FORMATION OF OUTER SOLAR SYSTEM BODIES : COMETS AND PLANETESIMALS

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Abstract. Observations of massive, extended discs around both pre-main-sequence and main-sequence stellar systems indicate that protoplanetary discs larger than the observed planetary system are a common phenomenon, while the existence of large comets suggests that the total cometary mass is much greater than previous estimates. Both observations suggest that theories of the origin of the solar system are best approached from the perspective provided by theories of star formation, in particular that the protoplanetary disc may have extended up to $\sim 10^3$ AU. A model with a surface density distribution similar to a minimum-mass solar nebula, but extending further in radius, is derived by considering the gravitational collapse of a uniform, slowly rotating molecular cloud. The boundary of the planetary system is determined not by lack of mass, as in previous 'mass-limited' models (*i.e.* those with a sharp decrease in surface density Σ beyond the radius of the observed planetary system), but instead by the increasing collision time between the comets or planetesimals initially formed by gravitational instability beyond the planetary zone. Bodies formed beyond ~ 50 AU have sizes on the order of 10^2 km and represent a collisionally unevolved population; they are composed of relatively small, unaltered clumps of interstellar dust and ices with individual sizes estimated to range up to ~ 10 m. By contrast, bodies formed closer in, for example in the Uranus-Neptune zone, consist of larger agglomerations of dust and ices with individual sizes ranging up to ~ 1 km. Planetesimals formed by gravitational instability at smaller heliocentric distances r are typically much smaller than those formed further out, the masses m_p being proportional to $\Sigma^3 r^6$, but subsequent collisional aggregation in the planetary region is expected to produce bodies with sizes ranging up to 10^2 km or more. In both cases the first-formed solid objects may be identified with observed cometary nuclei; some accumulate to produce the outer planets, but the majority are ejected, either to interstellar space or into the Oort cloud. Observed comets represent a dynamically well-mixed group from various sources; they are expected to comprise a heterogeneous mix of both pristine and relatively altered material and to have a broad mass distribution ranging up to the size of the largest planetesimals.

1. Introduction

Comets and planetesimals play a key role in discussions of the origin of the solar system. They have sizes typically in the range 1–100 km, intermediate between interstellar grains and planets, and provide crucial clues to the evolution of interstellar dust and the processes leading to the formation of the sun and planetary system. Theories of the origin of the latter span a very wide range, manifested at one extreme by the standard planetesimal hypothesis, in which a ready-formed sun is assumed to be surrounded by a dense gas-and-dust disc with surface density proportional to $r^{-3/2}$ or r^{-2} and normalized to reproduce the observed planetary

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masses corrected to solar abundances. Such a model is here defined to be 'mass-limited' if it has an outer radius comparable to the size of the observed planetary system. Depending on the surface density within the planetary system such a model may or may not also be a 'minimum-mass' nebula. A mass-limited minimum-mass model of the protoplanetary disc typically has a total nebular mass $\lesssim 0.05\,M_{\odot}$.

At the other extreme are theories which approach the problem of solar system formation from the perspective provided by star formation, and which begin either with a collapsing protostellar or molecular cloud, or with accretion of gas and dust on to a pre-main-sequence star from an extended protoplanetary disc. These theories discuss both star and planet formation and usually consider a much greater mass of circumstellar material, ejecting most of it to interstellar space. However, although the initial conditions for such a scenario are generally more easily defined, for example from observations of molecular clouds or star-forming regions, it is unclear precisely which initial conditions are most likely to lead to the formation of a single solar-mass star surrounded by the observed nine planets. The existence of comets introduces further complications (*e.g.* Bailey *et al.* 1990), the major uncertainty of principle being the theoretical possibility that comets may only recently have been captured into the solar system (within the past $\sim 10^6$–10^8 yr), having originally been formed in molecular clouds or star-forming regions (*e.g.* Napier 1990) and captured as a result of gravitational or other perturbations.

These different ideas for the origin of the solar system and for the significance or otherwise of comets in the overall cosmogonical picture each have various points in their favour. The main problem, in view of the wide range of possibilities (*e.g.* Williams 1974; Woolfson 1993), is to identify the particular grains of truth contained in each theory and to strike an appropriate balance between them. Comets play a key role in these discussions, with the most detailed theoretical studies being devoted to the standard planetesimal picture. This hypothesis has been particularly successful in unifying concepts relating to planet, planetesimal and comet formation and formation of the Oort cloud, but it faces potentially severe difficulties in resolving questions such as the timescale for formation of the planets (particularly Uranus and Neptune) and the total mass of comets in the Oort cloud. These problems suggest that the standard model should be revised to include aspects of the star-formation approach, although it is possible that the outcome of such a course might then be to lose some of the advantages of the former approach by decoupling theories of comet formation from those of the origin of planets (*e.g.* Hills 1982) and leaving open the question whether recently discovered bodies orbiting beyond Neptune, the so-called Kuiper-belt candidates, are best thought of as giant comets, primordial planetesimals, or merely as stray asteroids ejected from the inner solar throughout its 4 billion year lifetime.

This review primarily focusses on the standard planetesimal theory for the formation of comets in the protoplanetary disc, but argues for an approach placing it firmly in the context of star-formation theories for the origin of the solar system and the interstellar-dust model for the origin of comets. So far as the standard model is concerned, the principal difference is that the revised model accommodates a much larger, more massive protoplanetary disc, with an outer radius R_d on the order of 10^3 AU and a total mass of solids in the range 10^2–$10^3\,M_{\oplus}$. Such a disc is not mass-limited, in the sense of having a sharp cut-off in surface density beyond the observed planetary system, but the surface density within the planetary region is nevertheless close (*i.e.* within a factor of a few) to that of previously considered minimum-mass nebulae.

Evidence for the existence of extended discs is provided by observations of pre-main-sequence stars (*e.g.* Sargent 1989; Strom *et al.* 1989a,b; 1993; Weintraub *et al.* 1989; Beckwith *et al.* 1990; Beckwith and Sargent 1993; Montmerle *et al.* 1993; *cf.* Pringle 1989) and main-sequence stars such as Beta Pictoris and Vega (*e.g.* Aumann *et al.* 1984; Aumann 1985; Telesco *et al.* 1988; Artymowicz *et al.* 1989; Piirola *et al.* 1992; Bachman and Paresce 1993; Sicardy 1994). These data strongly suggest that the boundary of the solar system is not determined solely by a rapid decrease in surface density of the primordial disc near the edge of the observed planetary system; rather, the reason there are no major planets beyond Neptune is principally a result of accretion dynamics. In particular, the observed boundary may be understood as a consequence of the rapid increase in the collision time of the first solid bodies to be formed by gravitational instability on the outskirts of the protoplanetary disc : the edge of the planetary system occurs where the planetesimal collision timescale first exceeds $\sim 10^8$–10^9 yr. In addition to providing a theoretically attractive explanation for why the edge of the *planetary* system lies where it is, such a model has the significant advantage of accommodating a large initial mass of planetesimals at great heliocentric distances. Comets formed throughout the protoplanetary disc may be ejected by gravitational or other perturbations to produce both the Oort cloud and the massive inner core necessary to replenish the dynamically unstable outer layers of the system. Here we briefly review the components of such a theory of comet formation : the origin of a massive, extended disc; interstellar dust evolution and grain growth; and the argument based on cometary masses that the Oort cloud cannot have originated from planetesimals produced in a conventional mass-limited minimum-mass model of the protoplanetary disc.

2. Massive disc

There have been many recent reviews of the planetesimal theory, including planet formation in both the inner and outer solar system (up to the distance of Neptune) and comet formation in the outer planetary region extending roughly from Jupiter through Neptune (*e.g.* Safronov 1969; Öpik 1973; Horedt 1979; Wetherill 1980, 1989, 1990; Safronov and Ruzmaikina 1985; Greenberg 1989; Weidenschilling *et al.* 1989; Bailey *et al.* 1990; Weidenschilling and Cuzzi 1993; Lissauer and Stewart 1993; Lissauer 1993). According to this picture, the observed planetary masses when corrected to solar abundances and distributed over rings of appropriate width and heliocentric distance r imply an initial disc surface density $\Sigma(r) \gtrsim r^{-\alpha}$, where estimates of α lie in the range 1.5–2 (*e.g.* Weidenschilling 1977; Nakano 1987; Tremaine 1990) and the outer radius is on the order of 50 AU.

However, observations of pre-main-sequence stars demonstrate the existence of more massive protoplanetary discs than those usually envisaged in the planetesimal hypothesis, showing that such structures are a common feature of young stellar systems. Here we argue that a disc with a similar density profile to that of the standard model, but extending much further in radius, could naturally arise as a consequence of the gravitational collapse of a protostellar cloud. This supports an approach from the direction of star formation whilst retaining the principal advantages of the planetesimal picture (*cf.* Cameron 1962, 1978, 1985; Cameron and Pine 1973; Biermann and Michel 1978; Lin and Papaloizou 1985).

Consider a cold, slowly rotating molecular cloud with outer radius R_c in the range 0.1–1 pc, temperature $T \simeq 10\,\mathrm{K}$ and total mass M_c in the range 1–$2\,M_\odot$. Following Mestel (1963) and Mestel and Ray (1985), disc formation may be assumed to occur in two phases : formation of a 'projected disc' with radius R_0 similar to that R_c of the initial molecular cloud through gravitational collapse parallel to the rotation axis, followed by gradual contraction of the projected disc towards centrifugal equilibrium by a process that conserves both the mass and angular momentum of separate fluid elements within the projected disc. The original cloud is assumed to be threaded by a weak interstellar magnetic field, and to be uniformly rotating with a net rotational velocity $v_{\mathrm{rot}}(\varpi) = \beta(\varpi/R_c)v_{\mathrm{circ}}(R_c)$, where $v_{\mathrm{circ}}(r)$ denotes the circular velocity at radius r from the cloud centre and ϖ is the axial distance in the equatorial plane.

This leads to formation of a quasi-static disc, supported in the radial direction by magnetic stresses and in the direction perpendicular to the plane by thermal motions and possibly turbulence driven by residual infall of gas. Decay of the magnetic field by ambipolar diffusion (Mestel and Spitzer 1956; McKee *et al.* 1993) or magnetic reconnection results in slow contraction of the disc, culminating in a rotationally supported Keplerian configuration with radius $R_d \ll R_0$. Ignoring possible non-homologous collapse of the cloud core, expected to lead to the formation of a central star surrounded by a relatively small central accretion disc, and assuming that the original molecular cloud is uniform or has only a weak degree of central concentration (*e.g.* $\rho_c \simeq$ constant or $\rho_c \propto r^{-1}$), results in a Keplerian disc with surface density approximately proportional to $r^{-\alpha}$, with $\alpha \simeq 3/2$.

For example, if the cloud is uniform the projected disc has a surface density $\Sigma_{\mathrm{proj}}(\varpi) = 3M_c(1-x^2)^{1/2}/4\pi R_c^2$, where $x = \varpi/R_c$, and conservation of mass during evolution from an initial radius ϖ to a final radius r leads to a surface density $\Sigma(r)$ given by $\Sigma(r) = (\varpi/r)(d\varpi/dr)\Sigma_{\mathrm{proj}}(\varpi)$ The relation between r and ϖ evidently depends on the distribution of angular momentum in the projected disc, which in turn depends on that in the cloud. If the original cloud is uniformly rotating, for example $v_{\mathrm{rot}}(\varpi) = \beta\varpi(GM_c/R_c^3)^{1/2}$, then detailed conservation of angular momentum implies $rv_{\mathrm{circ}}(r) = \varpi v_{\mathrm{rot}}(\varpi)$, and hence $(\varpi/r)(d\varpi/dr) = R_c^{3/2}r^{-3/2}/4\beta$. The final Keplerian disc thus has $\Sigma(r)$ close to the standard form, *i.e.*

$$\Sigma(r) = \frac{1}{4\beta}R_c^{3/2}r^{-3/2}\Sigma_{\mathrm{proj}}(\varpi(r)) \tag{1}$$

where Σ_{proj} is a weak function of radius, $r = \beta^2\varpi^4/R_c^3$ and $R_d = \beta^2 R_c$.

This argument suggests that extended circumstellar discs will have surface densities that are generally close to the standard form $\Sigma(r) \propto r^{-3/2}$, although their radial extent will be primarily determined by the size and degree of rotation of the primordial molecular cloud. For values of β in the approximate range 0.1–0.5, the

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outer radius $R_d = \beta^2 R_c$ is much larger than the ~ 50 AU size of the observed planetary system. Normalizing the surface density to 500–1000 kg m^{-2} at $r_0 = 10$ AU, inferred from the observed planetary mass distribution, thus indicates a total disc mass between 10 AU and 1000 AU in the respective ranges 0.064–0.12 $M_\odot$ or 0.016–0.032 $M_\odot$, for values of $\alpha = 3/2$ or 2. If the effective surface density of solids (*i.e.* rock + ice) is close to 2% of the total mass density, *i.e.* $\Sigma_s(r) \simeq 0.02\Sigma$, the total mass of solids ~ 100–$800\,M_\oplus$, depending on the assumed surface density normalization and power-law index α. An extended protoplanetary disc with radial extent $R_d \simeq 10^3$ AU could easily contain several $100\,M_\oplus$ of dust and ice, not only representing a reservoir from which to make comets but also the dominant sink of heavy elements (apart from the sun) in the solar system.

3. Interstellar dust

3. 1. ORIGIN AND PRESTELLAR EVOLUTION

Following the initial condensation of solid material in gaseous outflows associated with late stages of stellar evolution (red giants, novae, supernovae; *e.g.* Bode 1988; Gehrz 1989; Tielens 1991), newly formed grains spend typically 10^7–10^9 yr in the interstellar medium before finally being incorporated into bodies the size of planetesimals, comets or asteroids. During this phase of prestellar evolution an individual interstellar dust grain will probably undergo many transitions between different components of the interstellar medium, for example from the diffuse high-temperature phase to the warm neutral phase; into a cool H I cloud or molecular cloud, and back again. During these excursions the grain may grow by accretion of volatiles or by inelastic grain-grain collisions, and fragments may be lost as a result of disruptive collisions in shocks, through sputtering, or simply by thermal evaporation in a locally more intense radiation field (Seab and Shull 1986; Seab 1988; Jenkins 1989; Tielens 1989; McKee 1989).

The resulting interstellar grain aggregates, modified by thermal and radiative processing, have a complex structure and abundances and chemistry which reflect the history of each grain (*e.g.* Greenberg 1988, 1989; Greenberg and Hage 1990; Clayton and Liffman 1988; Clayton *et al.* 1989; Liffman 1990). A few aggregates are bound to be larger than the average, and in general a percentage of interstellar particles will be much larger than the $\sim 0.25\,\mu$m upper limit imposed by the canonical Mathis *et al.* (1977) law based on observations of interstellar extinction (*cf.* Bailey 1987a,b, 1988, 1991a). Several lines of argument demonstrate the existence of exceptionally large grains (~ 1–$100\,\mu$m) in or around dense interstellar clouds (*e.g.* Lefèvre 1974; Jura 1980; Elmegreen 1981; Mathis and Wallenhorst 1981; Elsässer *et al.* 1982; Bhatt 1986), while it is also important to emphasize that observations of interstellar dust near Jupiter (Grün *et al.* 1993) and of apparently hyperbolic meteors on Earth (Baggaley *et al.* 1993; Taylor *et al.* 1994; *cf.* Brophy 1991; Fogg 1990; Napier 1990) also support the notion that interstellar dust includes a significant proportion of relatively large grains. Although hyperbolic meteoroids could be produced locally by sputtering or by erosion from the surfaces of much larger interstellar particles (*e.g.* comets), it seems reasonable to assume that whatever their immediate provenance such particles were originally produced by accretion as a result of grain-grain collisions in dense regions of the interstellar medium. They probably have a fluffy 'fractal' structure, in accordance with expectations based on models of random aggregation (*e.g.* Meakin *et al.* 1985; Donn and Hughes 1986; Meakin and Donn 1988; Donn 1990; Jewitt and Meech 1988; Brooks 1990, 1992). By the time a given parcel of interstellar gas has evolved to produce a gravitationally unstable cloud prior to forming a new solar system, it seems certain that it will include a significant number of large grains.

3. 2. PROTOSTELLAR COLLAPSE

A marginally unstable cloud of mass $M_c \simeq 1\,M_\odot$ destined to form a star has a radius (*cf.* Larson and Starrfield 1971) on the order of $R_c \simeq 0.41GM_c/c_s^2 \simeq 10^4$ AU, where $c_s = (kT/\bar{m})^{1/2} \simeq 186\,\mathrm{m\ s^{-1}}$ is the isothermal sound speed in the cloud and the numerical value assumes $T = 10\,\mathrm{K}$ and a mean particle mass $\bar{m} = 4.0 \times 10^{-27}$ kg, appropriate for a molecular cloud of solar composition. Assuming the cloud is approximately uniform with a mean mass-density of solids $\rho_s = \zeta\rho_c \simeq 0.02\rho_c$, grains of mean radius $a \simeq 0.1\,\mu\mathrm{m}$ and bulk density ρ_g, the grain-grain collision time $t_{\mathrm{coll}} = 1/(n_g 4\pi a^2 v_{\mathrm{rel}})$ is on the order of

$$t_{\mathrm{coll}} = 4.4 \times 10^5 \left(\frac{\rho_g}{1\mathrm{g\ cm^{-3}}}\right)\left(\frac{a}{0.1\,\mu\mathrm{m}}\right)\left(\frac{1\,\mathrm{m\ s^{-1}}}{v_{\mathrm{rel}}}\right)\left(\frac{10\,\mathrm{K}}{T}\right)^3\left(\frac{M_c}{1\,M_\odot}\right)^2 \quad \mathrm{yr} \quad (2)$$

comparable to the collapse timescale $\sim(G\rho_c)^{-1/2}$ for the cloud. The larger particles in the system will thus grow during collapse of the cloud, and a substantial proportion of the smallest grains will accrete into systematically larger particles (Burke and Silk 1976; Arnold 1977; Kessel'man 1978, 1979). Insofar as the chemistry of a collapsing protostellar cloud differs in detail from that in a dense molecular cloud (Fegley and Prinn 1989; Van Dishoeck *et al.* 1993; Prinn 1993), so too any molecular ices condensing on or within these prestellar grain aggregates will reflect the conditions of their formation. Comets or planetesimals are thus expected to contain grains and interstellar condensates that reflect the 'interstellar' environment at the time of the grains' initial formation and growth.

3. 3. PROTOPLANETARY DISC

Following the Mestel-Ray prescription for the origin of a flattened Keplerian disc, a uniform, slowly rotating cloud with initial radius $R_c \approx 10^4$ AU and rotational velocity $v_{\mathrm{rot}}(\varpi)$ will evolve to produce a massive, extended protoplanetary disc with surface density $\Sigma(r) \gtrsim r^{-3/2}$ and outer radius R_d on the order of 10^2–10^3 AU, where we assume $\beta \approx 0.1$–0.5. Interstellar grains are expected to coalesce throughout the collapse phase, producing composite particles with a loosely bound fractal structure and a tendency for the volatile compounds and ices to reside on the surfaces of the growing grains and to fill the voids in the overall grain structure. Whereas grains in the inner regions of the disc are likely to be destroyed by collisions or by heating associated with formation of the pre-main-sequence star and its surrounding accretion disc (*e.g.* Morfill and Völk 1984; Tscharnuter and Boss 1993), those in the outer region are expected to retain their cosmic chemical memory (Clayton

1982; Sandford 1989) and to have a complex, hierarchical physical structure which may be sampled *in situ* next century by the European cometary mission Rosetta.

4. Grain growth

4. 1. GAS DISC

Following these prestellar phases of grain growth, the process of accumulation of grains in the protoplanetary disc may be divided into two phases : that in the presence of gas, lasting $\sim 10^6$–10^7 yr (Strom *et al.* 1993), and that in a gas-free environment following dispersal of the gas disc. Considering the first of these, if we take a grain of radius a, which we assume to be somewhat larger than the mean radius a_f of the background 'field' population, then its collision cross-section with respect to the background grains is $\sigma_c = \pi(a + a_f)^2 \simeq \pi a^2$. Turbulence in the gas, expected to occur, will drive significant relative velocities $v_{\rm rel}$ between grains of different sizes (Völk *et al.* 1980; Mizuno 1989; Weidenschilling and Cuzzi 1993), leading to grain growth at a rate given by

$$\frac{da}{dt} \simeq \frac{\rho_s v_{\rm rel}}{4\rho_g} \tag{3}$$

Assuming that the field particles have a Maxwellian velocity distribution with a one-dimensional velocity dispersion c_f and that the large grains have a significantly smaller velocity dispersion owing to their greater mass, then $v_{\rm rel} \simeq (8/\pi)^{1/2} c_f$ and hydrostatic equilibrium of the small grains perpendicular to the plane results in a Gaussian density distribution normal to the plane, given by $\rho_s(z) = \rho_s(0)\exp(-z^2/2h_f^2)$ where $h_f = c_f/\Omega = c_f(r^3/GM_\odot)^{1/2}$. The total surface density of solids in the disc is thus $\Sigma_s = \sqrt{2\pi}\rho_s(0)h_f$, so

$$\frac{da}{dt} = \frac{\Sigma_s \Omega}{2\pi\rho_g} \tag{4}$$

Thus the grain radius at time t is given by $a(t) = a_0 + \Sigma_s t/P\rho_g$, where $P(r) = 2\pi/\Omega$ is the orbital period of grains at heliocentric distance r.

We now consider a general power-law model of the form $\Sigma_s = k_s r^{-\alpha}$ for the surface density of solids, allowing α to be either 3/2 or 2 and choosing the normalization so that the dust surface density at 10 AU is 10 kg m^{-2}, roughly corresponding to that of a minimum-mass nebula within the planetary system. Ignoring the initial grain radius, equation (4) implies $a(t) = k_s(GM_\odot)^{1/2} r^{-\alpha-3/2}/2\pi\rho_g$, or

$$a(t) = \begin{cases} 0.32\left(\frac{100\,\mathrm{AU}}{r}\right)^3\left(\frac{t}{1\,\mathrm{Myr}}\right) \ \mathrm{m} \quad \text{and} \quad \alpha = 3/2 \\ 0.10\left(\frac{100\,\mathrm{AU}}{r}\right)^{7/2}\left(\frac{t}{1\,\mathrm{Myr}}\right) \ \mathrm{m} \quad \text{and} \quad \alpha = 2 \end{cases} \tag{5}$$

where we have assumed $\Omega = (GM_\odot/r^3)^{1/2}$. We conclude that substantial growth of grains occurs before dispersal of the gas disc, producing a population of large particles close to the equatorial plane. Equation (5) shows that after 3 Myr the dimensions of particles in the Uranus-Neptune zone ($r \simeq 25$ AU) are on the order of 50 m whereas those formed at a distance of 100 AU or more have radii $\lesssim 1$ m. Turbulent grain growth in the presence of gas thus leads to a strong gradient in mean particle size, producing bodies with sizes ranging from ~1–10 km in the Jupiter-Saturn zone to less than 1 m beyond 100 AU. This result jointly arises from the increase in orbital period at large heliocentric distances and the assumed decrease in the primordial disc surface density.

4. 2. DUST DISC

The phase of random accumulation in the presence of nebular gas ends with dispersal of the latter after $\sim 10^6$–10^7 yr. The clock is reset and the 'initial' conditions become those appropriate to a quiescent dust disc containing cometary building blocks of various sizes, comprising ice-covered interstellar dust aggregates and molecules reflecting the history of the dust in the presence of gas. Although grain growth by coagulation will continue, it seems likely that due to decreasing grain-grain relative velocities (no longer driven by turbulence) the process of random accretion will be overtaken by gravitational instability. As discussed by Goldreich and Ward (1973), the dust disc fragments into subdiscs with a characteristic length-scale that depends on the surface density and heliocentric distance. The first gravitationally unstable modes have a wavelength $\lambda_p = 4\pi^2 G\Sigma_s/\Omega^2$, while the most unstable mode has a wavelength about half this (Binney and Tremaine 1987). In this way, the mass of the first-formed planetesimals is approximately

$$m_p \simeq \pi \left(\frac{\lambda_p}{8}\right)^2 \Sigma_s = \frac{\pi^5 \Sigma_s^3 r^6}{4M_\odot^2} = \frac{\pi^5 k_s^3 r^{6-3\alpha}}{4M_\odot^2} \tag{6}$$

where we have assumed $\Omega = (GM_\odot/r^3)^{1/2}$. The first planetesimals in a disc with initial surface density $\Sigma_s \propto r^{-\alpha}$ thus have masses m_p proportional to $r^{6-3\alpha}$. Since the timescale for the instability to grow is on the order of $1/\Omega$, or about the rotation period at radius r, *i.e.* on the order of 3×10^4 yr at $r = 1000$ AU, the disc is expected to fragment rapidly and to form a large number of separate planetesimals with individual masses at radius r on the order of

$$m_p = \begin{cases} 6.9 \times 10^{18} \left(\frac{r}{100\,\mathrm{AU}}\right)^{3/2} \ \mathrm{kg} \quad \text{and} \quad \alpha = 3/2 \\ 2.2 \times 10^{17} \ \mathrm{kg} \quad \text{and} \quad \alpha = 2 \end{cases} \tag{7}$$

According to this theory, the first solid bodies to be formed by gravitational instability in the outer solar system may be identified with cometary nuclei or planetesimals. If they have a bulk density on the order of unity their diameters are on the order of 10^2 km, close to those of the 6 recently discovered Kuiper-belt candidates, namely 1992 QB_1 (220 km), 1993 FW (280 km), 1993 RO (180 km), 1993 RP (90 km), 1993 SB (180 km) and 1993 SC (280 km), adopting conventional low albedos ($\simeq 0.04$) for these outer solar system objects. This must be counted as a success of the theory. It is also worth noting that whereas the predicted planetesimal building blocks are ice-covered interstellar grain aggregates ranging in size from ~1 km (in the Saturn-Uranus zone) down to <1 m (beyond 100 AU), the predicted size of the resulting planetesimals or cometary nuclei is either constant or a slowly increasing function of heliocentric distance (*cf.* Tremaine 1990). The bodies formed further out are expected to be larger, and to comprise smaller building blocks, than those formed closer to the observed planetary system; observed comets should have the same range of properties.

4. 3. COLLISIONAL EVOLUTION

Detailed discussions of the collisional evolution of planetesimals formed by gravitational instability have been given, for example, by Nakagawa *et al.* (1983), Greenberg (1985, 1989), Wetherill (1990), Lissauer (1993), Lissauer and Stewart (1993) and Weidenschilling and Cuzzi (1993). In the planetary zones ranging from Jupiter to Neptune the planetesimals, identified as cometary or protocometary nuclei, are either accreted on to planets or dynamically ejected to interstellar space or to the inner and outer regions of the Oort cloud (Öpik 1973; Duncan *et al.* 1987). The process has been reviewed, for example, by Bailey *et al.* (1990), Fernández and Ip (1991) and Duncan and Quinn (1993a,b). However, as discussed by Greenberg *et al.* (1984) these theories are not without difficulties, and it remains uncertain whether the standard planetesimal theory can produce both comets and planets in the timescale available and explain, for example, the time-evolution of the inner solar system impactor flux. A further important question is the value of the placement efficiency, defined as the ratio of the initial cometary mass in the Oort cloud divided by the original cometary mass required in the protoplanetary disc. Current estimates (*e.g.* Bailey *et al.* 1990) suggest that this quantity may be quite small, *i.e.* $\lesssim 20\%$. This implies that the original cometary mass in the protoplanetary disc must have been at least 5 times the initial mass of the Oort cloud.

In the outer solar system, a discussion of the evolution of planetesimals produced by gravitational instability has been given by Yamamoto and Kozasa (1988). Their theory also provides an explanation of the recently discovered outer solar system bodies 1992 QB_1 and 1993 FW (Yamamoto *et al.* 1993). Here we briefly review these ideas, emphasizing again the good agreement between the predicted sizes of the initial planetesimals and those of the observed objects, and the fact that such a theory provides a natural explanation for the lack of planet-sized bodies beyond a heliocentric distance on the order of 30–50 AU.

Following previous authors (Safronov 1969; Yamamoto and Kozasa 1988), the newly formed planetesimals have relative velocities $v_{\rm rel}$ determined by the competition between acceleration during close encounters and collisional damping. A simple kinetic-theory approach contains the essential physics, and assuming that the particles have a Maxwellian velocity distribution with a one-dimensional velocity dispersion c_p, their mean relative velocity will be $\sqrt{2}\bar{v} = 4c_p/\sqrt{\pi}$. The density distribution of planetesimals normal to the disc is approximately Gaussian, with a scale height $h_p = c_p/\Omega$, and the central density is therefore $\rho_s \simeq \Sigma_s\Omega/\sqrt{2\pi}c_p$. Allowing for a factor $(1 + 2\theta)$ due to gravitational focussing, where $\theta = Gm_p/a_p v_{\rm rel}^2 = v_{\rm esc}^2/2v_{\rm rel}^2$, a_p is the radius of the first-formed planetesimals and $v_{\rm esc}$ is the escape velocity from their surface, and assuming a collision cross-section $\sigma_c = 4\pi a_p^2$ (since the planetesimals at each heliocentric distance are initially of comparable size), the expression for the mid-plane collision timescale $t_{\rm coll} = 1/[n_p\sigma_c v_{\rm rel}(1+2\theta)]$ becomes $t_{\rm coll} = 0.975(1+2\theta)^{-1}G^{-1/2}M_\odot^{-7/6}\rho_p^{2/3}r^{7/2}$, *i.e.*

$$t_{\rm coll} = 2.2\times 10^{10}(1+2\theta)^{-1}\left(\frac{\rho_p}{1\,{\rm g\ cm^{-3}}}\right)^{2/3}\left(\frac{r}{100\,{\rm AU}}\right)^{7/2}\quad {\rm yr} \qquad (8)$$

where $\rho_p \approx 1$ g cm^{-3} is the bulk density of the newly formed planetesimals and the steady-state value of θ is close to 0.5. The significance of this expression (*cf.* Fig. 1 of Yamamoto and Kozasa 1988) is that once gravitational instability has occurred, the initial collision timescale is not only independent of the assumed surface density of the disc but is also a sharply increasing function of heliocentric distance. At $r \simeq 50$ AU the collision timescale is on the order of 10^9 yr, and effectively infinite beyond, suggesting that significant accumulation of planetesimals into planets can only occur within the region of the observed planetary system. If, as in the standard planetesimal theory, comets are interpreted as the result of the formation of planetesimals in the outer planetary region (*i.e.* in the Jupiter, Saturn, Uranus and Neptune accretion zones), bodies formed beyond ~50–100 AU are likely to represent a collisionally unevolved system, *i.e.* a population of pristine planetesimals with predominantly cometary characteristics.

5. Total cometary mass

Recent years have seen several lines of argument converge to the conclusion that typical cometary nuclei may be much larger than formerly believed and that the cumulative diameter distribution is approximately proportional to d^{-2} (Bailey *et al.* 1994). The mean cometary mass is dominated by the size of the largest bodies, implying a significant upwards revision of the total cometary mass in the solar system (*cf.* Bailey and Stagg 1988; Bailey 1990, 1991b). For example, we may consider a spherically symmetrical model of the Oort cloud with an inner edge corresponding to a semi-major axis $a_0 = 4000$ AU, a value $a_t = 3.3\times 10^4$ AU for the semi-major axis above which new comets are directly injected into the inner solar system by the Galactic tide, and a power-law energy index $\gamma = 0$ (leading to a total number of comets roughly proportional to a_0^{-1}). The total number of comets brighter than visual absolute magnitude $H_{10} = 7$ is then on the order of 5.7×10^{11} for the above parameters, of which 5.2×10^{10} have semi-major axes greater than a_t and the remainder comprise the cloud's dense inner core. Following Donnison (1986) and Hughes (1987), the cumulative luminosity distribution of observed long-period comets can be written in the form $\log[N(\leq H_{10})] = 0.3H_{10} + {\rm constant}$, a result which may be converted into a cumulative mass distribution if the mass-magnitude relation is known, and hence into a cumulative diameter distribution given the mean density of the cometary nucleus. Adopting three recent determinations for these quantities (Bailey *et al.* 1992; Weissman 1990; Hughes 1987) and a density for the cometary nucleus on the order of 1 g cm^{-3}, the corresponding expressions for the mean cometary mass per object brighter than $H_{10} = 7$ as a function of the maximum diameter $d_{\rm max}$ in the size distribution can be calculated. The respective results are $\bar{m}/1\,{\rm kg} = 4.6\times 10^{16}(d_{\rm max}/300\,{\rm km})^{1.125}$, $4.0\times 10^{15}(d_{\rm max}/300\,{\rm km})^{0.75}$ and

$3.5 \times 10^{16}(d_{\max}/300\,\mathrm{km})^{1.50}$, suggesting that despite large uncertainty in the mean cometary mass and the precise form of the cumulative diameter distribution the present cometary mass must be at least $380\,M_\oplus$ if the upper limit on the diameter is taken to be as large as 300 km. The original mass must have been substantially more than this owing to the combined placement and survival probability being $\lesssim 20\%$. It is clear that the total cometary mass in the solar system cannot be accommodated within a standard mass-limited minimum-mass planetesimal picture (*cf.* Mendis and Marconi 1986), the evidence from cometary masses thereby providing an important additional reason for modifying the the theory to encompass a more massive, extended disc. However, we note for completeness that an extended disc model does not provide the unique solution to this problem; other ideas for the origin of comets, also rooted in the star-formation approach to the origin of the solar system, should perhaps be given equal weight (*e.g.* Hills 1981, 1982; Cameron 1988; Marochnik and Mukhin 1988; Marochnik *et al.* 1988, 1989).

6. Discussion

Theorists investigating the origin of the solar system have tended to follow one of two paths. Some have approached the problem from the point of view of star formation, starting with the gravitational collapse of a dense molecular cloud to form the sun surrounded by a massive, extended accretion disc in which the planets and lesser bodies are eventually formed as a result of coagulation of ice-covered interstellar dust grains and gravitational instabilities in an extended dust disc. Others have followed the standard planetesimal hypothesis, a theory founded not on star formation but on planet formation. This assumes a ready-formed sun initially surrounded by a relatively low-mass disc of gas and dust with surface density proportional to $r^{-3/2}$ and an outer boundary on the order of 30–50 AU.

Here, we have presented the case for adopting a modified planetesimal theory, involving aggregation of ice-covered interstellar dust grains during distinct phases of prestellar evolution culminating in the formation and evolution of a relatively massive, extended protoplanetary disc. The theory has been developed particularly by Yamamoto and colleagues, and appears to be consistent with a wide range of observational data, not least the argument that cometary ices have much in common with those expected to occur in cool interstellar clouds (*e.g.* Knacke 1989; Bar-Nun and Kleinfeld 1989; Lunine 1989; Engel *et al.* 1990; Yamamota 1991; Mumma *et al.* 1993). Several aspects of the extended disc model clearly need further study, for example the mechanisms by which comets are formed at large heliocentric distances and ejected to produce the Oort cloud (and, of course, *its* long-term evolution and structure), and the detailed differences in size, physical structure and chemical composition expected for comets formed in different parts of the disc, and whether such differences are detectable by remote observations. But despite these uncertainties, the outer solar system bodies — both comets and planetesimals — provide an important link between the sun and other stellar systems. The problem of their origin, properly understood, offers the exciting prospect of placing theories of the origin of the solar system at the heart of current developments in observational and theoretical astrophysics; its solution will provide key insights into the formation not only of our solar system but also that of other stellar and planetary systems in the Galaxy.

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