLICATIONS

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Received 1995 February 15; revised 1995 May 1

ABSTRACT

We explore the rate of collisions among bodies in the present-day Kuiper Disk as a function the total mass and population size structure of the disk. We find that collisional evolution is an important evolutionary process in the disk as a whole, and indeed, that it is likely the dominant evolutionary process beyond ≈42 AU, where dynamical instability time scales exceed the age of the solar system. Two key findings we report from this modeling work are: (i) That unless the disk's population structure is sharply truncated for radii smaller than ~1–2 km, collisions between comets and smaller debris are occurring so frequently in the disk, and with high enough velocities, that the small body (i.e., KM-class object) population in the disk has probably developed into a collisional cascade, thereby implying that the Kuiper Disk comets may not all be primordial, and (ii) that the rate of collisions of smaller bodies with larger $100<R<400$ km objects (like $1992QB_1$ and its cohorts) is so low that there appears to be a dilemma in explaining how QB_1's could have grown by binary accretion in the disk as we know it. Given these findings, it appears that either the present-day paradigm for the formation of Kuiper Disk is failed in some fundamental respect, or that the present-day disk is no longer representative of the ancient structure from which it evolved. This in turn suggests the intriguing possibility that the present-day Kuiper Disk evolved through a more erosional stage reminiscent of the disks around the stars β Pictorus, α PsA, and α Lyr. © *1995 American Astronomical Society.*

1. INTRODUCTION

Over the past few years, both the theoretical underpinnings and the observational evidence for a disk of comets and larger bodies beyond the orbit of Neptune has become increasingly secure (Jewitt & Luu 1995; Cochran *et al.* 1995). It now appears assured that the solar system possesses such a disk of material, and that this region is likely to contain the source population for the low-inclination, short-period, Jupiter Family Comets (Stern 1995a).

In this paper I explore the rate at which objects collide in the Kuiper Disk region. The basic rationale for such a study is rooted in the combination of a 10^3–10^4 times higher number density of comets and 10^1 times average orbital speed in the KD, compared to the Oort Cloud (Stern 1988), which together imply that collision rates should be 10^7–10^9 times higher in the Kuiper Disk. Further rationale is provided by analogy to the asteroid belt. The average surface mass density in the Kuiper Disk ($\sim 10^{23}$–10^{24} g AU^{-2}) is similar to the value of $\sim 3\times10^{23}$ g AU^{-2} in the asteroid belt, where collisions play an important and well-known evolutionary role. Even accounting for the ~4 times lower random velocities at 40 AU in the Kuiper Disk (as opposed to 2 AU in the asteroid belt), the collisional intensity in the Disk (i.e., collisions cm^{-2} s^{-1} on a given target) is not very different from the asteroid belt.

Among the questions about the Kuiper Disk that one wishes to address with collision rate modeling are: What is the rate of collisions in the disk today? Is the Kuiper Disk collisionally evolved; that is, are cratering collisions an important surface modification process in the disk, and is the rate of collisions high enough to permit evolution in the size spectrum of bodies in the disk? Is it possible to constrain the properties of the ancient disk via collisional results? Is it possible to constrain the properties of the distant, as-yet undetected reaches of the disk via collisional results? And, are there detectable signatures of these collisions?

This paper represents an initial attack on several of these questions. It is organized as follows: In Sec. 2, I briefly review the evidence for the Kuiper Disk; Section 3 describes a model for computing collision rates in the present-day Kuiper Disk; Section 4 describes the results of model runs for the present-day Kuiper Disk; Section 5 examines the implications of these results; Section 6 explores whether collisions in the present-day disk promote accretion or erosion; Section 7 summarizes the results obtained in this paper and points out two significant inconsistencies between the collisional modeling results obtained here and the present understanding of the origin of objects in Kuiper Disk. Among the implications of the work reported here is that the present-day disk appears to be the remnant of a former disk with more mass, and very likely lower mean eccentricities, than observed today.

2. THE KUIPER DISK

Almost a half-century ago, Edgeworth (1949), and later Kuiper (1951), made prescient predictions that the Sun should be surrounded by a disklike ensemble of comets and other "debris" located beyond the orbit of Neptune. The case

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for such a primordial reservoir was strengthened when it was pointed out that such a disk could be an efficient source region to populate the low-inclination, short-period comets (Fernández 1980). Convincing dynamical simulations supporting this link between most short-period comets, and the Kuiper Disk (KD) region, first appeared when Duncan *et al.* (1988) and later Quinn *et al.* (1991) showed that a low-inclination source region appears to be required for the low-inclination orbit distribution of the Jupiter Family Comets. Figure 1 is a schematic diagram revealing the gross architecture of the disk in relationship to the orbits of the five known outer planets.

The computational capabilities available to Duncan and co-workers in the mid-1980s required some important approximations be accepted (for reviews of this work, cf. Weissman 1993, and Stern 1995a). These compromises were criticized by Bailey & Stagg (1990), but Duncan *et al.*'s work generated interest in the Kuiper Disk by both modelers and observers. Of particular relevance are the Holman & Wisdom (1993) and Levison & Duncan (1993) studies of orbital evolution in the disk. These two groups found a time-dependent dynamical erosion of the disk population inside ~42 AU, caused by nonlinear perturbations from the giant planets. The dynamical chaos resulting from these perturbations is ultimately responsible for the transport of short-period comets from the long-lived Kuiper Disk reservoir to planet crossing orbits where they can be routinely detected. Based on the bias-corrected population of Jupiter Family comets and the dynamical transport efficiency of comets from the Kuiper Disk to the inner planets region, Duncan *et al.* (1995) have estimated that 6×10^9 comets orbit in the Disk between 30 and 50 AU from the Sun.

Observational confirmation of the Kuiper Disk was first achieved with the discovery of object 1992QB$_1$ by Jewitt & Luu (1993). As of early 1994, no fewer than 25 QB$_1$-like, *trans*-Neptunian objects have been discovered (Jewitt & Luu 1995; Stern 1995a). These icy outer solar system bodies are expected to have dark surfaces consisting of an icy matrix contaminated by silicates and organics. Assuming a typical (i.e., cometary) geometric albedo of 4%, and the absence of coma, the distances and magnitudes of these objects indicate they have radii between roughly 50 and 180 km. Based on the detection statistics obtained to date, one can easily estimate that a complete ecliptic survey would reveal $\sim3.5\times10^4$ such bodies orbiting between ~30 and 50 AU. Simple power-law extensions of this population predict a cometary population (which we define as bodies with radii between 1 and 6 km) of $\sim10^{10}$, which is similar to dynamical modeling results obtained by Duncan *et al.* (1995) to satisfy the short-period comet flux. Very recently, Cochran *et al.* (1995) have reported Hubble Space Telescope results giving the first direct evidence for comets in the Kuiper Disk.

3. COLLISION RATE MODELING

Our model for estimating collision rates in the Kuiper Disk begins by defining the Disk in terms of a power law exponent, α, on the size distribution of objects in the disk, so that the number of objects $dN(r)$ between radius r and $r+dr$ is given by

$$dN(r)=N_0 r^{\alpha} dr, \tag{1}$$

where N_0 is a normalization constant set by the estimated number of QB$_1$ objects. For the runs presented here, the bodies in each successive size bin r are a factor of 1.6 times larger in size (and equivalently, 4 times higher in mass). We *a priori* assume a size range beginning at $r=0.1$ km, and extending upward to $r=162$ km.

We also define a power law exponent β on the radial distribution of surface mass density $\Sigma(R)$ in the disk, so that

$$\Sigma(R)=\Sigma_0 R^{\beta}, \tag{2}$$

where Σ_0 is the normalization constant.

Once an input disk is defined as described above, the model bins the disk into a series of concentric tori that are 1 AU in radial width. For each radius bin/heliocentric bin pair, the model computes the collision rate a target will experience

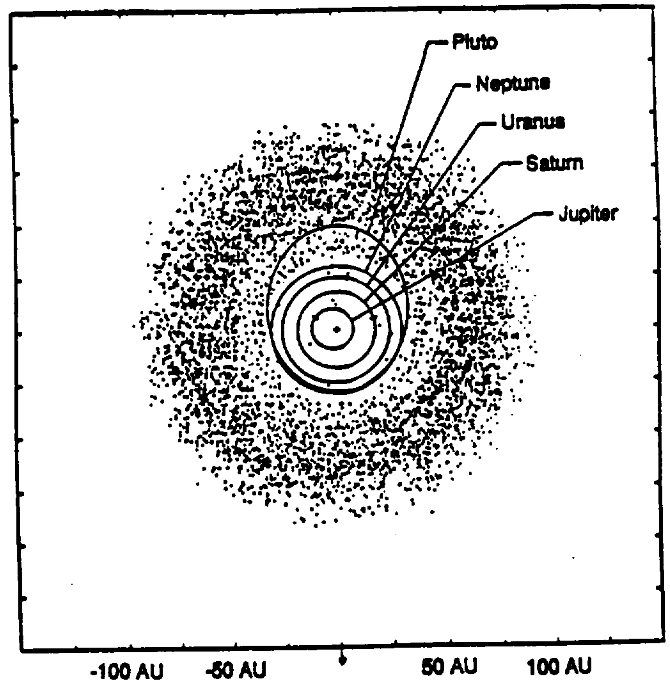

FIG. 1. Schematic depiction of the Kuiper Disk and the orbits of the outer planets, including Pluto. The clearing between the orbit of Neptune and the inner edge of the present day disk is created by the dynamical perturbations of the giant planets (cf. Holman & Wisdom 1993; Levison & Duncan 1993). The position of the outer boundary of the Kuiper Disk is not well constrained, and may well extend much farther than shown here.

TABLE 1. Collision model run cases.

Model	$\mathcal{M}_{disk}$ 30 AU < R < 50 AU	Population Type	Disk Type	N_{QB1s} 30 AU < R < 50 AU	N_{comets} 30 AU < R < 50 AU
CSD 1e4 15	0.16 $M_\oplus$	NOM	CMB	36,461	9×10^9
CSD 1e4 25	0.12 $M_\oplus$	NOM	DMB	27,740	7×10^9
CSD 1e4 13	0.42 $M_\oplus$	CM	CMB	41,162	5×10^{10}
CSD 1e4 23	0.32 $M_\oplus$	CM	DMB	31,316	3×10^{10}
CSD 3e4 15	0.07 $M_\oplus$	NOM	CMB	17,950	4×10^9
CSD 1e6 13	12.3 $M_\oplus$	CM	CMB	1.2×10^6	1.3×10^{12}

Notes to TABLE 1

$\mathcal{M}_{disk}$ is the integral mass over all size bins. CMB=constant mass per radial bin ($\beta=-1$); DMB=constant mass per radial bin ($\beta=-2$). NOM=Nominal mass per size bin ($\alpha=-11/3$); CM=constant mass per size bin ($\alpha=-4$).

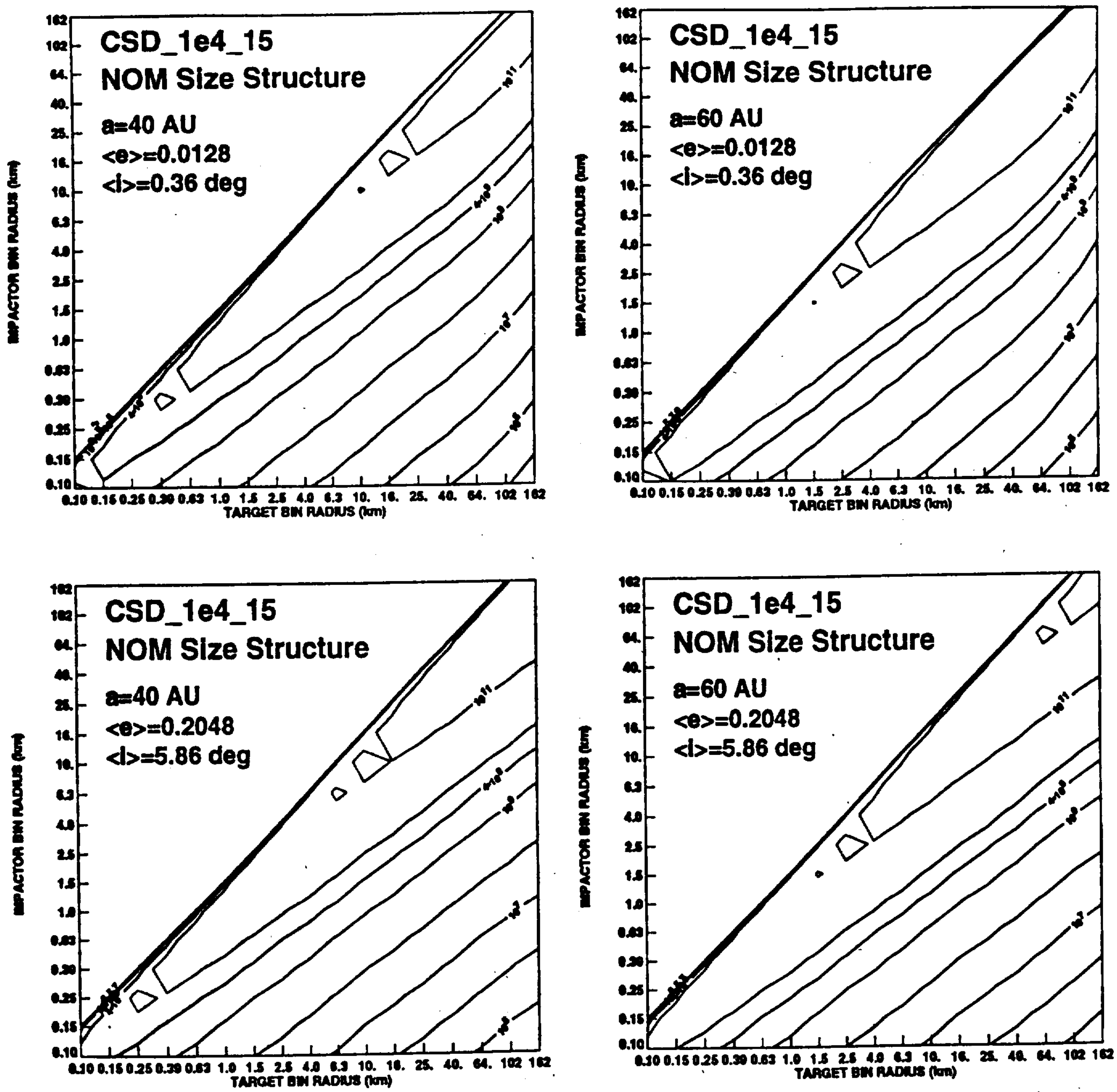

FIG. 2. Contours of the collision time scales (in years) at two locations in the Kuiper Disk (40 and 60 AU), as a function of target and impactor size for the model run with a constant mass per heliocentric bin (CMB) and a "nominal" size structure. The upper panels are for a disk with $\langle e\rangle \sim 0.01$; the lower panels are for a disk with $\langle e\rangle \sim 0.20$.

from objects in all bins of equal or smaller size. This is of course a function of $\langle e\rangle$, since $\langle e\rangle$ controls both the internal velocity dispersion in the disk, as well as the degree of heliocentric bin crossing. In what follows we assume $\langle i\rangle = \frac{1}{2}\langle e\rangle$. Because there is presently no information on the way in which ensemble-averaged inclinations ($\langle i\rangle$) and eccentricities ($\langle e\rangle$) vary in the Kuiper Disk, we adopt a disk-wide $\langle i\rangle$ and $\langle e\rangle$ for each run, and vary these quantities from run to run as free parameters to explore how sensitive the model results are to these variables.

Collisions are not allowed outside the boundaries of the disk, so in the case of moderate or high eccentricity orbits, objects can spend significant time in "open" space outside the disk where collisions are not allowed to occur. This creates edge effects, but such effects may actually occur if the disk in fact sharply truncates at its boundaries.

To compute collision rates we adopt a particle in a box formalism. In this approach, the instantaneous collision rate c of objects with semimajor axis a, eccentricity e, and radius r_x being struck by objects of radius r_y is

$$c(r_x,r_y,a,e)=n\sigma_g v, \tag{3a}$$

where n is the local space density of impactors, v, is the local average crossing velocity of the target body against the KD population at distance R, and σ_g is the collision cross section of the impactor+target pair, corrected for gravitational focusing. Gravitational focusing is an important correction for targets in the QB_1 size range and larger, particularly in the case of very low disk eccentricities (e.g., $\langle e\rangle < 10^{-2}$). The orbit-averaged collision rate $\bar{c}(r_x,r_y,a,e)$

can be written to show its implicit dependencies in the model as:

$$\bar{c}(r_x,r_y,a,e)=\sum_{R=a(1-\langle e\rangle)}^{a(1+\langle e\rangle)} f(a,\langle e\rangle,R)n(r_y,R)\times v_{xy}(a,\langle e\rangle,\langle i\rangle,R)\sigma_g(r_x,r_y,v_{xy},v_{\mathrm{esc}(x+y)}). \tag{3b}$$

Here the term f represents the ratio of $T(a,\langle e\rangle,R)$, the time the target body in an orbit defined by $(a,\langle e\rangle,\langle i\rangle)$ spends in each torus it crosses during its orbit, to this target's orbital period, $(4\pi^2a^3/GM_\odot)^{1/2}$.

To compute $T(a,\langle e\rangle,R$, I solve the central-field Kepler time of flight equation explicitly for every $(a,\langle e\rangle)$ pair in the run parameter space. The number density of impactors $n(r_y,R)$ in the torus centered at distance R is computed from the defining mass of the disk, its wedge angle $\langle i\rangle$, its radial surface density power law, and the population size structure power law.

To compute the average crossing velocity of the impactor population on the target body when the target is in the bin at heliocentric distance R, we use

$$v_{xy}=v_K(a)\sqrt{2\langle e\rangle^2+2\langle i\rangle^2-3\left(\frac{a-R}{a+R}\right)^2} \tag{4}$$

(Petit & Hénon 1987), where v_K is the average Keplerian orbital speed of the target body, and the term under the radical is the relative velocity correction for crossing orbits. The collision cross section σ_g is computed according to

$$\sigma_g=\pi(r_x+r_y)^2\left[1+\frac{2G(m_x+m_y)}{v_{xy}^2(r_x+r_y)}\right], \tag{5}$$

where the term in brackets adjusts for gravitational focusing. To compute masses from radii I assume a density of 1 g cm^{-3}.

As a result of these calculations and the nested loops in a,r_x, and r_y, the model produces an array of collision rates $\bar{c}(r_x,r_y,a,e)$ throughout the specified disk, where the free parameters defining the disk are the total number of QB$_1$'s interior to 50 AU, α, β, and $\langle e\rangle$. From this array the model computes subsidiary quantities such as the mean time between collisions $\tau(r_x,r_y,a,e)$,

$$\tau(r_x,r_y,a,e)=\bar{c}^{-1}(r_x,r_y,a,e), \tag{6}$$

the mass impact rate from all impactors on each target size class:

$$\dot{M}(r_x,a,e)=\sum_{r_y=r_{\min}}^{r_x}\bar{c}(r_x,r_y,a,e)m(r_y), \tag{7}$$

and the total collision rate on entire population in each target size bin:

$$\bar{C}(r_x,a,e)=\sum_{r_y=r_{\min}}^{r_x}\bar{c}(r_x,r_y,a,e)N(r_x,a), \tag{8}$$

where $N(r_x,a)$ is the population of targets of radius r_x with semimajor axis a. We also compute a characteristic time for growth, τ_G, as

$$\tau_G(r_x,a,e)=\frac{M(r_x,a)}{\eta\dot{M}(r_x,a,e)}, \tag{9}$$

where η is the mass accretion efficiency per collision.

4. MODEL INPUT PARAMETERS

In the runs presented below, I assume a disk inner radius of 35 AU and an outer radius of 70 AU. I let eccentricity range as a free parameter from 1×10^{-4} to 2×10^{-1}, which extends over the range of detected eccentricites of QB$_1$ objects detected to date (Jewitt & Luu 1995; H. Levison, personal communication 1995). As noted above, I assume the equilibrium condition $\langle i\rangle=\frac{1}{2}\langle e\rangle$.

Four cases defining the radial mass dependence and size distribution of objects in the disk have been studied. These four cases represent the various combinations of two radial mass distributions [cf., α in Eq. (1)] and two size distributions [cf., β in Eq. (2)].

For the radial distribution of mass in the disk, the two cases we run are defined as follows One case assumes a constant mass per radial bin (CMB; $\alpha=-1$), which corresponds to a surface mass density that declines with heliocentric distance as R^{-1}. The second, and more realistic case, assumes a declining mass per bin (DMB; $\alpha=-2$), corresponding to a surface mass density falling like R^{-2}. These two cases bracket the realistic range of parameter space (Lissauer 1987).

Concerning the size distribution of objects in the disk population, the model grid allows for 17 size bins, each a factor of 1.6 larger in radius. We assume a minimum radius for KD impactors of 0.1 km. This results in an upper size limit of $r=162$ km, which is consistent with the largest detected bodies among the QB$_1$ population. Our favored size distribution, which we call the nominal (NOM) case, connects the observationally estimated $\sim3.5\times10^4$ QB$_1$-sized objects (Jewitt & Luu 1995) inside 50 AU with the modeling-derived estimates of $\sim10^{10}$ comets (Duncan *et al.* 1995) in a single power law with $\alpha=-11/3$. Our second case assumes $\alpha=-4$, which gives a constant mass in every logarithmic size bin; this case is called the CM case. Relative to the NOM case which produces $\approx10^{10}$ for 35,000 QB$_1$'s (100 km in radius or larger), the CM case produces $\approx5\times10^{10}$ comets.

Table I summarizes some the important attributes of these four run cases, as well as two additional run cases described in Secs. 6 and 7. With these preliminaries described, we now discuss the results relating to these four model cases.

5. MODEL RESULTS: COLLISION AND GROWTH TIME SCALES

Figures 2 and 3 depict the collision time scale results obtained using the model described in Secs. 3 and 4. Results are presented at two heliocentric distances, 40 AU (on the left) and 60 AU (on the right). In each figure, the upper panels show the collision time scale for $\langle e\rangle\approx10^{-2}$, and the lower panels show the collision time scale for $\langle e\rangle\approx2\times10^{-1}$. These values of $\langle e\rangle$ bound the measured eccentricity of all Kuiper Disk objects with known eccentricities. Similar data

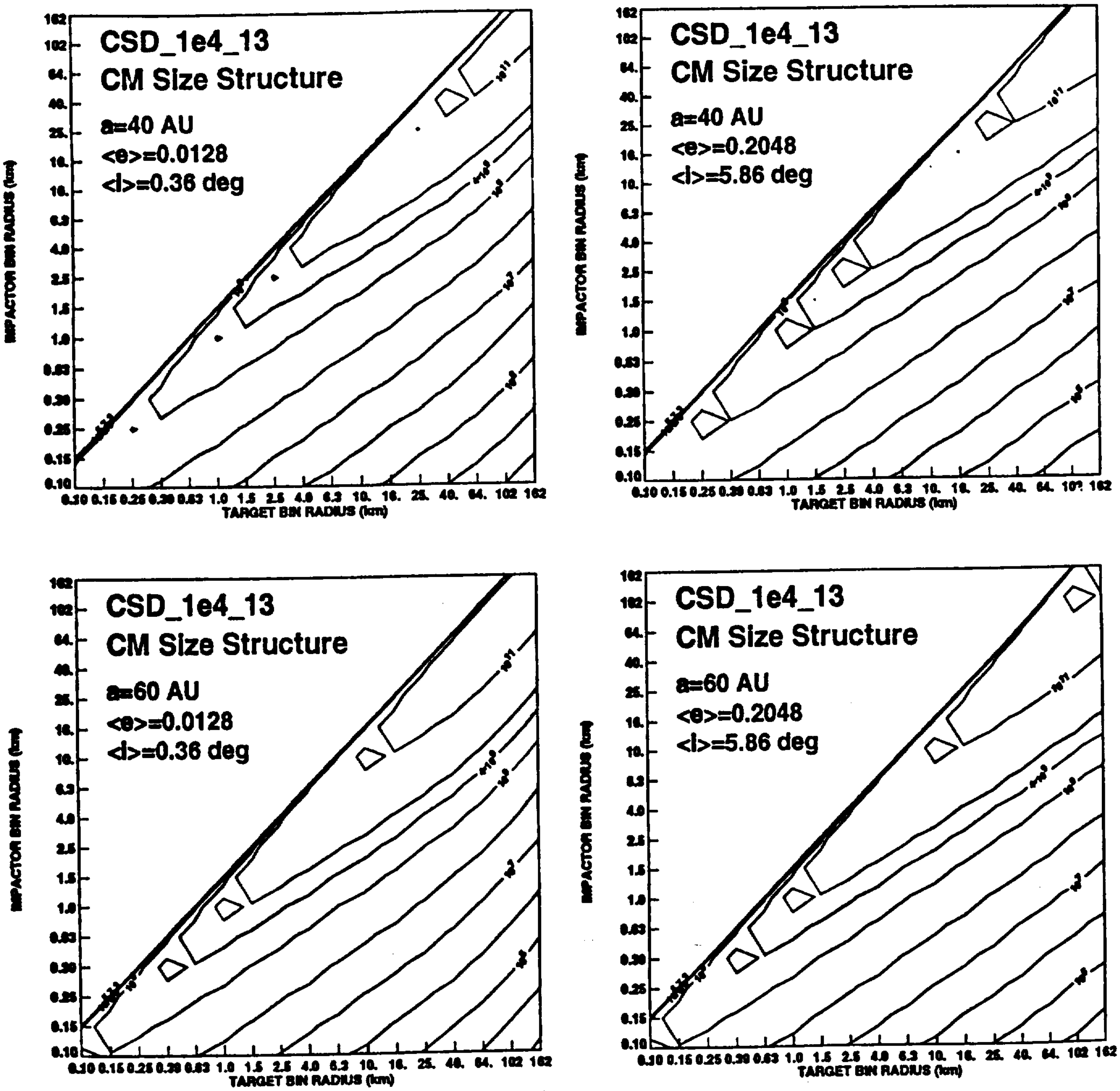

FIG. 3. Contours of the collision time scales (in years) at two locations in the Kuiper Disk (40 and 60 AU), as a function of target and impactor size for the model run with a constant mass per heliocentric bin (CMB) and constant mass (CM) per bin size structure. The upper panels are for a disk with $\langle e \rangle \sim 0.01$; the lower panels are for a disk with $\langle e \rangle \sim 0.20$.

that have been computed for the two DMB ($\Sigma \sim R^{-2}$) cases are not shown because the results are not significantly different.

These data can be used to ascertain a number of interesting facts about collisions in the present-day disk. Two results that are relevant to our later discussions concern the following.

(1) *Collisional Time scales on Comets in the Disk:* We define a "comet" as those disk objects in the radii bins from 1 to 6 km. In the case of the NOM population structure (cf., Fig. 2), the largest impactor a comet at 40 AU typically collides with in 4×10^9 yr has a radius $\sim$5 times smaller than the comet itself; at 60 AU the largest impactor on a comet is typically $\approx$10 times smaller. In the case of a CM population structure (cf., Fig. 3), which has more small bodies and therefore shorter collisional time scales than the nominal-case population, comets are expected to be struck by approximately like-sized impactors at 40 AU, and 2.5 times smaller objects at 60 AU. And,

(2) *Collisional Time scales on QB_1 Bodies:* We define "QB_1 bodies" to be objects in the 102 and 162 km radius bins, which span essentially the range of detected QB_1 radii (see, e.g., Jewitt & Luu 1995). Notice in Figs. 2 and 3 that over the age of the solar system, the largest impactor on a typical QB_1 body will be $\sim$6–16 km in radius, depending on the population structure and eccentricity of the disk. Notice also that each QB_1 object will suffer a cratering collision with a km-class object every 10^6–10^7 yr in a CM population and every $\sim 10^7$–10^8 yr in the NOM population. Among the entire population of $\sim 3.5 \times 10^4$ QB_1 bodies inside $\sim$50 AU,

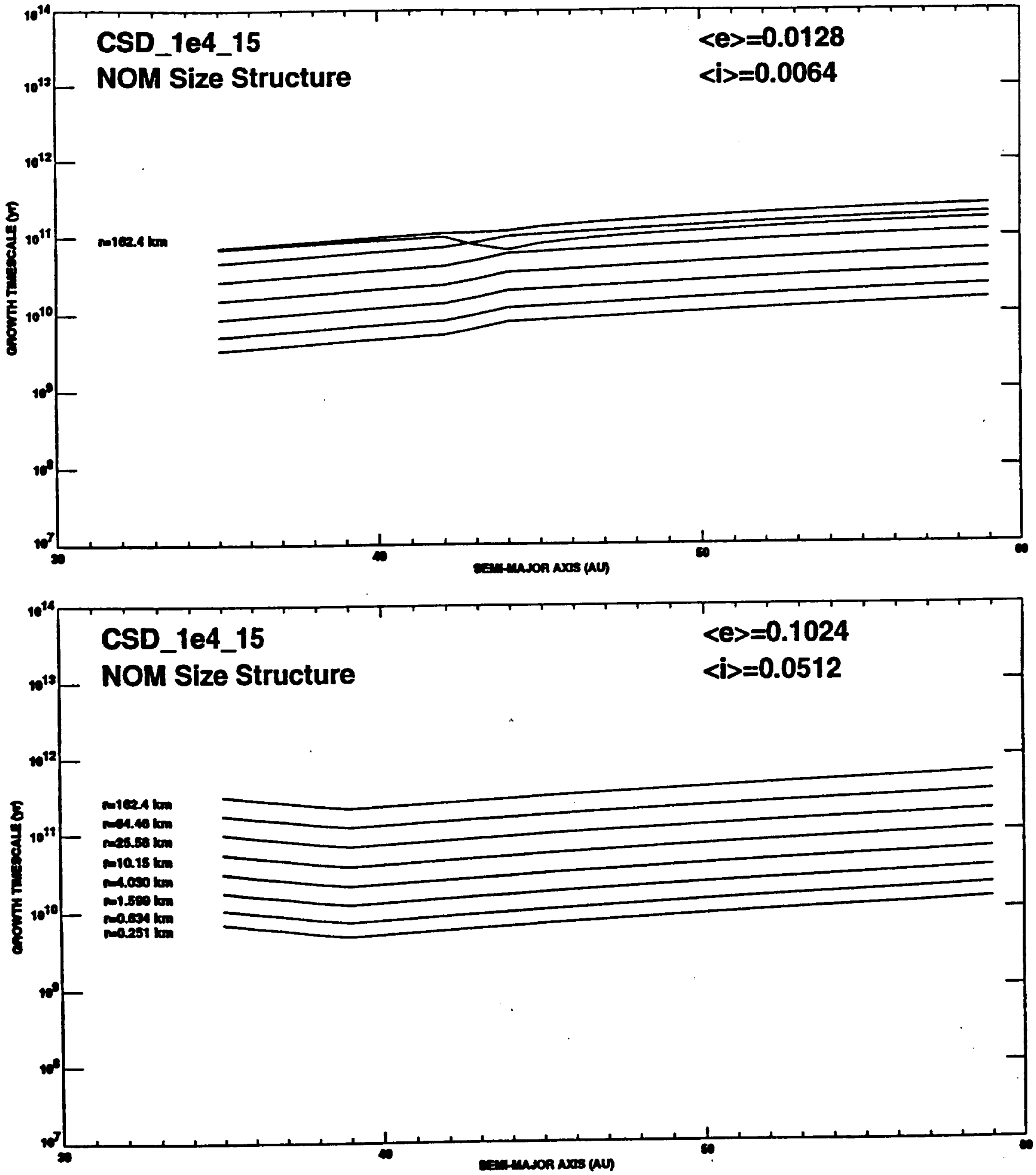

FIG. 4. Lower limit growth time scales as a function of target size and heliocentric distance for the model run with a Constant Mass per heliocentric bin (CMB) and a nominal size structure.

one expects $\sim 10^2$–10^3 collisions with a km-class objects every year, depending on whether the population structure is more like the NOM or CM case. These collision rates suggest that although impacts on individual objects occur infrequently, the population ensemble produces collisions frequently. This in turn suggests that a significant amount of dust may be injected into the Kuiper Disk every year, possibly leading to detectable signatures. This subject is beyond the scope of this paper, but is thoroughly investigated elsewhere (cf., Stern 1995b).

The results presented in Figs. 2 and 3 demonstrate very clearly that both small and large objects in the Kuiper Disk suffer collisions on time scales much shorter than the age of the solar system.

It is next crucial to ask whether present-day rate of colli-

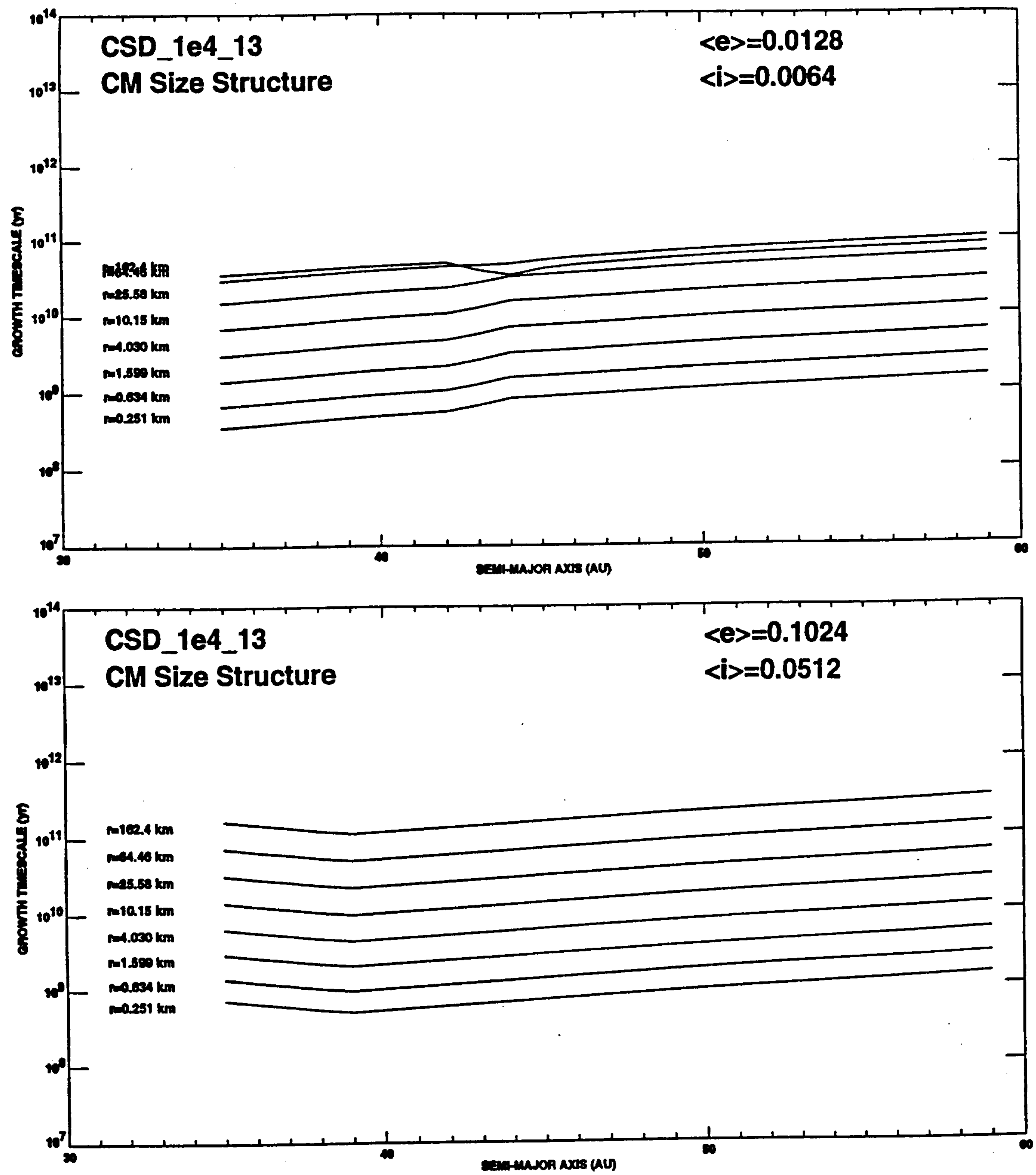

FIG. 5. Lower limit growth timescales as a function of target size as heliocentric distance for the model run with a Constant Mass per heliocentric bin (CMB) and constant mass (CM) per bin size structure.

sions is large enough to have built the largest (i.e., QB_1) bodies we see in the disk. To address this question I have computed growth times using the formalism imbedded in Eq. (9), with the assumption that the growth efficiency factor (i.e., the mass accreted divided by mass incident) is unity. With $\eta=1$, collisions are completely inelastic. This is physically unrealistic, since many collisions will result in erosion of the target rather than net accretion; however, it provides a useful *lower limit* to the actual growth times. As we shall see, even the lower limit QB_1 growth times are longer than the age of the solar system.

Figures 4 and 5 depict the results of such lower-limit growth time calculations for the same two model runs that produced the collision time scales in Figs. 2 and 3, respectively.

The results shown in Figs. 4 and 5 can be summarized as follows. For both the NOM and CM population size structures, collisions are so infrequent that even km-scale bodies

cannot not accrete their own mass in the age of the solar system, even if every collision is perfectly accretional (i.e., inelastic). In the case of the CM population structure, the largest objects that can be grown in 4×10^9 yr are only a few km in radius.

These results are not a strong function of $\langle e\rangle$ if $\langle e\rangle > 0.01$, as appears to be the case in the present-day disk. *As a result, we must conclude that binary accretion in the present day disk cannot explain the growth of QB_1-class bodies on time scales less than about an order of magnitude longer than the age of the solar system.* The implications of this finding will be discussed in more detail in Sec. 7.

6. ECCENTRICITIES FOR GROWTH AND EROSION

Up to this point we have not been strongly concerned with the issue of whether collisions in the KD promote communition or growth. Instead we have been satisfied to simply count collisions and compute time scales. We have seen that binary collisions are too infrequent to explain the growth of objects larger than a few km in radius, even if all collisions promote growth. Now we explore whether growth can take place at all, or whether instead the collisions promote erosion.

Whether a given collision between an impactor and a target results in growth or erosion depends primarily on the energy of the impact. In the Kuiper Disk a typical approach velocity of two objects at a distance large compared to the Hill sphere of the target can be reasonably-well approximated by

$$v_\infty=\sqrt{2}v_K(\langle e^2\rangle+\langle i^2\rangle)^{1/2}, \tag{10}$$

where v_K is the local Keplerian velocity. For the standard assumption that $\langle i\rangle=\frac{1}{2}\langle e\rangle$, we have,

$$v_\infty=\sqrt{3}\langle e^2\rangle^{1/2}v_K. \tag{11}$$

The energy at impact is therefore given by

$$\tfrac{1}{2}\mu v_{\rm imp}^2=\tfrac{1}{2}\mu(v_{\rm esc}+\sqrt{3}\langle e^2\rangle^{1/2}v_k)^2, \tag{12}$$

where μ is the reduced mass and $v_{\rm esc}$ is the escape velocity of the two colliding bodies measured at the radius of impact. The critical velocity for net erosion to occur is given by the requirement that the specific impact energy must exceed the combined energy lost (a) to dissipation, (b) to break up the surface, and then (c) to disperse the ejecta out of the gravitational well of the combined mass of the impactor/target collision pair. The impact energy, $E_{\rm imp}$, as given by Eq. (12), must equal or exceed these energy sinks; if it does not, the target will accrete some mass in the collision. The critical condition for the target to lose mass occurs when the mass of the ejecta exceeds the mass of the impactor. Therefore, if the impactor mass is small compared to the target, we require

$$\tfrac{1}{2}v_{\rm imp}^2>\kappa(v_s^2+\tfrac{1}{2}v_{\rm sec}^2), \tag{13}$$

where v_s represents the velocity required to mechanically shatter the target surface, $v_{\rm esc}$ represents the velocity required to disperse the debris to infinity, and κ is a factor that takes into account energy losses partitioned into heat, sublimation, hydrodynamic effects, and other factors. We take the specific

TABLE 2. Critical eccentricities (e^*) for erosion.

Target Radius	35 AU (Strong)	60 AU (Strong)	35 AU (Weak)	60 AU (Weak)
001 km	7×10^{-3}	9×10^{-3}	1×10^{-3}	1×10^{-3}
010 km	6×10^{-3}	7×10^{-3}	2×10^{-3}	3×10^{-3}
100 km	5×10^{-2}	6×10^{-2}	2×10^{-2}	3×10^{-2}
170 km	9×10^{-2}	1×10^{-1}	4×10^{-2}	5×10^{-2}

Notes to TABLE 2

Strong implies $\rho=2$ g cm^{-3} and $s=3\times10^6$ erg g^{-1}; weak implies $\rho=0.5$ g cm^{-3} and $s=3\times10^4$ erg g^{-1}. In both cases we take $\kappa=8$ and $v_{\rm ej}=0.20v_{\rm esc}$ (e.g., Davis *et al.* 1989); see Sec. 6 for additional details.

energy for mechanical breakup of the target surface to be

$$v_s=\sqrt{s}, \tag{14}$$

where s is the specific strength of the target material at zero compression. And of course the escape velocity is given by

$$v_{\rm esc}=\sqrt{\frac{2GM_t}{r_t}}, \tag{15}$$

where G is the universal gravitational constant, M_t is the combined mass of the target and impactor, and r_t is the combined radii of these two objects. From Eqs. (9)–(15) one can derive the condition which we must solve for:

$$v_{\rm esc}^2+2\sqrt{(3)}e^*v_Kv_{\rm esc}+3(e^*)^2v_K^2-\kappa v_s^2-\kappa v_{\rm ej}^2=0, \tag{16}$$

to obtain e^*, the critical eccentricity at which impact energies are high enough to promote net erosion. Notice e^* is a function of several parameters, including the target strength, size, and mass, as well as the heliocentric distance.

Table 2 gives solutions to Eq. (16) for the critical erosion eccentricity e^*, both for impacts onto strong (e.g., rock/ice) targets ($\rho=2$ g cm^{-3} and $s=3\times10^6$ erg g^{-1}), and relatively weak (e.g., snowlike) targets ($\rho=0.5$ g cm^{-3} and $s=3\times10^4$ erg g^{-1}) at heliocentric distances of 35 and 60 AU. Following the results discussed in Fujiwara *et al.* (1989), we assume $v_{\rm ej}=0.2v_{\rm imp}$ and $\kappa=8$.

The results presented in Table 2 show that e^* for QB_1-sized targets with radii near 100 km, $e^*\geqslant0.02$–0.03 is required for net erosion if they are weak, and $e^*\geqslant0.05$–0.06 is required if they are strong. Similarly, for QB_1-like objects with $R=170$ km, which is comparable to the largest-discovered objects in the disk to date, $e^*\geqslant0.04$–0.05 is required to result in net erosion if the objects are weak, and $e^*\geqslant0.09$–0.10 is required if the objects are strong. For reference, at 35 AU an $\langle e\rangle=0.01$ corresponds to a typical encounter velocity at infinity of 87 m/s. We conclude from these results and the orbits of objects detected to date that some QB_1's should be undergoing erosion, while others may be in an accretional regime, depending on their eccentricity and strength. However, it is worthwhile to note that if the characteristic ejecta velocity v_{ej} is as low as a few percent of the impact speeds $v_{\rm imp}$, then e^* will rise dramatically and the QB_1 population will be in an accretional mode, even for eccentricities as high as 0.2–0.5. Unfortunately, until much better eccentricity statistics become available, it is not possible to determine if the QB_1 population as a whole is gaining or losing mass. All we can say is that the range of de-

tected eccentricities spans the range of e^*'s, creating a complex situation.

The results presented in Table 2 show that e^* for comets is in the neighborhood of 10^{-3} to 10^{-2}, depending in large part on the true strength of comets. These results remain valid even if the characteristic ejecta velocity is as low as 5% of the impact speed, instead of 20%, as assumed in Table 2. This result and the fact that cometary orbit inclinations in the disk appear to be like QB_1 inclinations, imply that collisions on comets today are erosive. This finding also indicates that a collisional cascade is probably taking place among the small bodies in the Kuiper Disk. As pointed out by P. Farinella (personal communication 1995), this finding strengthens the analogy made in Sec. 1 between the Kuiper Disk and asteroid belt collisional regimes.

To determine how much mass a typical comet will loose in the age of the solar system, we combine the collision time scales in Figs. 2 and 3 with the algorithm outlined in Eqs. (10)–(16) to calculate a characteristic time scale ($M/\dot{M}$) for such objects to erode to zero mass. This is accomplished through a numerical code, which we point out, only allows mass loss when $e > e^*$. With this code, we find that between 35 and 55 AU, the critical size for catastrophic (i.e., complete) erosion is $\approx 1-2$ km, depending on the properties of the target and the disk population structure. In addition, we find that comets perhaps as large as 4 km in radius can exhibit erosion timescales shorter than the age of the solar system inside ≈ 40 AU, if $\langle e \rangle > 0.04$.

To support these conclusions, Fig. 6 shows a set of erosion time scales calculated for a mechanically strong (i.e., $s = 3 \times 10^6$ erg g^{-1}) comet 1 km in radius, assuming $v_{ej} = 0.1 v_{imp}$. The impact time scales used in this calculation were from the Fig. 2 dataset. Figure 6 shows that throughout the region from 35 to 55 AU, the erosion time for such bodies is less than or equal to the age of the solar system. These erosion time scales will be further shortened if either comets are weaker than assumed in Fig. 6 (as is likely), or if the characteristic ejecta velocity v_{ej} is a smaller fraction of the impact velocity (which is quite possible). Substituting the collision statistics developed in the run for Fig. 3 marginally increases the erosion times over what is shown in Fig. 6, but does not materially affect our conclusions.

Therefore, unless the population of sub-km objects (which dominate the collision rates on comets in our model) was severely depleted below that predicted by the NOM and CM power laws, these results imply (i) that objects with radii $\sim 1-2$ km and smaller are probably not mechanically primordial and (ii) that a change in the slope of the size distribution probably occurs for radii below $\sim 2-4$ km. Depending on the slope structure of the primordial KD population power law, it may also be that the present-day disk contains far fewer comets than in the distant past.

One factor that could stymie the collisional cascade among small bodies in the $\sim 30-60$ AU region of Kuiper Disk would be a sharp cutoff in the number of small bodies. The recent detection of comets in the 40 AU region by Cochran *et al.* (1995) provides strong evidence that any such cutoff must occur below the *HST* detection threshold, which corresponds to a radius near 6 km. To test this hypothesis, another run was made using the fifth disk input case shown in Table 2. In this run, the population of bodies in the Kuiper Disk was fully truncated below 1 km. As shown in Fig. 7, the resulting survival time scales against erosion for 1 km objects increase to much longer than the age of the solar system, even for eccentricities as high as 20%. As such, it can be concluded that the collisional cascade indicated by the results shown in Fig. 6 can be prevented if the Kuiper Disk population is somehow severely truncated below 1 km. If this is in fact the situation in the disk today, then it implies that either the number of sub-km KD bodies has always been severely depleted (i.e., there was a primordial size cutoff below 1 km), or that this condition arose through subsequent collisional evolution.

Whether in fact collisions caused a depletion of sub-km sized objects to develop, or as may be more likely, collisions have created a collisional cascade to develop at sizes around a few km and less, two facts remain clear: First, collisional evolution has played a key role in shaping the population structure of the Kuiper Disk we observe today. And, second, that the signature of this collisional evolution should reveal itself in a distinct break in the population structure of the Kuiper Disk for objects with radii somewhere between ~ 1 and ~ 6 km.

7. SUMMARY AND DISCUSSION

The results obtained in this paper provide strong evidence that collisions have been an important evolutionary mechanism in the Kuiper Disk. Indeed, because the dynamical instability time in the disk beyond ≈ 42 AU exceeds the age of the solar system (e.g., Levison & Duncan 1993; Duncan *et al.* 1995; Morbidelli *et al.* 1995), collisions appear to be the dominant evolutionary mechanism in the disk, at least inside 60 AU.

The most important results obtained from the first-generation collision model described in this paper are as follows.

(1) That the total rate of collisions of smaller bodies with QB_1-class objects is so small that there appears to be a dilemma in explaining how QB_1's could have grown by binary accretion in the disk as we know it.
(2) That present-day eccentricities in the disk preferentially promote erosion over accumulation for objects a few km in radius and smaller.
(3) As a result, it appears that either the population of objects smaller than ~ 1 km in radius was originally deficient, or the present-day population structure of the Disk is involved in a collisional cascade; if that later is the case, then many Kuiper Disk comets may not be structurally primordial. And,
(4) That, owing to the frequency and energetics of collisions between several-km class and smaller bodies, a distinct break in the population structure of the Kuiper Disk likely occurs for objects with radii somewhere between ~ 1 and ~ 6 km.

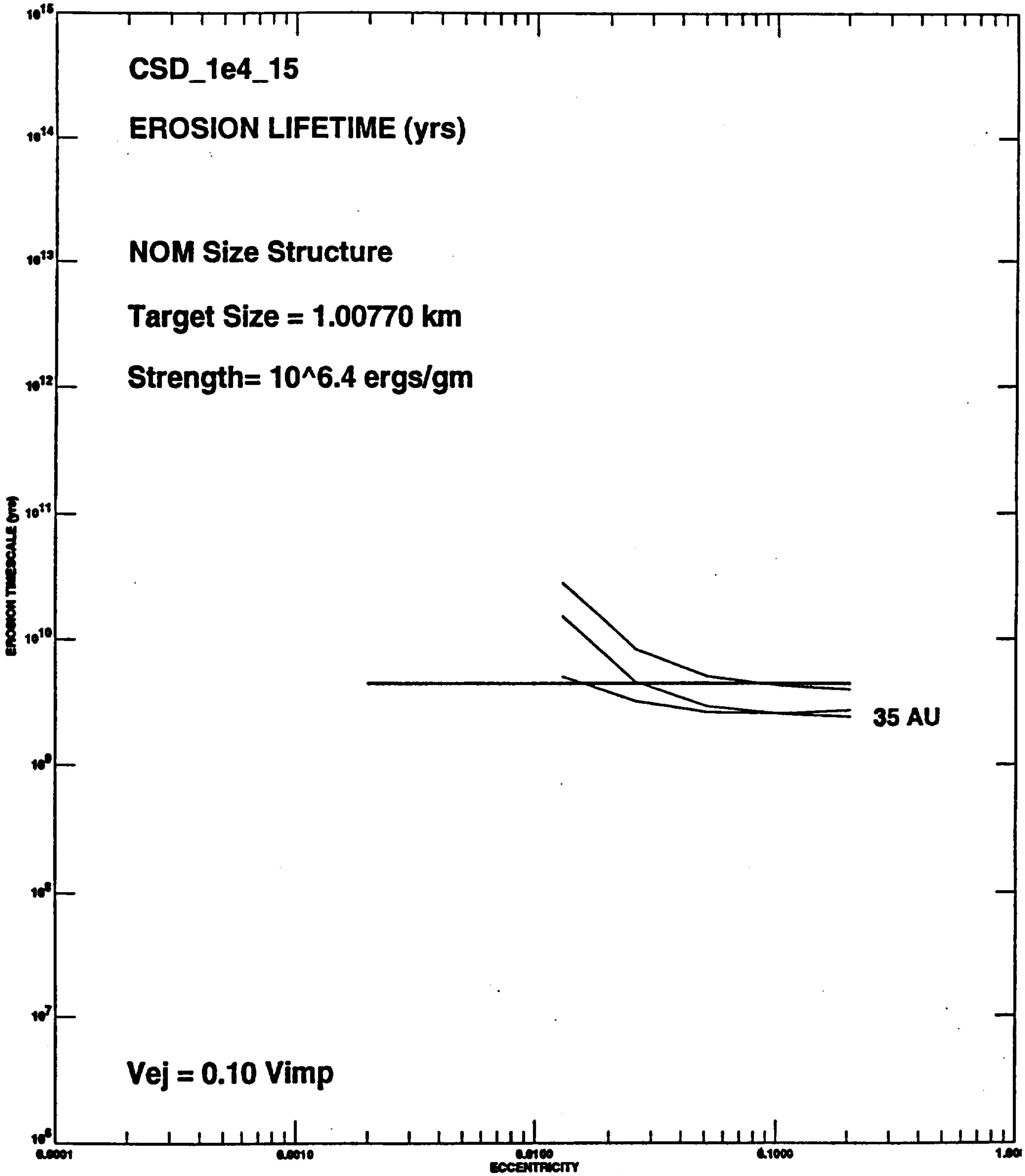

FIG. 6. The time scale against erosion for 1 km radius objects at 35, 45, and 55 AU in the NOM/ CMB case, as a function of their $\langle e \rangle$, compared to the age of the solar system (shown as the horizontal bar). Both weaker and smaller objects erode even more rapidly.

Conclusion (1) is particularly important. Simply put, it implies that collisions appear to be too infrequent to accumulate QB_1-sized objects in anything approaching the age of the solar system. This appears to provide evidence that either the mass and population structure of the Kuiper Disk have strongly evolved over time, or that large objects like the QB_1's were not built via the aufbau (i.e., "building up") process of binary accretion.

Together, findings (1)–(3) strongly suggest that something fundamental is missing in our present state of knowledge about the Kuiper Disk. One possibility is that the QB_1-class bodies were formed directly from the nebula, rather than by binary accretion of smaller objects. Alternatively, two possibilities based on the temporal evolution of the Disk suggest themselves.

First, it may be that the mass of solids in the disk was

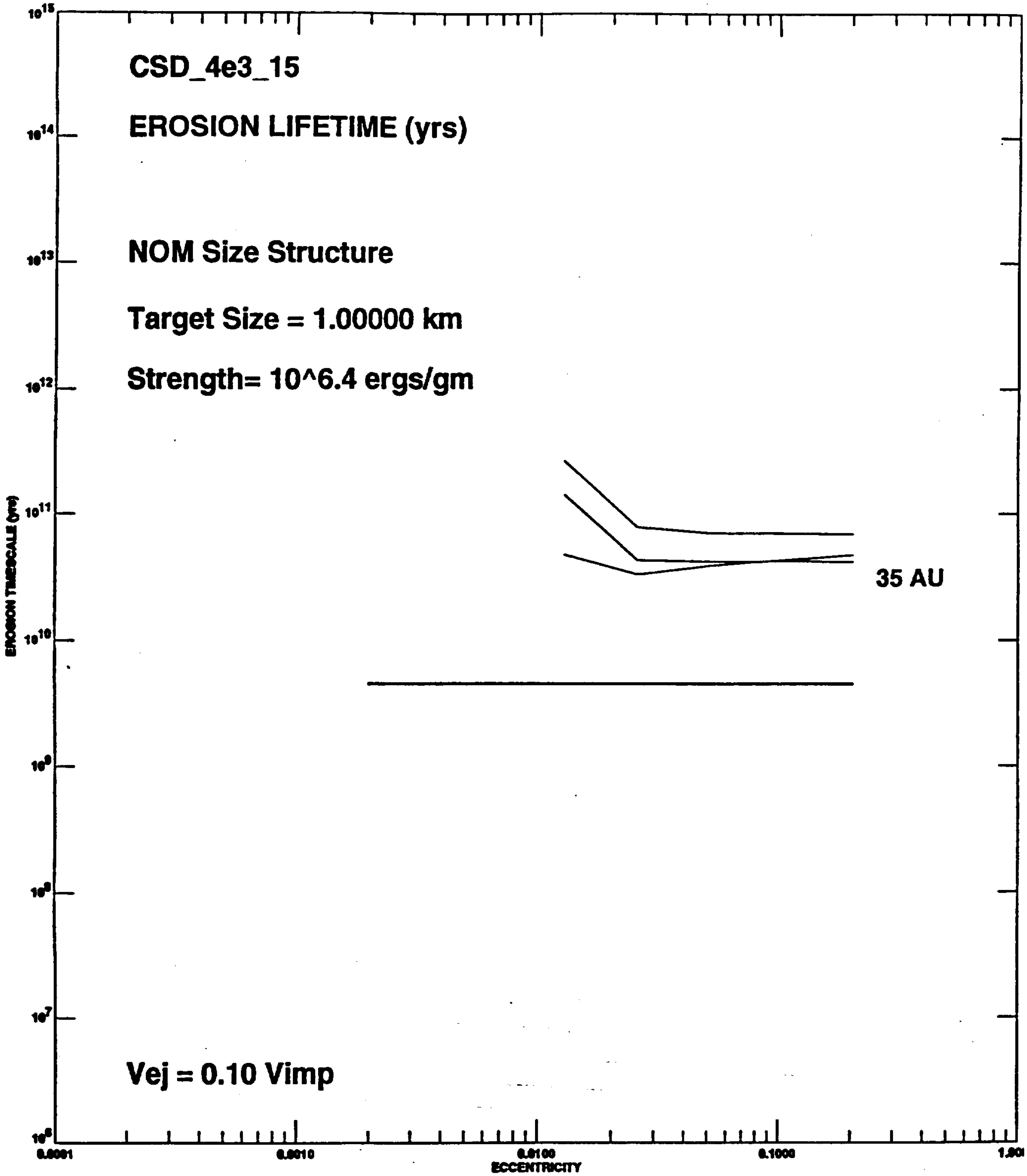

FIG. 7. Erosion time scales at 35, 45, and 55 AU in the Kuiper Disk, as a function of $\langle e \rangle$, for the final collision run case shown in Table 1. In this case the population structure is truncated for objects with radii <1 km. With the population truncated this way, cometary bodies suffer fewer collisions and therefore easily survive for longer than the age of the solar system, even for eccentricities high enough to promote erosion.

much higher in the past than in the present. A higher mass and therefore a higher mass density would have promoted faster growth of QB_1 bodies. The upper panel in Fig. 8 shows the lower-limit growth times for such a case, with $\mathcal{M}_{disk} = 12.3\mathcal{M}_{\oplus}$. This disk mass would be consistent with a continuation from 30 to 60 AU of the rather smooth surface mass density power law for solid material that extends from Jupiter to Neptune, but is today truncated at 30 AU. The lower panel in Fig. 8 clearly shows that "restoring the missing mass" in the 30–60 AU zone does indeed reduce the lower limit to QB_1 growth times sufficiently. However, because collisions between small bodies would still be erosional in a higher mass disk with such $\langle e \rangle$'s, adding mass to the KD region is not (alone) sufficient to solve the QB_1 dilemma.

Much lower eccentricities could provide a remedy, how-

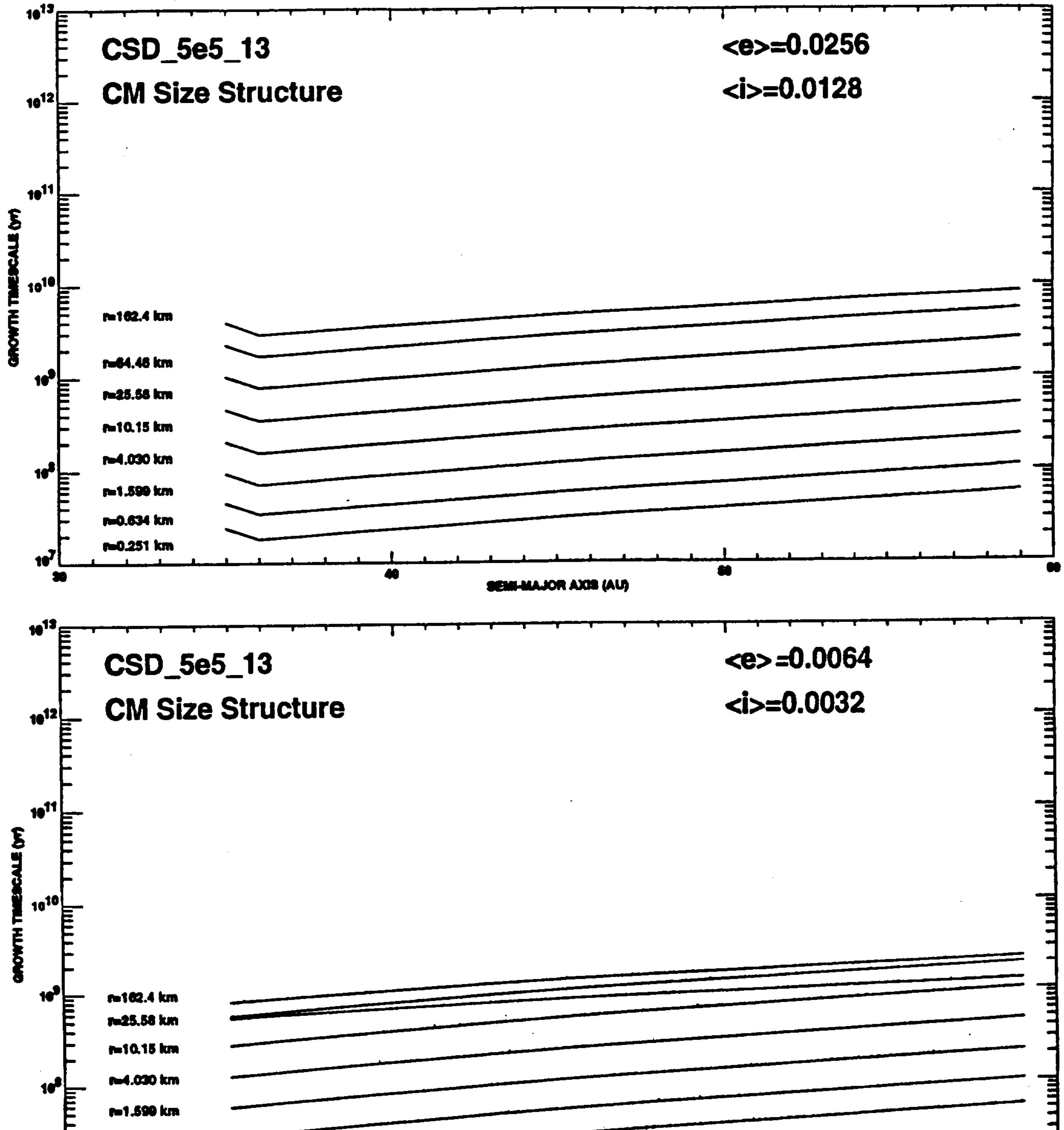

FIG. 8. The lower limit growth time scales in a 12.3 $\mathcal{M}_\oplus$ disk with $\langle e\rangle \sim 3\times10^{-2}$ (upper panel) and $\sim 6\times10^{-3}$ (lower panel). The data in the upper panel demonstrate the effectiveness of increasing the disk mass, as a means of growing QB_1 bodies in less than the age of the solar system in a disk with a mean eccentricity of up to 3%. Calculations not shown here demonstrate that further increasing the disk mass to $\sim 30\mathcal{M}_\oplus$ makes growth at $\langle e\rangle = 10^{-1}$ feasible. However, as described in Secs. 6 and 7, eccentricities below $\sim$1% are required to permit km-class bodies to grow. The lower panel shows growth time scales in the same disk with a very low $\langle e\rangle = 6\times10^{-3}$, which permits efficient collisional accretion from km-scale bodies upward.

ever, by converting the collisional regime from an erosional state to an accretional state favoring accelerated growth. This is shown in the bottom panel of Fig. 8, which is a calculation using the same input disk as in the top panel of Fig. 8, but an $\langle e\rangle$ low enough to ensure efficient growth. If such low eccentricities were in fact extant early in the history of the solar system (e.g., before perturbations excited orbits in the disk or when significant nebular gas was still present), then the growth of larger objects would be promoted (owing in part to the gentler nature of collisions, and in part to the enhanced role of gravitational focusing at low relative velocities).

Determining whether a higher disk mass and/or lower

disk eccentricities could have resulted in the growth of the QB_1's work requires the development of more sophisticated, time-dependent models that incorporate both velocity evolution and a complete representation of the accretion process. We are proceeding on the latter front now.

Before closing, however, it is useful to point out that the results obtained here suggest the intriguing possibility that the present-day Kuiper Disk shed considerable mass as it evolved through a more erosional stage reminiscent of the disks around the A stars β Pictorus, α PsA, and α Lyr. If so, our Kuiper Disk might be considered an older remnant of such a disk.

My colleagues Don Davis, Martin Duncan, Hal Levison, and Glen Stewart provided useful insights during this work. Paolo Farinella and Eli Dwek also provided helpful comments on an early version of this manuscript. This research was supported by the NASA Origins of Solar Systems Program.

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Astronomer finds young, growing planets are easier to detect than mature ones

San Antonio, Texas — October 23, 1996 — One of the hottest, and most publicly exciting areas of planetary research today is the search for planetary systems around other stars. Astronomers and planetary scientists want to know how common planetary formation is, what the range of solar system architectures is, and how common Earth-like bodies are in the Galaxy.

In a significant finding, Dr. Alan Stern of the Southwest Research Institute, which is based in San Antonio, Texas, has found that young planets may be easier to detect than older ones, and that some planned groundbased telescope facilities, such as the Keck Interferometer in Hawaii, have the capability to observe young planets orbiting their parent stars by virtue of the heat the young objects give off. This research was recently published in *The Astronomical Journal*, under support from the NASA Origins of Solar System Program.

Detecting planets around stars has long been an observational challenge fraught with difficulty because extrasolar planets normally only reflect light and are therefore intrinsically difficult to directly detect. (Typically, an Earth-like planet is a million or more times fainter than its parent star.)

Dr. Stern's work examined the detectability of planets, particularly, Earth-sized planets, during the short but unique epoch of giant impacts that is a hallmark of the standard theory of planetary formation. This period is believed to have lasted some 30 to 60 Myr in our solar system.

- more -

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Sufficiently large impacts during this era, such as that believed to have formed the Earth's moon when a Mars-sized object struck Earth, are capable of turning the entire planet molten (i.e., at temperatures of 1,500 to 2,000 degrees K) and its atmosphere luminous, in some cases for periods of between several hundred to 1,000 years. While in this state, a young planet can be detected by its infrared radiation, which can be up to 10,000 times greater than when the same planet is cool later in its life.

Stern's work found that thermally luminous Earth-sized objects can be detected in nearby star forming regions (which are about 125 parsecs, or almost 400 light years away) in one to two nights of observing time. However, because even young planets are only sporadically heated by the truly enormous impacts needed to turn their surfaces molten, predictions indicate that about 250 young stars would have to be searched to expect to find one hot, terrestrial-sized planet. A dedicated observing program using, for example, 20 percent of the Keck Interferometer's observing time for 5 years, could find 1 to 10 such objects. These results suggest a new strategy for the detection of young solar systems and also offer, for the first time, the potential to confirm the standard model of late-stage planetary accretion, which involves large impacts between forming planets.

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Seeking Rogue Comets

Bob Eggleton

We know interstellar comets exist, but astronomers have never seen one — yet.

by S. Alan Stern

Remember those old, silent Keystone Cops movies of a busy 1920s downtown intersection, brimming with cars, kids, cops, and robbers, but without a single traffic light in sight? Confusion abounded. Collisions were common. Chaos reigned. That's the image that comes to mind when I picture our solar system's early days, 4.5 billion years ago.

Over the past 40 years, careful studies of meteorites, lunar samples, and planetary surfaces, along with increasingly sophisticated computer models, have led the planetary science community to converge on a fairly consistent picture of how planets are built. And the truth is it's an inefficient and messy business.

The process tosses tremendous amounts of debris out of the solar system into the galactic disk, including trillions of comets. If solar systems like ours are common, then with billions of stars ejecting trillions of comets into the Galaxy, there must be huge numbers of comets roaming interstellar space.

In the shell of space between here and Alpha Centauri — the nearest star system — there may be as many as 50 trillion rogue comets, ejected from as many as 100 billion galactic planetary systems, each silently coursing its way through eons of interstellar night. Stored at temperatures only a few degrees above absolute zero, these comets contain a treasure trove of information about the formation of planetary systems across the Milky Way. The effort to find these denizens of deep interstellar space could begin before the decade is out.

Throwing Their Weight Around

One of the most interesting phases of planet building comes late in the game. Protoplanets larger than Earth have already formed. At this size, they begin to throw their weight (OK, actually their mass) around, their gravity begins to significantly stir the paths of objects in nearby orbits. This process is called gravitational scattering, and it has two profound effects. First, it increases the growth rate of the protoplanets,

When Oort Clouds Mingle: An Interstellar Comet Shower

Comets roam interstellar space unattached to other stars. However, comets don't have to be free of their parent stars to pass through our solar system. Oort Clouds, the shells of comets that surround stars, can intermingle.

Oort Clouds can be pictured as little bubbles in space, full of comets, with a diameter of roughly 20,000 AU, about ⅓ of a light-year. Whenever two stars with Oort Clouds pass within 20,000 AU of each other, their comet clouds temporarily intersect. Such encounters last about 3,000 years on average.

If half the stars in the Milky Way have Oort Clouds like our own, then about 500 encounters with foreign Oort Clouds have occurred over the age of the solar system. That's about one every 10 million years, on average. Of course, Oort Clouds may not exist around half of all stars, so these kinds of events could be much rarer. But if even one star in 1,000 has an Oort Cloud, then our solar system should have seen at least one comet shower from another sun.

During each encounter, up to 1,000 comets from the intruder Oort Cloud could be passing within 10 AU of the Sun at any given time, about 30 of which would be close enough to exhibit tails. Amateur astronomers would walk around like insomniacs from staying up late and looking at 30 comets every night. The odds of Earth being hit by any of these comets, however, are minuscule; only about one comet should hit Earth for every 300 intruder Oort Clouds that pass through our solar system.

because the rate at which they collide with smaller bodies increases. Second, it also begins to dramatically affect the orbits of bodies coming close to, but not colliding with these objects.

It's just this action that generates the Keystone Cops scenes. As you can imagine, small bodies, ranging in size from rocks to Manhattans, become corks adrift in a rather rough sea. With many protoplanets growing at once, these small bodies become billiard balls careening among the protoplanets.

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In the case of giant planets like Jupiter and Saturn, their gravitational effects are so strong that objects passing near them are frequently ejected into interstellar space. (This still occasionally happens today when a comet comes close to one of these behemoths). Of course, not all objects are ejected. Some, like Comet Shoemaker-Levy 9, actually do strike planets and help them grow. Others are scattered inward, closer to the Sun, where it's much harder for them to escape. Still others are not ejected because they don't quite get enough boost; these planetesimals end up in long, lonely orbits that can reach to distances as great as tens of thousands of astronomical units (AU) from the Sun. This process is the one that populated the Sun's Oort Cloud with the icy planetesimals we call comets.

Scott Tremaine of the Canadian Institute for Theoretical Astronomy has recently shown that Jupiter and Saturn were so massive they tended to eject most of the planetesimals that came close to them. However, he also found that less massive Uranus and Neptune threw a much greater fraction of the planetesimals in their region of the solar system into the Oort Cloud, rather than onto one-way trips to galactic exile.

Other studies, by Wing Ip of the Max-Planck-Institute in Germany and Julio Fernández of the University of Montevideo in Uruguay, indicate that Jupiter and Saturn probably ejected about 10 objects from the solar system for every one they scattered to the Oort Cloud. But Uranus and Neptune only ejected one object for every two or three they injected into the cloud. Overall, the process of building the giant planets in our solar system is estimated to have injected several trillion (i.e., up to 3×10^{12}) planetesimals into the Oort cloud, and between 10 and 100 trillion planetesimals into interstellar space. This planet-building stuff really is a messy business!

Put another way, our solar system alone ejected so many objects into the Galaxy that the number (but certainly not the mass) of comets in the Milky Way vastly exceeds the number of stars. If solar systems like our own are common, then this scenario has repeated itself billions of times, and the population of interstellar comets is impressive indeed.

Life in the Interstellar Outback

What is life like for interstellar comets? It isn't very exciting. They are subject to an eternal deep freeze that for all practical purposes puts them in permanent and very effective long-term cold storage.

The main heat sources are the cosmic microwave background (a 3° bath from the Big Bang) and plain old starlight from the dark interstellar sky. Together, these two feeble radiations aren't likely to warm comets much above 5° or 6° C above absolute zero. At these cryogenic temperatures, chemical reactions are so slow as to be effectively nonexistent, and none of the common cometary surface ices that turn into gas when heated in the planetary region, like water, carbon monoxide, nitrogen, and methane, show any activity. You might say deep interstellar space makes a very nice morgue, preserving our friendly comets for all eternity.

Well, not quite. Research in the last decade or so has revealed that a few types of very subtle changes can occur on the surfaces of interstellar comets. The first breakthrough came when Bob Johnson at the University of Virginia, Lou Lanzerotti of Bell Labs, and their co-workers showed that cosmic rays and ultraviolet radiation from distant stars will penetrate the upper surface layers to a depth of perhaps a meter or two, driving out lightweight volatile molecules and creating micro-flaws in ice crystals. These kinds of radiation damage may darken and perhaps redden the icy cometary surfaces over billions of years.

A few years later, work I did with Mike Shull of the University of Colorado showed that two other effects are also important. First, passing hot and massive O type and B type stars, and nearby supernovae explosions, will occasionally heat interstellar comets to comparatively balmy temperatures — perhaps 30° C above absolute zero (that's still about –440° F). At these very cold temperatures, which are ten times what interstellar comets normally experience, it's possible for noble gases and a few molecules like nitrogen and carbon monoxide to leak out of the surface layers.

More importantly, we also found that micro-impacts from smoke-sized interstellar grain particles will erode the surfaces of interstellar comets, perhaps removing their outer, radiation-damaged rind. But that's it. It's like the Middle Ages in Europe — only worse: *Time goes by, but nothing ever changes.*

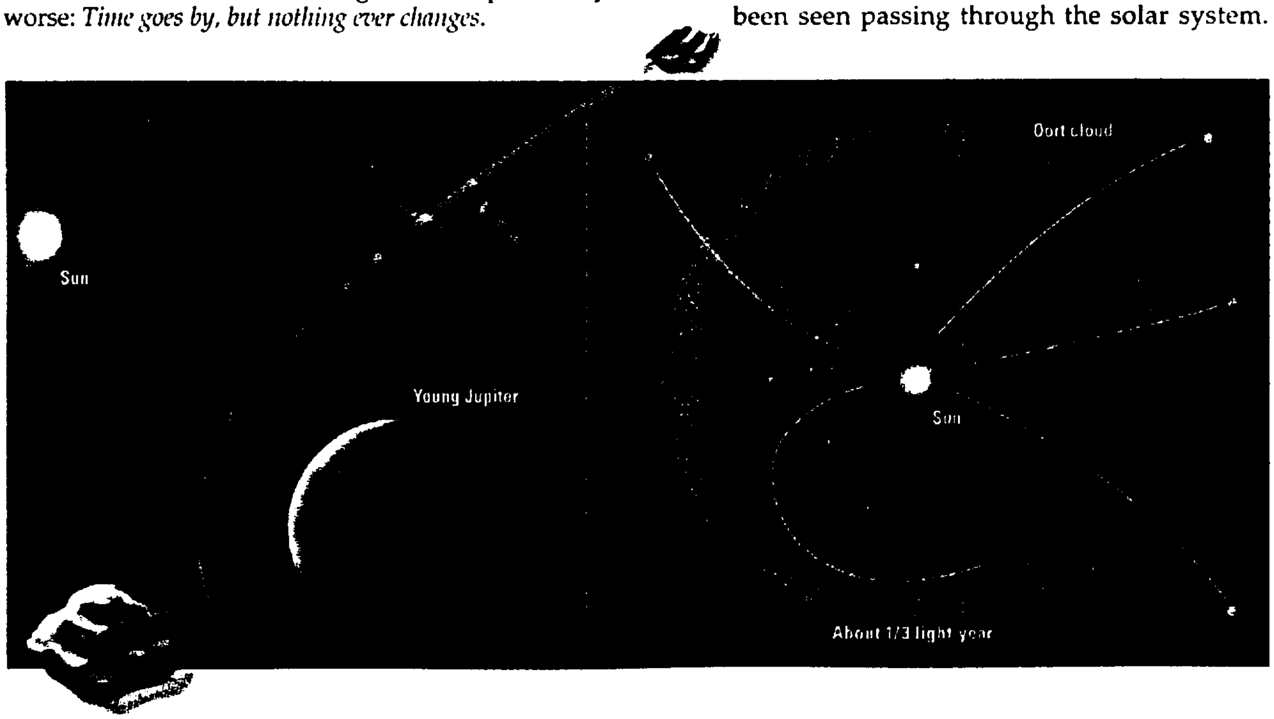
The Number of the Beasties

The wonderful thing about interstellar comets is that they are a direct product of giant planet formation. According to what we now know, if you form giant planets, you eject a lot of interstellar comets. The number of interstellar comets produced per solar system depends strongly on the spacing and masses of the giant planets, the mass of the disks from which the planets formed, the race between the rate at which giant planets form and begin to eject comets, and the length of time the disk-like planetary nebula retains its gas. Still, it's an exciting prospect to think that by measuring the population of nearby interstellar comets we can get information on the total number of solar systems in the Milky Way's disk that have giant planets.

Deep interstellar space makes a very nice morgue, preserving our friendly comets for all eternity.

But exactly how many interstellar comets should one expect in the Milky Way? There are two ways to get a rough handle on the size of this population. First, one could suppose all 200 billion stars in the Milky Way have formed Oort Clouds just like our own, each star ejecting some 30 trillion or so planetesimals. That would imply a population of roughly 6 X 10^{24} interstellar comets (that's 6 trillion trillion of the beasties, with a total mass of about 170 million Suns).

To get a second estimate on the number of comets, one can use the fact that no interstellar comet has ever been seen passing through the solar system.



ASTRONOMY: Phil Kirchmeier

This gives astronomers an upper limit on their concentration in space. From this, Zdenek Sekanina of the Jet Propulsion Lab calculated that on average, there is no more than one interstellar comet for every 1,500 cubic astronomical units of space near the Sun. We can use this number to crudely estimate the upper limit by multiplying the concentration of comets ($1/1500$, or 0.00068 per cubic AU) and the volume of the galaxy (about 200 billion cubic parsecs, or 1.5×10^{27} cubic AU), which gives one trillion trillion (10^{24}) comets.

It's surprising that these two estimates are in rough agreement. It means that the observational data don't tell us very much about the population of interstellar comets. As much as 20 percent of the stars in the Galaxy could have produced Jupiter- and Saturn-mass planets and we still wouldn't have run across an interstellar comet in our normal comet hunting.

It could take 1,500 years at the present rate of comet discovery to find an interstellar comet.

But don't take that 20 percent number to the bank. Our solar system might have ejected an unusually large number of planetesimals, in which case the existing constraints on the interstellar comet population could be consistent with jovian planets around every star in the whole Galaxy. Simply put, we just don't know enough to know — we must go and look.

Visitors from Another Pond

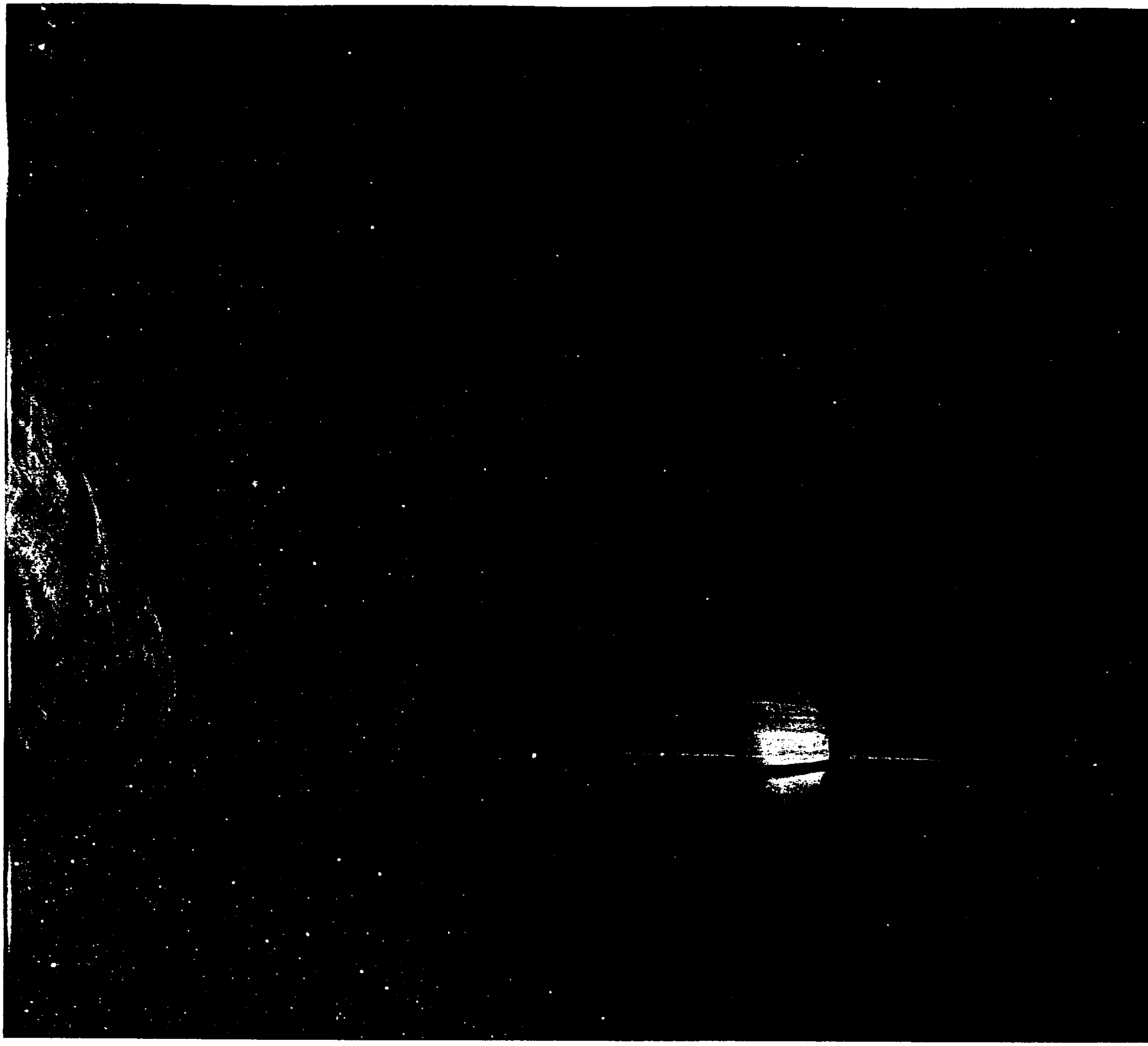
Interstellar comets would be easily distinguishable from solar system comets because they will pass through the solar system with, on average, the same speed that the Sun is making against the local stars. That's about 20 to 30 kilometers per second, compared to 10 km per second for comets from our own Oort Cloud. Because of their high velocity, interstellar comets follow a hyperbolic trajectory, unlike the parabolic trajectory coursed by solar system comets such as Hale-Bopp. The hyperbolic velocity of 20 to 30 kilometers per second would make an unmistakable John Hancock for interstellar comet confirmation.

Comet hunters regularly detect comets from our Oort Cloud, but after 250 years of comet hunting, no comet with a clearly interstellar orbit has been found. Tom McGlynn and Bob Chapman of NASA's Goddard Space Flight Center have estimated that it could take 1,500 years at the present rate of comet discovery to find an interstellar comet, or to prove they are rare. We can do far better if we try an active search.

How would one conduct a search for interstellar comets? With a little ingenuity. As noted earlier, the best upper limit on the space density of interstellar

comets is about one per 1,500 cubic AU. That means that the mean distance between interstellar comets in the Milky Way could be as little as 11 AU. It might even be a little higher near the Sun, because the Sun's gravity will attract them toward our direction. That's about the distance from the Sun to Saturn, which means that at any time (such as now) there should be one interstellar comet somewhere in the shell of space around the Sun as defined by Saturn's orbit.

At a distance of 11 AU from the Sun a comet like Hale-Bopp would be inactive, and therefore would be a dark nucleus reflecting the diluted light of the distant Sun. As seen from Earth, it would have a visual magnitude between 22 and 25. This is faint, but not too faint to discourage us; most of the recently-discovered Kuiper Disk objects have magnitudes this faint.



Bob Eggleton

But where to search? Scouring the entire sky to 24th or 25th magnitude is a little much to ask. Fortunately we know something about where the needles are in this haystack. Interstellar comets will come from the apex of motion in the direction the Sun is moving in space, toward Hercules. It's a little like a meteor shower radiant, except for the fact that the so-called "meteors" are comets, and they will appear at the rate of perhaps one every few years. By searching a 1 degree-wide-strip about 45 degrees in radius centered on the apex of solar motion about once a week, one can ensure that no interstellar comet will slip by. Candidate objects can be followed up with subsequent observations after they pass through the detection strip in order to confirm whether or not they are in fact on hyperbolic trajectories from interstellar space.

With a search strategy like this, astronomers could double the present-day interstellar comet detection limit after about 18 months. After 10 years, a ten-fold improvement could be achieved. By that time, it's possible, maybe even probable, that a real, bona fide interstellar would have been bagged, giving us not only a chance to study a comet from another solar system, but also some solid evidence about the galaxy-wide frequency of solar systems with giant planets like our own. □

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Chiron and the Centaurs: escapees from the Kuiper belt

Alan Stern & Humberto Campins

The Centaurs—a group of objects orbiting chaotically among the giant planets of our Solar System—appear to be a population transitional in size between typical short-period comets and the large Kuiper-belt objects that orbit beyond Neptune. They promise to reveal much about the origin of and interrelationships between the icy bodies of the outer Solar System.

THE outer Solar System has long appeared to be a largely empty place, inhabited only by the four giant planets, Pluto and a transient population of comets. In 1977 however, a faint and enigmatic object—2060 Chiron—was discovered[1] moving on a moderately inclined, strongly chaotic 51-year orbit which takes it from just inside Saturn's orbit out almost as far as that of Uranus. It was not initially clear from where Chiron originated.

Following Chiron's discovery, almost 15 years elapsed before other similar objects were discovered; five more have now been identified[1]. Based on the detection statistics implied by these discoveries, it has become clear that these objects belong to a significant population of several hundred (or possibly several thousand) large icy bodies moving on relatively short-lived orbits between the giant planets. This new class of objects, known collectively as the Centaurs, are intermediate in diameter between typical comets (1–20 km) and small icy planets such as Pluto (~2,300 km) and Triton (~2,700 km). Although the Centaurs are interesting in their own right, they have taken on added significance following the recognition that they most probably originated in the ancient reservoir of comets and larger objects located beyond the orbit of Neptune known as the Kuiper belt.

Origin of the Centaurs

The first clue to the origin of the Centaurs came about as a result of dynamical studies of Chiron's orbit. At first discovered in the late 1970s[3], and forcefully reiterated in more modern calculations[4], Chiron's orbit is highly unstable to perturbations by the giant planets. As a result, Chiron's orbital lifetime among the giant planets is short, leading to the conclusion that its origin was in a more stable reservoir, either in the asteroid belt, or beyond the giant planets. The discovery of a coma around Chiron[5-7], in the late 1980s, indicated the presence of surface volatiles which could not have survived the age of the Solar System in the comparatively warm asteroid belt[8]; such volatiles therefore strongly indicate that Chiron originated in a distant reservoir, beyond the giant planets.

A second line of evidence relating to Chiron's origin came about from simulations of cometary dynamics. These studies[9-12] demonstrated that the dominant dynamical class of short-period comets, called the Jupiter-family comets (JFC) cannot be derived from the classical, Oort-cloud cometary reservoir. The reason for this is that their characteristically low orbital inclinations cannot be efficiently produced by the action of planetary perturbations on orbits initially in the inclination-randomized (that is, nearly spherical) Oort cloud.

Instead, the JFC seem to derive from a dynamically stable reservoir concentrated near the plane of the planetary system. Any such reservoir for the JFC must satisfy the criterion that the loss rate of objects from it be low enough that the reservoir can persist for the age of the Solar System. Because the dynamical clearing time for orbits between the planets is characteristically one to two orders of magnitude shorter than the age of the Solar System[12-14], there are few regions of space that provide stable, candidate source locations for the JFC. One such region is the zone beyond Neptune's orbit (at 30 AU, astronomical units) where nonlinear perturbations by Neptune and the other giant planets can excite orbital eccentricities on timescales comparable to the age of the Solar System. Once orbital eccentricities are excited sufficiently to cause objects to cross Neptune's orbit, a fraction of these objects become temporarily trapped on Centaur-like orbits among the giant planets. Other such objects are dynamically transported by subsequent encounters with the other giant planets onto orbits that pass within 1–2 AU of the Sun[15], where they generate comae and become easily detectable. A second possible source region for the JFC is the slowly dynamically evaporating jovian Trojan clouds, whose dynamics are controlled by the stability of a narrow phase space surrounding the leading and trailing lagrangian points of Jupiter. However, recent dynamical simulations[16] show that the jovian Trojan clouds are not as effective as the so-called trans-neptunian zone in populating the JFC and Centaur populations. Following historical suggestions dating back as far as the 1940s that a disk-shaped reservoir of planetesimals and other small objects might reside beyond the Neptune[17,18], the trans-neptunian region has been dubbed the Kuiper belt, or in analogy to debris belts around the other stars, the Kuiper disk.

The pivotal breakthrough concerning the reality of the hypothesized Kuiper belt came in 1992, with the discovery of a faint (R-band magnitude near 23), 180-km diameter object[19] designated $1992QB_1$. $1992QB_1$ orbits the Sun in a stable, nearly circular orbit some 14 AU beyond Neptune. In the four years since $1992QB_1$ was found, over three dozen similar objects have been discovered in the trans-neptunian region[2]. Estimates[2,20] indicate that some of these objects have diameters approaching 400 km. Based on the efficiency with which such objects are being detected and their surface density on the sky, it has been estimated that around 7×10^4 objects with diameters greater than 100 km orbit between 30 and 50 AU (ref. 2). Here we refer to these larger objects populating the Kuiper Belt as QB_1s.

Following the discoveries of numerous QB_1s in the Kuiper belt, the Hubble Space Telescope (HST) was used to conduct a search for the much smaller, and much fainter, cometary nuclei which must be present in this region if it is indeed a source of the JFCs. Last year, Cochran *et al.*[21] reported exciting evidence, near the limit of HST's capabilities, for numerous objects with V-band magnitudes of ~28.6, corresponding to comet-like diameters of a few kilometres to ~10 km. This evidence corresponds to a population of several hundred million comet-sized objects. If this result is coupled with models[12] that predict the ratio of the population detected in the region searched by Cochran to the entire trans-neptunian zone, a total population is calculated of several billion comets in the 30–50 AU region. As such, it appears that the Kuiper belt is indeed the source region of most JFC, as dynamical simulations predicted[9,14].

Taken together, the discovery of both QB_1- and comet-sized objects in the Kuiper-belt region indicates that the Kuiper belt supplies a wide size range of objects onto orbits in the giant-planet region. Based both on expectations resulting from the planetesimal accretion codes, and the observational evidence for many more comets than QB_1s, it appears that a power-law-like source population histogramm exists in the Kuiper belt, with many more small bodies than QB_1s. Because the dynamical transport process that brings objects from the belt to planet-crossing orbits is essentially independent of the mass of the object being transported[15], it is expected that the population of objects ranging in size from Centaurs down to JFC orbiting among the giant planets is representative of the population of objects in the 30–50 AU zone from which they are derived.

TABLE 1 Orbital characteristics of the known Centaurs

Object	Semi-major axis	Perihelion distance	Eccentricity	Inclination	Present opposition V magnitude
2060 Chiron	13.70 AU	8.46 AU	0.38	25°	15.5
5145 Pholus	20.30 AU	8.68 AU	0.57	7°	17.9
1993HA$_2$	24.73 AU	11.84 AU	0.52	16°	21.0
1994TA	16.82 AU	10.69 AU	0.31	5°	23.8
1995DW2	25.03 AU	18.84 AU	0.25	4°	21.9
1995GO	18.14 AU	6.79 AU	0.62	18°	20.3

These characteristics are taken from ref. 53. Although the basic orbital properties of the third to sixth objects are known, they have not yet been named because, by IAU convention, objects must first be observed for long enough to produce astrometrically reliable orbits.

Physical attributes of the Centaurs

It is now established that the slow leakage of objects from the Kuiper belt due to planetary perturbations creates a population of objects on comparatively short-lived, planet-crossing orbits in the giant-planet region between 5 and 30 AU from the Sun. Studies of the dynamical evolution of orbits dislodged from the Kuiper belt[15] predict a characteristic equilibrium population of objects on planet-crossing orbits that is $\sim 10^{-4}$ of the population of the Kuiper-belt reservoir from which they are derived. These studies also predict that the median lifetime of such orbits is of the order of 5×10^7 years. Such findings imply that a population of $\sim 5 \times 10^5$ to perhaps 10^6 comets, and ~30–300 Centaur objects of diameter 100 km or larger, are orbiting between the giant planets.

Chiron and its recently discovered cohort of Centaurs are thus now seen to be objects derived from the Kuiper belt. Table 1 summarizes the orbital attributes of the six known Centaurs; Fig. 1 depicts the orbits of these objects and their dynamical context in the outer Solar System.

As escapees from the Kuiper belt, the Centaurs are an important population for study. Indeed, owing to their greater proximity to the Sun, the brightest centaurs are some 5–7 astronomical magnitudes (factors of ~100 to ~600) brighter than the brightest Kuiper-belt objects, which enables more detailed studies of the Centaurs than are possible with the QB_1s and Kuiper-belt comets. Additionally, being closer to the Sun, the Centaurs experience greater heating, which generates characteristic perihelion surface temperatures in the range ~120 to 150K (ref. 22); by contrast, Kuiper-belt objects probably never experience surface temperatures in excess of 60–70K. Therefore, because vapour pressure depends exponentially on the temperature of the ice, Centaurs are much more likely than Kuiper-belt objects to show sublimation-generated activity. Although such heating causes the surfaces of the Centaurs to evolve chemically and physically over long time-scales[23], it also causes the surface ices to sublime, and thus reveal valuable insights into the nature of these objects.

Unfortunately, although the Centaurs are brighter than Kuiper-belt objects, they are still faint in absolute terms, so considerable dedication is required to obtain physical information on them. As a result, comparatively little work has been done to reveal their compositions, colours, shapes, rotational properties and other attributes (Table 2). Despite the great deficits in our knowledge about the physical and chemical characteristics of this unique population, several important pieces of information are emerging.

First, with regard to the derived sizes of the Centaurs discovered to date, roughly half appear to be near 60 km in diameter, but 2060 Chiron[22,24] and 5145 Pholus[25] are much larger, with ~180-km diameters that are comparable to typical QB_1s being discovered in the trans-neptunian zone. Second, infrared spectroscopy and colour photometry have given the first clues about the surface compositions of these objects. The first clearly detected spectral

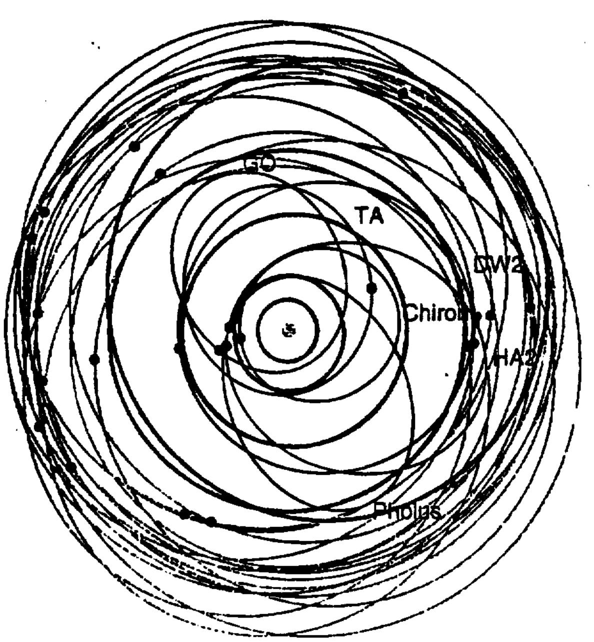

FIG. 1 The orbits of the giant planets (black lines), the six known Centaurs (red lines) and those Kuiper-belt objects with well established orbits (green lines). The dot on each orbit depicts the current location of the object. For scale, Jupiter's orbit is approximately 10 AU across. Abbreviations on the figure as follows: GO, 1995GO; TA, 1994TA; DW2, 1995DW2; Chiron, 2060 Chiron; HA2, 1993HA$_2$; Pholus, 5145 Pholus. (Figure courtesy of H. F. Levison)

TABLE 2 Physical characteristics of the known Centaurs

Object	Diameter* (km)	Geometric albedo (in V)	Rotational period	Rotational amplitude	$V-J$ colour‡	Detected activity
2060 Chiron	182 ± 10	0.11–0.20	5.92 h	9%	1.13 ± 0.04	Yes
5145 Pholus	185 ± 22	0.04 ± 0.02	9.98 h	20%	2.53 ± 0.06	No
1993HA$_2$	62 km†	0.05			2.07 ± 0.40	No
1994TA	28 km†	0.05				No
1995DW2	68 km†	0.05				No
1995GO	60 km†	0.05				No

* The sizes of Chiron and Pholus were obtained[22,24,25] from thermal fluxes, with computed albedos based on their sizes and V magnitudes. Chiron's albedo is strictly an upper limit owing to a possible, small, residual coma contribution.

† These sizes were computed by assuming a V-band geometric albedo of 5%, a value which is commonly found for cometary surfaces.

‡ Colour data are discussed in the text[27,31,32]. Note a $V-J$ colour of 1.116 would be identical to the Sun[47], thereby indicating a neutrally coloured surface. Higher $V-J$ colours indicate red surfaces.

absorption feature among the Centaurs was a deep 2.25-μm absorption on Pholus[26]. This feature has been associated with light organic solids mixed with ices[27,28]. Importantly a 2.04-μm absorption features has also now been detected, both in Pholus and Chiron[29], which Cruikshank *et al.* identify[30] in Chiron as an absorption band of water-ice. Third, although none of the three Centaurs that have been explored in the infrared have displayed any statistically significant colour variation with rotational phase[31], they do show striking colour differences between one another (refs 27, 32 and Fig. 2). Indeed, whereas Chiron's intrinsic colour is grey (that is, neutral) throughout the 0.3–2.5 μm band, Pholus, which lies in a similar orbit and is similar in size, is extremely red. 1993HA$_2$, though smaller and in a more distant orbit, is also very red compared to Chiron. How much of these differences between various Centaurs is due to evolutionary mechanisms (as opposed to intrinsic attributes) is not yet clear, but it is well established that long-term exposure to cosmic rays and solar ultraviolet radiation darkens (and initially reddens) surfaces containing light-weight organics, in turn creating a more complex chemical mélange.

Additionally, the determination of well constrained albedos for 2060 Chiron, and more particularly 5145 Pholus (because it is not active), provides useful information for predicting the sizes of QB$_1$s from their observed magnitudes.

The particular value of Chiron

Chiron is uniquely valuable among the Centaurs because of the long history of its sporadic outbursts. Why has such activity only been detected in Chiron? Possibly Chiron is dynamically younger, and therefore more active than the other objects. Alternatively the other objects may have thicker surface mantles, may be fundamentally different in their composition or simply may have not been observed long enough to expect to detect activity. Chiron's uniqueness in showing activity is perhaps the most intriguing observable obtained on the Centaurs so far.

Chiron's activity was first recognized when it suffered an outburst that increased its brightness by a factor (in 1989) of just over two[33,34]. In 1989–91 Chiron was also observed to show a highly variable particulate coma and tail extending as far as 2×10^6 km (refs 35, 36), and a cloud of CN gas[37] presumably derived from the photodissociation of some heavier, parent molecule. When these various observations were made, Chiron was still more than 10 AU from the Sun, where the solar radiation field is too weak to sublime water-ice, the common volatile that powers the cometary activity close to the Sun. Although other mechanisms remain plausible, the sublimation of highly volatile ices like CO, N_2 or CH_4 (buried a short distance below the surface) were therefore flavoured as the source of Chiron's activity. Further evidence for the sublimation of such volatiles was obtained through the discovery of even more extreme activity on archival, pre-discovery images of Chiron obtained when it was near its aphelion at 19 AU, and therefore far too cold to sublime anything but highly volatile ices like those mentioned above[38]. The final confirmation of this hypothesis came in 1995, though the discovery of CO gas itself in Chiron's coma[39,40].

The fact that Chiron's activity was greater at its aphelion than it has been at any time since provides compelling evidence that its level of activity is not a simple function of heliocentric distance alone. Instead, Chiron's activity probably involves a complex interaction between the level of insolation reaching its surface, the obliquity of its spin axis, the location of its near-surface volatiles and extensive surface mantling by substances (possibly including silicates, water-ice and carbonaceous materials) which do not strongly sublime that far from the Sun.

Chiron's strong variability and the low gas-production rate inferred from CN and CO gas detections in its coma provide

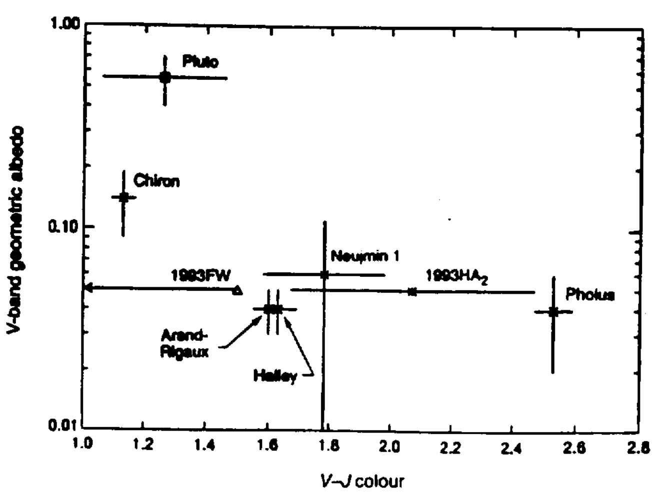

FIG. 2 Colour–albedo diagram showing the visible-band albedos and visible–infrared (that is, $V-J$) colours for several Centaurs (Chiron, Pholus and 1993HA$_2$), several cometary nuclei (Arend-Rigaux, Halley and Neujmin 1), Pluto and the one QB$_1$ (1993FW) for which applicable data are available. A neutrally coloured surface would have the $V-J$ colour of the Sun, 1.116 (ref. 54). Note that the Centaur Pholus is quite red; in fact, it is far redder than any other object in the Solar System. The $V-J$ colour for 1993FW is an upper limit. $V-J$ for Pluto was obtained form D. P. Cruikshank (personal communication; the V-albedo error bars for Pluto represent its intrinsic rotational lightcurve variation.

strong evidence that Chiron's activity is generated by localized sources covering <1% of the surface. The case supporting highly localized vents or jets on the surface is further supported by short-term brightness fluctuations in Chiron's coma[41,42] that occur on timescales consistent with clouds of material being ejected onto suborbital trajectories, and by the detection of complex opacity structures in Chiron's coma during two recently observed stellar occultations by Chiron[24,43]. It has been pointed out[44] that these vents or jets may resemble the geysers detected on the surface of Neptune's large, captured satellite, Triton.

Chiron's low gravity creates a situation in which its escape speed ($\sim 10^2\,\mathrm{m\,s^{-1}}$) is comparable to both the thermal velocity of subliming gas ($\sim 2 \times 10^2\,\mathrm{m\,s^{-1}}$), and the estimated muzzle velocity of Triton-like geysers[45] (of the order of 40–$300\,\mathrm{m\,s^{-1}}$). As a result, some of the gas and entrained particulates ejected from Chiron's surface would be deposited into high suborbital trajectories; much would also escape. Modellers have only begun to explore the range of interesting physical phenomena likely to result in this intermediate regime between freely escaping cometary comae and strongly bound planetary atmospheres[46]. Among these is the distinct possibility that Chiron's neutral colour and comparatively high albedo are the direct result of its activity, which probably causes a thin veneer of icy particulates to rain back onto the surface from suborbital trajectories.

An emerging view

We are witnessing a revolution in our understanding of the content and architecture of the outer Solar System. Whereas a decade ago, the outer Solar System seemed to consist only of the outer planets, the Oort-cloud comets and the then-rogue object Chiron, we now see revealed both the teeming Kuiper belt and its progeny, the comets and Centaur-sized objects orbiting among the outer planets. As a result, we have come to recognize that the outer Solar System is littered with icy objects intermediate in size between comets and the giant planets.

We have also learned that the early stages of planetary formation, with widespread growth from planetesimals to objects with diameters of several hundreds of kilometres, provide concrete evidence for an ancient era of planet-building in the Kuiper-belt region[47,48]. For some reason (probably involving the role of Neptune that excited orbital eccentricities that were not conducive to further growth), the era of accretion in the Kuiper belt was prematurely trunctated at a stage where intermediate-sized objects had formed[49]. The strong circumstantial evidence for the early formation of numerous objects in the 1,000-km class, of which Pluto and Triton are apparently the sole extant remnants within observational reach[50,51], further supports the case for initially strong but eventually arrested planetary accretion in the Kuiper-belt region[48,52]. As such, the Kuiper belt has become one of the most important regions in the Solar System for studies of planetary origins. The Centaurs and $\mathrm{QB_1}$s therefore represent a valuable, relic population of icy objects whose growth was arrested at a fascinating, intermediate stage between comets and small planets.

The Centaurs also serve as bright proxies for distant comets, as laboratories for studying surface processes occurring on comets, Triton and perhaps Pluto, and as nearby proxies for the $\mathrm{QB_1}$s and other intermediate-scale bodies that bridge the size gap between comets, Pluto and Triton. As such, they hold special promise for understanding the origin and interrelationships among the icy bodies of the outer Solar System. □

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ACKNOWLEDGEMENTS. We thank our colleagues D. Cruikshank, D. Jewitt, S. Larson, H. Levison, R. Marcialis, B. Marsden, W. McKinnon, W. Merlini, J. Parker and P. Weissman for comments, and A. Fitzsimmons for a helpful review.

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