Comets formed from icy grains in the outer region of the solar nebula. Their coagulation into macroscopic bodies was driven by differential motions induced by nebular gas drag. The hierarchical growth by collisions produced “rubble pile” structures with sizes up to ~100 km on timescales on the order of 1 m.y. Two-dimensional models of this growth, including orbital decay due to drag, show radial mixing that lessens the tendency seen in one-dimensional models for components of a single characteristic size. Radial migration causes redistribution of condensed matter in the outer nebula, and produces a sharp outer edge to the Kuiper belt.

1. INTRODUCTION

Cometary nuclei are planetesimals that formed in the outer reaches of the solar nebula. Presumably, they were produced by the same process that formed planetesimals in the region of the terrestrial planets and the asteroid belt, but incorporated volatiles (notably water ice) that were in solid form in the cold outer nebula. While comets may not be pristine, they are probably the least-altered objects surviving from the origin of the solar system. While much can be learned about their formation from their chemistry, they may also provide a unique record of the physical processes involved in their accretion. The material now present in any comet originally existed in the solar nebula as microscopic grains, probably a mixture of surviving interstellar grains and nebular condensates. Somehow, these submicrometer-sized particles were assembled into bodies of sizes at least tens to hundreds of kilometers. It is clear that comets are not uniform aggregates of grains, but have structure on larger scales. They display complex behavior that varies both temporally and spatially (outbursts and jetting), and implies inhomogeneities on scales of tens to hundreds of meters (Mumma et al., 1993; Weissman et al., 2004). On the other hand, imaging of the nuclei of Comets Halley and Borrelly at comparable resolution did not reveal obvious larger structural units; although both bodies were irregular in shape, they did not appear to be lumpy on kilometer scales. Comets are structurally weak, as demonstrated by shedding of fragments, occasional splitting, tidal disruption of Shoemaker-Levy 9 during its encounter with Jupiter (Asphaug and Benz, 1996), and the spontaneous disruption of Comet LINEAR (Weaver et al., 2001). The observed properties of nuclei are consistent with “rubble pile” structures with components ~100 m in size that are very weakly bonded, or perhaps held together only by gravity. These properties are the expected result of formation by accretion in the solar nebula.

2. PARTICLE MOTIONS IN THE SOLAR NEBULA

The motions of solid particles in the solar nebula are dominated by drag forces due to gas; this is true even in the outermost region, where the density is low, and solids are relatively more abundant due to condensation of volatiles at low temperatures. The radial pressure gradient partially supports the gas against the Sun’s gravity, causing it to rotate at slightly less than the local Kepler velocity (Whipple, 1972). The fractional deviation from Keplerian rotation is approximately the ratio of the thermal energy of the gas to its orbital kinetic energy. One can show that $\Delta V$, the difference between the gas velocity and Kepler velocity $V_k$, is proportional to the temperature $T$ and the square root of the heliocentric distance $R$ (Weidenschilling, 1977). A typical magnitude for $\Delta V$ is ~50 m s$^{-1}$ for plausible nebular models. As $T$ decreases with $R$, $\Delta V$ does not vary strongly; for a plausible temperature gradient of $T \propto R^{-1/2}$, $\Delta V$ is independent of $R$. Thus, the deviation from Keplerian motion is larger in proportion to the orbital velocity at larger heliocentric distances. Typically, $\Delta V/V_k$ is a few times $10^{-3}$ in the region of the terrestrial planets, but can exceed $10^{-2}$ beyond Neptune’s distance.

Solid particles are not supported by pressure forces. As a consequence, no particle can be at rest with respect to the gas, but always has some components of radial and transverse velocity. Their magnitudes depend on the particle size (more precisely, area/mass ratio) and drag law (Adachi et al., 1976; Weidenschilling, 1977). A small particle moves with the angular velocity of the gas (negligible transverse component), but drifts radially inward at a rate that increases with size. A large body pursues a Kepler orbit, experiencing a transverse “headwind” that causes its orbit to decay; the rate of decay decreases with size. The peak radial velocity, equal to $\Delta V$, occurs at the transition between these regimes. The size at which this peak velocity is reached...
does not vary strongly with heliocentric distance, and is typically on the order of 1 m (Fig. 1).

The size dependence of the drag-induced velocity means that any bodies that are not identical move relative to each other and any ensemble of bodies having a range of sizes will experience collisions. For small bodies (d ≤ 1 m), only radial drift is significant, and their relative velocities will be the difference between their radial velocities (far from the central plane of the nebula, their settling velocities may also be significant). Large bodies have high transverse velocity relative to the gas, but the same magnitude, ∆V, for all such bodies, so the relative velocity between any pair of large bodies is essentially the difference between their radial velocities. The relative velocity between a small and large body is essentially the latter’s transverse velocity.

At the low temperatures of a few tens of degrees or less in the outer nebula, thermal motions dominate for micrometer-sized grains, but are negligible for larger bodies. Mutual gravitational perturbations are significant for bodies larger than about 1 km. Between those limits, gas drag dominates. If turbulence is present, it can also induce relative motions. However, strong turbulence is unlikely to persist at large heliocentric distances. In the outer nebula, the surface density may be low enough to allow ionization by cosmic rays, driving magnetorotational instability (Sano et al., 2000), but the low gas density also favors dissipation by ambipolar diffusion. The intensity of turbulence generated by this mechanism is unclear. In any case, the largest eddies would have turnover timescales, imposed by the nebula’s rotation, comparable to the Kepler period. Bodies larger than about 1 m cannot respond to turbulent fluctuations on such timescales, while motions of smaller bodies are correlated, leading to relative velocities smaller than the turbulent velocity (Weidenschilling and Cuzzi, 1993). Unless the turbulence is very strong, the dominant source of relative velocities is differential motion due to gas drag.

3. COLLISIONAL COAGULATION

If collisions between particles are to result in growth, there must be some mechanism that allows them to stick together. Perfect sticking is not required (and is unlikely under most conditions for real materials), but at least some collisions must yield net growth for bodies of all sizes. This is not a problem for the initial stage of coagulation, involving micrometer-sized grains. For small particles, the relative velocities (thermal or drift) are low enough to allow sticking by van der Waals surface forces. Theoretical models (Dominik and Tielens, 1997) and laboratory experiments (Blum and Wurm, 2000) confirm that coagulation under such conditions produces fluffy, fractal-like aggregates with densities that decrease with increasing size.

Under zero-gravity conditions in the solar nebula, this process may produce gossamer structures of macroscopic (approximately centimeter-sized) dimensions. However, this type of growth cannot continue indefinitely; as the aggregates become larger their drift velocities increase, and collisions become energetic enough to allow some compaction by rearranging bonds between grains. As the aggregates become denser, their drift speeds increase further.

Bodies of comparable size will collide rarely, and only at low velocities. As shown in the simulations of Weidenschilling (1997), most collisions occur between bodies of quite different sizes. This circumstance favors growth, because the smaller “projectile” does not deliver enough kinetic energy to disrupt the larger “target,” unless the latter has very low impact strength. However, although a low probability of disruption is necessary for growth, it is not sufficient. The increase in drift velocities with size leads to a problem: As can be seen from Figs. 1 and 2, meter-sized bodies will have velocities relative to centimeter-sized particles as large as ∆V, i.e., tens of meters per second [if the particles settle into a dense layer in the central plane of the nebula, collective motion of particles and gas reduces the effective value of ∆V (cf. Nakagawa et al., 1986)]. If such impacts do not result in net mass gain, then growth might stall before meter-sized bodies could form. If collisions (or some other process) can produce bodies larger than this critical threshold, then further growth to kilometer size, at which gravity can contribute to sticking, is assured. The centimeter-to-kilometer range is the critical stage of collisional accretion.

It is not clear whether impacts at such speeds would result in net gain or loss of mass. This question cannot be answered definitively, as we do not know the mechanical properties and impact strength of cometary material. Sirono and Greenberg (2000) estimated the tensile and compressive strengths of porous aggregates of icy grains, and concluded that compaction would dissipate a large fraction of energy during collisions, and would produce merged bodies.
Gravitational stirring dominates at sizes larger than about 1 km. Bodies of nearly equal size have low relative velocities due to drag. The “valley” in the central region shows that bodies of nearly equal size have low relative velocities due to drag. Gravitational stirring dominates at sizes larger than about 1 km.

Weidenschilling resulted in net growth, but the range of allowable parameters remains to be determined. Whether a given body would grow or erode would depend not only on the impact strength of the bodies, but on the size distribution of the ensemble, which would itself be a function of their strength. The impact strength assumed by Weidenschilling resulted in net growth, but the range of allowable parameters remains to be determined.

Wurm et al. (2001) suggested that accretion of meter-sized bodies would be aided by aerodynamic forces acting on small grains. Grains would impact on the leading side, brought by the “headwind” due to the body’s motion through the gas. Grains or small aggregates striking at velocities $\Delta V$ would rebound (or displace grains from the target) at speeds lower by perhaps an order of magnitude. The gas flow would reverse their motion and return them to the body’s surface, reimpacting at speeds low enough for sticking by surface forces between the grains. This mechanism could aid accretion at $R \sim 1$ AU, where plausible values for the gas density yield trajectories of only a few centimeters for bouncing grains. However, it would not be effective in the outer nebula, where impact speeds are comparable, but the gas density is lower by orders of magnitude; the “turnaround distance” for grains would be correspondingly larger, and their probability of reimpacting on a meter-sized target would be minuscule. Thus, particle coagulation in the region of comet formation appears to require effective sticking in collisions.

4. GRAVITATIONAL INSTABILITY

With the uncertainties attendant upon the messy and poorly constrained mechanism of collisional sticking, the possibility of forming planetesimals by gravitational instability remains enticing. In the “classical” instability scenario (Safronov, 1969; Goldreich and Ward, 1973), small particles settle to form a layer in the midplane of the solar nebula. When this layer reaches a critical density it becomes unstable to density perturbations, which produce condensations that collapse under their own gravity into solid bodies. However, bodies formed by this mechanism in the outer nebula would be much larger than typical comets, and would not have any structure on macroscopic scales. In any case, gravitational instability does not eliminate the need for particle coagulation. As pointed out by Weidenschilling (1980), before the particle layer can reach the critical density, it drags the entrained gas at a velocity higher than that of the pressure-supported nebula. The resulting shear flow is unstable, and becomes turbulent, preventing further settling. A layer of small (centimeter-sized or smaller) particles cannot attain the critical density.

If the bodies can accrete to sizes large enough to decouple from the shear-induced turbulence ($\geq 1$ m), then they can settle enough for the layer to attain the critical density. This condition is necessary for instability, but is not sufficient. The velocity dispersion must also be small enough to allow density perturbations to grow. When the particle velocities are controlled by gas drag, they are not isotropic. As bodies of this size are too large to be stirred by turbulence, but too small for gravitational perturbations to be effective, their vertical velocity dispersion is very small; however, they may have a significant dispersion in radial velocity. If all particles were identical, then they would have the same radial velocity due to drag, but any real ensemble of particles produced by coagulation should have a range of...
sizes and corresponding velocities. The resulting dispersion inhibits gravitational instability (Weidenschilling, 1995). Ward (2000) showed that if the particle layer was bimodal with two different velocities, density perturbations in the populations would be decoupled. For bodies larger than about a meter, the radial velocity decreases with size (Fig. 1); the dispersion will diminish as the bodies grow, and the mean radial velocity decreases. The conditions for gravitational instability (density and velocity dispersion) can be attained, but only after collisional coagulation has produced bodies with mean size $\geq 10$ m. As this is larger than the size of maximum radial velocity, there is no obstacle to further growth by collisions; gravitational instability becomes unnecessary by the time it becomes feasible. The instability may still occur at that point, but its outcome will be different from the classical model. Bodies tens of meters in size are poorly damped by either drag or collisions, so the layer maintains a significant velocity dispersion, which allows only density perturbations of long wavelength to grow (Weidenschilling, 1995). The layer may break up into self-gravitating clusters of particles, but these condensations are too large (i.e., have too much angular momentum due to the rotation of the nebula) to collapse directly into solid objects. Such condensations would probably be transient features, which would be torn apart by differential rotation. It is suggestive that for plausible values of the nebula’s surface density, the characteristic wavelength of instability corresponds to condensation masses equal to those of compact bodies with diameters $\sim 100$ km, about the size of typical Kuiper belt objects. However, this may be coincidental; it will be shown below that bodies of this size could grow by collisions within the lifetime of the solar nebula.

5. MODELING THE GROWTH OF COMETESIMALS

5.1. One-Dimensional Models

Weidenschilling (1997) applied a numerical model of particle coagulation and settling in the solar nebula to cometary formation; details of the model are described therein, and will be summarized only briefly here. That model is one-dimensional in the vertical direction, treating the particle population in a series of levels at a single heliocentric distance. In each level, the particle size distribution is modeled by the mass in logarithmic diameter bins from $10^{-4}$ cm to $100$ km. The evolution of the size distribution is computed in each of a series of levels, with collision rates due to thermal motion, differential settling, and radial and transverse motions due to gas drag. Particle densities are assumed to vary with size, to simulate fractal structure of small aggregates and compaction of macroscopic bodies. Collisional outcomes depend on particle sizes and impact velocities, consistent with an assumed impact strength. At each timestep, the number of collisions between particles of various sizes and the consequent changes in the size distribution are computed within each level. Bodies are transferred between levels, downward toward the midplane at rates proportional to their settling velocities, and by diffusion upward and downward along concentration gradients where turbulence is present. Formation of a dense midplane layer results in shear-induced turbulence, and the structure of the layer is determined by a balance between settling and turbulent diffusion, with gravitational stirring included for bodies large enough to decouple from the gas. The model parameters were chosen for a low-mass solar nebula at 30 AU, with surface density of solids and gas of 0.4 and 29 g cm$^{-2}$, respectively. From the assumed initial state, with all solids present as micrometer-sized grains with a uniform solids/gas mass ratio, the ensemble of particles evolved on a timescale of few times $10^5$ yr, or a few thousand orbital periods. This evolution could be divided into rather distinct stages. During the first few times $10^4$ yr, thermal coagulation produced low-density, fractal-like aggregates, with sizes $\sim 10^{-2}$ cm, at all levels. As the aggregates in the upper levels settled toward the midplane, larger ones grew by sweeping up smaller ones; this led to rapid growth and “rainout” of approximately centimeter-sized aggregates, which formed a layer with density greater than that of the gas. The shear between this layer and the surrounding pressure-supported gas produced turbulence, which prevented settling of the small aggregates within the layer. However, collisional growth continued, and a thinner sublayer of larger bodies developed. This sublayer attained a density much higher than the classical threshold for gravitational instability (solids/gas ratio $\sim 10^3$), but the velocity dispersion was large enough to prevent instability until the mean size was tens of meters. With the assumption that instabilities in a poorly damped system would not collapse, the collisional evolution was continued until bodies tens of kilometers in size accreted, after a model time of $2.5 \times 10^7$ yr. By that point, gravitational stirring became effective and the velocity dispersion increased, with a significant vertical component. This caused the particle layer to become thicker, and its density decreased; presumably still larger bodies would continue to grow by gravitational accretion.

The size distribution of the accreting bodies (Fig. 3) developed a distinct peak in the size range of tens to hundreds of meters. The cause of this peak was the dependence of radial velocity on size (Fig. 1) and the fact that collisions were due primarily to differences in radial velocity. The bodies with the largest velocities were quickly depleted by impacting larger bodies, opening a “valley” in the size distribution at meter sizes. Bodies in the size range from tens of meters to about a kilometer still had velocities larger than their escape velocities, so there was no gravitational enhancement of their collision rates. Because their radial velocities decreased with size, the larger bodies grew more slowly, allowing smaller ones to catch up, and keeping the peak narrow. Eventually, the largest bodies began to have significant gravitational enhancement of their collision rates, and the peak became broader. During this stage of growth the mean collision velocities decreased with increasing size, reaching a minimum value at the transition from drag-con-
accretion disk. The properties of the particle layer are averaged through its thickness, so their model is effectively one-dimensional in the radial direction, and complementary to that of Weidenschilling (1997). They do not compute a size distribution, but only a mean particle size as a function of time at a given radius. This approach neglects differential drift motions among bodies of different sizes, and allows only collisions due to turbulence, so their model breaks down for disks with low turbulence. Despite these limitations, they demonstrated that orbital decay due to gas drag during particle growth could substantially alter the radial distribution of solids relative to the gas during the \(10^8-10^7\)-yr lifetime of the solar nebula.

5.2. Two-Dimensional Models

In order to overcome the limitations of one-dimensional approaches, Weidenschilling (in preparation, 2003) has developed a fully two-dimensional model of planetesimal formation. Its operation is similar to the one-dimensional model described above, but the vertical structure of the particle layer and its size distribution are computed in a series of zones over a range of heliocentric distance. Bodies are transferred between zones at rates corresponding to their radial velocities. The model also includes collective radial motion of the particle layer due to turbulent shear stress acting in the boundary layer (Goldreich and Ward, 1973) and radial diffusion by turbulence, but for macroscopic bodies these are generally unimportant compared to orbital decay due to the drag of the “headwind.” Application of this two-dimensional model reveals some significant differences from the one-dimensional case.

Figure 4 shows the size distribution in the range resulting from a two-dimensional simulation from 30 to 90 AU, at model time of \(5 \times 10^5\) yr. The innermost zone at this time corresponds to the final stage reached by the one-dimensional simulation in Fig. 3. While the size distributions are similar, in the two-dimensional case the “valley” around \(~1\) m is much shallower, and the peak at \(~100\) m is broader and more subdued. The apparent reason for this difference is the dependence of the growth time on heliocentric distance. It can be seen that large bodies form more slowly at larger values of \(R\), due to the lower surface density. Recall that in the one-dimensional model, once bodies with sizes of tens of meters formed, meter-sized bodies were depleted by colliding with the larger ones due to their high radial velocities; this is the cause of the gap in the size distribution.

In the two-dimensional model, meter-sized bodies that form at larger distances migrate inward, continually replenishing the population at that size and filling the gap. The addition of these bodies also keeps the median size smaller. The model for gravitational stirring scales the out-of-plane random velocity to the escape velocity of the median-sized body in the midplane; the smaller median size in the two-dimensional case results in a more flattened particle layer than in the one-dimensional model.
The gaseous component of the solar nebula is assumed to remain constant, but radial migration results in significant redistribution of the solid matter (Fig. 5). The inner zones are initially depleted by orbital decay of the first-formed meter-sized bodies. After ~2 x 10^5 yr, the innermost zone contains bodies larger than 100 km, while no bodies larger than 1 km have formed beyond ~40 AU. In the inner zones, the “valley” at ~1–10 m is less distinct due to inward migration of bodies of this size that formed at larger distances.

Fig. 4. Results of a two-dimensional simulation performed in 20 zones from 30 to 90 AU, with an R^-1 variation in surface density. The assumed surface density in the innermost zone is about half that in the one-dimensional simulation, approximately doubling the evolution timescale. After 5 x 10^5 yr, the innermost zone contains bodies larger than 100 km, while no bodies larger than 1 km have formed beyond ~40 AU. In the inner zones, the “valley” at ~1–10 m is less distinct due to inward migration of bodies of this size that formed at larger distances.

The gaseous component of the solar nebula is assumed to remain constant, but radial migration results in significant redistribution of the solid matter (Fig. 5). The inner zones are initially depleted by orbital decay of the first-formed meter-sized bodies. After ~2 x 10^5 yr the surface density in the inner region rises again due to the formation of kilometer-sized or larger bodies that resist orbital decay. These grow by catching the smaller bodies migrating inward from larger distances. The gradient of the surface density of solids becomes much steeper, and develops a rather sharp “edge” in the range 40–50 AU, at about half the radius of the nebula. The reason for this behavior is due to the fact that the peak radial velocity induced by gas drag, and the size at which this peak occurs, do not vary significantly with heliocentric distance. Most of the migration occurs during growth from about 0.1 to 10 m diameter. This growth takes longer at the lower densities found at greater distances, so a body that begins to accrete at a larger distance moves inward by a greater amount. Empirically, the growth time varies approximately as R^{3/2}, so the fractional change of distance increases with R, causing the surface density gradient to steepen. Because the particle layer is highly flattened, small bodies migrating inward are efficiently captured by larger bodies that have stopped their orbital decay. Mass tends to pile up at the outermost distance where kilometer-sized bodies grow, which further steepens the gradient of surface density. A similar “pileup” occurs in the radial one-dimensional model of Stepinski and Valageas (1997), so this effect is not sensitive to details of the model. This transition is also accompanied by a steep decline in the mean size of planetesimals. It can be seen in Fig. 4 that no bodies larger than ~1 km have accreted beyond 50 AU. Continuation of the simulation to later times would not produce any large bodies at this distance, as the surface density of solid material is too low for further growth.

This simulation assumed a laminar nebula, i.e., the only turbulence is that produced locally near the central plane by shear between the particle layer and the surrounding gas. If there is an additional source of turbulence, e.g., magneto-rotational instability, then its main effect would be to increase the thickness of the particle layer. The lower density would cause accretion to be slower, allowing more migration during growth. Thus, the initial extent of the nebula would have to be even greater to yield an edge at this distance.

6. FORMATION TIMESCALES

Motions induced by drag lead to relatively rapid formation of sizable bodies, compared with purely gravitational accretion in the absence of gas. Kenyon (2002) modeled planetesimal accretion in the Kuiper belt. His simulations included gravitational stirring and fragmentation; most did not include gas drag, or considered only damping of eccentricities and inclinations without orbital decay. The assumed surface density of the planetesimal swarm was comparable to the cases discussed above, but the initial size distribution was quite different: a power law with most of the mass in bodies of radius ~100 m. Kenyon’s model required ~10 m.y. to accrete 100-km bodies while drag-driven accretion produces such in <1 m.y. in regions that are not depleted by radial migration. Part of this difference can be ascribed to the starting conditions. Gravitational accretion would be faster for smaller initial sizes, which produce less
stirring and lower velocities, with earlier transition to runaway growth. However, gravitational stirring is isotropic, producing out-of-plane velocities that thicken the layer and reduce the collision rate as the mean size increases. Drag-induced motions are more favorable to accretion because they are parallel to the nebular midplane. Turbulent stirring is ineffective for meter-sized and larger bodies, so the particle layer can attain high density, while the radial and transverse velocities are high enough to allow frequent collisions. In contrast, the inner zones in the simulation experience a net increase in surface density of solids over the initial value, allowing more rapid growth there.

The rapid formation of 100-km-sized bodies may have consequences for their thermal evolution. If short-lived radionuclides such as $^{26}$Al were present in the outer part of the solar nebula, accretion times $\sim$1 m.y. imply that Kuiper belt objects of this size probably experienced enough heating to undergo melting and differentiation in their interiors (Priplak et al., 2004). In that case, they might be rather compact bodies with low porosity and moderately high density and strength. However, modeling of the collisional evolution of the Kuiper belt since its formation (Farinella et al., 2000) shows that fragmentation of such large bodies is rare, and implies that most objects with sizes of a few kilometer are derived from smaller parent bodies a few tens of kilometers in size. The typical cometary nucleus formed as a rubble pile, and has remained as such throughout the history of the solar system.

7. CONCLUSIONS

Most of the results of the one-dimensional particle coagulation/settling model remain valid: Cometary nuclei formed by collisional coagulation driven by differential motions due to gas drag in the solar nebula, with “rubble pile” structures resulting from hierarchical accretion. The timescale for growth of bodies as large as typical Kuiper belt objects ($\sim$100 m) is $\sim$1 m.y., well within the estimated lifetime of the solar nebula.

The one-dimensional results also suggested that comets should be composed of components with a characteristic size $\sim$100 m. The two-dimensional model alters that picture: Radial migration mixes bodies of different sizes that formed at different heliocentric distances; there should be less of a deficit of meter-sized components, and a size distribution of subunits within a given nucleus with more resemblance to a power law. The variety of component sizes would result in a smaller fraction of void space within a nucleus than that produced by a single size. There may still be some preference for 100-m subunits, as this size is subjected to the lowest impact velocity during accretion. The smaller (meter-sized) components are accreted at higher impact velocities than larger ones, and may be more compacted at such scales.

There is compelling observational evidence that the Kuiper belt has an abrupt outer edge in the range $\sim$45–50 AU (Trujillo and Brown, 2001). This feature cannot be accounted for by gravitational accretion models that do not include radial migration, as growth timescales and sizes vary too gradually with heliocentric distance to produce such a sharp transition (Kenyon and Luu, 1998, 1999). While there are other possible explanations for truncation of the Kuiper belt, such as a stellar encounter during formation of the solar system (Kobayashi and Ida, 2001), drag-induced migration during planetesimal formation provides a plausible — perhaps unavoidable — mechanism for producing a sharp edge. The increasing difficulty of accretion with distance also puts in doubt the existence of a massive primordial belt of material in the region $\sim$50–100 AU, as suggested by Stern (1996). The solar nebula probably had to extend to such a distance simply to account for the present extent of the Kuiper belt, but most of the condensed matter originally present there was removed by gas drag before it could form bodies of significant size. Bodies in the region of the current Kuiper belt (40–50 AU) probably contain a substantial fraction of material that originally condensed (or survived from the presolar cloud) at much larger distances, possibly beyond 100 AU. In the denser inner region of the nebula, accretion times were shorter and the migration distance was less. Comets that formed in the region of the giant planets probably comprise material derived from a smaller range of heliocentric distances.

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