Planetary system formation in thermally evolving viscous protoplanetary discs

Richard P. Nelson, Phil Hellary, Stephen M. Fendyke and Gavin Coleman

Astronomy Unit, Queen Mary, University of London, Mile End Road, London E1 4NS, UK

Observations of extrasolar planets are providing new opportunities for furthering our understanding of planetary formation processes. In this paper, we review planet formation and migration scenarios and describe some recent simulations that combine planetary accretion and gas-disc-driven migration. While the simulations are successful at forming populations of low- and intermediate-mass planets with short orbital periods, similar to those that are being observed by ground- and space-based surveys, our models fail to form any gas giant planets that survive migration into the central star. The simulation results are contrasted with observations, and areas of future model development are discussed.

1. Introduction

Observations of extrasolar planets using a variety of techniques are uncovering the extraordinary diversity of planetary systems within our Galaxy [1–3]. This ‘planetary zoo’ consists currently of gas giant Jupiter-like and Saturn-like planets orbiting with periods ranging from a few days to a few years, warm and hot Neptunes and super-Earths with masses between 2 and $10\,M_\oplus$ (Earth masses). Earth-like planets (and bodies whose sizes are apparently smaller than the Earth’s) are just being discovered—including the recently announced planet Kepler 37b that is inferred to have a radius smaller than Mercury’s [4]. Examples exist of single-planet systems with no evidence of companion planets (e.g. 51 Peg). Numerous multi-planet systems have been discovered. Some contain a combination of high- and low-mass bodies (e.g. GJ 876, 55 Cancri, HD 181433), whereas others appear to host just giant planets (e.g. Kepler 9) or systems of lower-mass
Neptunes and super-Earths (e.g. Kepler 11). Planets are also being discovered within binary systems, orbiting just one of the binary components (e.g. gamma Cephei) or both components in a circumbinary configuration (e.g. Kepler 16, 34, 35).1

The above planets have been discovered largely from radial-velocity and/or transit surveys. Microlensing discoveries suggest the existence of both high- and low-mass planets orbiting at intermediate distance from their stars [5], whereas direct imaging surveys are beginning to uncover a population of giant planets orbiting at 10–100 astronomical units (AU) from their parent stars [2]. Reproducing and explaining this enormous diversity in physical and orbital characteristics provides a rather daunting challenge for planet formation theory. The purpose of this article is to provide a brief status report of one particular programme that aims to combine various processes involved in planet formation into a coherent model that will eventually be able to describe the formation histories of observed exoplanetary systems.

2. Planet formation

(a) Core accretion

The most widely accepted theory of planet formation involves a multi-stage process within a circumstellar disc consisting initially of a mixture of gas and submicrometre-sized dust grains. Dust grains collide and stick because of the combined action of Brownian motion/small-scale turbulence and van der Waals forces, settle towards the disc midplane and continue growing through either binary collisions [6] or collective processes, for example the streaming instability [7], until planetesimals in the 1–100 km size range are formed. Gravitational focusing may allow a subpopulation of these planetesimals to grow rapidly (‘runaway growth’) until dynamical heating of the surrounding planetesimals causes growth to enter a slower phase (‘oligarchic growth’).

For in situ terrestrial planet formation (orbital migration neglected), oligarchic growth ceases when growing embryos deplete their feeding zones and approach their isolation masses. Further growth requires ‘giant impacts’ between planetary embryos (expected to have masses in the Moon to Mars range), occurring on time scales of a few $10^7$ years [8].

Formation of giant planets is expected to begin further from the star, where condensation of ices augments the inventory of solids that can build planetary cores. Oligarchic growth is proposed to form cores of approximately $10 \, M_{\oplus}$ onto which gaseous envelopes accrete. If the planet forms early enough in the disc lifetime, it may become a gas giant planet when runaway gas accretion occurs. Otherwise, settling of a gaseous envelope onto the core forms Neptune-like planets consisting largely of icy and rocky material with a modest hydrogen/helium envelope [9].

(b) Gravitational instability

The idea that planets form through gravitational fragmentation of protostellar discs goes back at least to Cameron [10] and has been the subject of ongoing study since that time [11]. It is now generally agreed that fragmentation is most likely to occur in the low-temperature outer regions of protoplanetary discs where the cooling time is short [12]. Recent discovery of massive gas giant planets orbiting at tens of astronomical units from their central stars through direct imaging surveys [2] may provide evidence for planetary formation occurring through gravitational instability, but it seems unlikely that this mode of formation explains the numerous systems of short-period super-Earths and Neptune-like planets being discovered in abundance.

1Extrasolar planet data may be obtained from http://exoplanet.eu/.
3. Planetary migration

The above descriptions of planet formation clearly do not tell the full story. Observations of extrasolar planets indicate substantial mobility: the existence of short-period Jupiter-, Saturn- and Neptune-like planets indicates that either the planets themselves or their building blocks must have experienced substantial inward orbital migration. Systems of closely packed low-mass bodies detected by Kepler (e.g. Kepler 11) clearly support a disc-driven scenario. Planets whose orbits are significantly eccentric [13] or whose orbit planes are significantly inclined relative to the equatorial plane of the host star [14] may have experienced gravitational scattering with additional planets in the system, with tidal interaction with the central star also playing a role for the short-period circular systems [15].

(a) Type I migration

The nature of gas-disc-driven migration depends on the planet mass \( m_p \) and local scale height of the protoplanetary disc, \( H \), with other physical properties, such as viscosity and thermal evolution, also being important. When the planet’s Hill sphere radius \( R_H = a(m_p/3M_*)^{1/3} < H \) (here \( a \) is semi-major axis and \( M_* \) is stellar mass), then the disc response to the planet’s gravity is expected to be quasi-linear, and the planet will undergo type I migration [16]. Migration torques experienced by an embedded planet are composed of Lindblad and corotation torques, the former arising because of the excitation of spiral density waves at Lindblad resonances and the latter due to material in the vicinity of the planet semi-major axis (the corotation region) where the fluid follows horseshoe streamlines. The Lindblad torque is always essentially present in the disc and may be written [17] as

\[
\Gamma_{LR} = \left( \frac{\Gamma_0}{\gamma} \right) [-2.5 - 1.7\beta + 0.1\alpha],
\]

where \( \gamma \) is the ratio of specific heats, and \( \alpha \) and \( \beta \) are the exponents in the surface density and temperature radial profiles, respectively. The most important component of the corotation torque is often referred to as ‘horseshoe drag’ and arises because of gradients in either entropy and/or vortensity (ratio of vorticity and surface density) across the horseshoe region. An expression for the horseshoe drag may be written [17] as

\[
\Gamma_{VHS} + \Gamma_{EHS} = \left( \frac{\Gamma_0}{\gamma} \right) \left[ 1.1 \left( \frac{3}{2} - \alpha \right) + 7.9 \zeta \right],
\]

where the first term in square brackets arises from the vortensity gradient, the second term is from the entropy gradient and \( \zeta \) is given by

\[
\zeta = \beta - (\gamma - 1)\alpha.
\]

In the above, \( \Gamma_0 \) sets the magnitude of the torque and is given by

\[
\Gamma_0 = \left( \frac{m_p}{M_*} \right) \left( \frac{m_p}{\Sigma_p a_p^2} \right) \left( \frac{a_p}{c_s} \right)^2 \Omega_p^2 a_p^2 \Omega_p^2,
\]

where \( a_p \) is the planet semi-major axis, \( \Sigma_p \) is the surface density, \( c_s \) is the sound speed, \( \Omega_p \) is the disc angular velocity and the subscript ‘p’ indicates that quantities should be evaluated at the orbital location of the planet. The horseshoe drag is a nonlinear corotation torque because it arises from the horseshoe trajectories followed by disc fluid elements (and these are an inherently nonlinear phenomenon). Linear perturbation theory also predicts the existence of a corotation torque due to material corotating with the planet. This is smaller than the horseshoe drag and is important when the horseshoe drag is rendered inoperative due to viscous/thermal diffusion processes in the disc acting on time scales that are short relative to the horseshoe U-turn time scale.

The corotation torque (horseshoe drag plus linear contribution) is prone to saturation because material phase mixes in the horseshoe region. The effect is to erase the entropy or vortensity gradient that feeds the corotation torque, causing the torque to disappear on the horseshoe
libration time scale, $\tau_{\text{lib}}$. Saturation can be prevented if viscosity and thermal diffusion are present and able to re-establish the vortensity and entropy gradients. This occurs when the thermal diffusion time scale, $\tau_{\text{therm}}$, and viscous time scale, $\tau_{\text{visc}}$, across the horseshoe region are approximately equal to the libration time scale, $\tau_{\text{lib}}$. If, on the other hand, $\tau_{\text{therm}} \ll \tau_{\text{lib}}$, then the entropy contribution to the horseshoe drag is erased and only the linear contribution remains. If $\tau_{\text{visc}} \ll \tau_{\text{lib}}$, then the vortensity contribution to the horseshoe drag is erased and only the linear contribution remains. If $\tau_{\text{therm}}$ and $\tau_{\text{visc}} \gg \tau_{\text{lib}}$, then the corotation torque saturates completely.

The corotation torque can also be substantially reduced in the presence of planetary eccentricity [18]. In a recent study, Hellary & Nelson [19] suggested that this could strongly influence the evolution of planetary swarms undergoing oligarchic growth. Results from a detailed study of this effect are discussed briefly in §4.

(b) Type II migration

Migration transitions from type I to type II when a planet opens a gap in the disc. The conditions for this are that the disc response to the planet perturbation must be nonlinear and the tidal torque due to the planet must exceed the viscous torque in the disc [20]. Inward migration under these conditions then occurs on the viscous evolution time scale of the disc [21,22].

It is noteworthy that planets formed through either core accretion or gravitational fragmentation may undergo substantial migration. The dense gaseous clumps that form through gravitational instability are prone to extremely rapid inward migration [23]. Realization that this rapid inward migration may occur has led to suggestions that these gaseous protoplanets may experience tidal downsizing, as they migrate inwards and fill their Hill spheres [24]. This, however, is not a scenario that we consider further in this article.

4. Corotation torques experienced by eccentric low-mass planets

Planetary orbital eccentricity can strongly influence Lindblad migration torques [25] and eccentricity/inclination damping rates of embedded planets [26]. In a recent study, Bitsch & Kley [18] showed that corotation torques decrease significantly with modest growth of eccentricity. We present here a brief summary of recent calculations that explore this issue further, motivated by the simple observation that planet formation in the oligarchic growth scenario necessarily leads to eccentricity excitation through mutual encounters between embryos.

Hydrodynamic simulations were performed to examine how eccentricity influences corotation torques. Details about the simulation set-up and results are given in Fendyke & Nelson [27]. These two-dimensional simulations were performed for 5 M$_\oplus$ planets embedded in discs with scale height $h = 0.03, 0.05, 0.07$ and 0.1. Additional simulations for 10 M$_\oplus$ planets embedded in a disc with $h = 0.1$ were also performed. Eccentricities in the range $0 \leq e \leq 0.3$ were considered.

Figure 1(a) shows the time-averaged surface density perturbation for the $h = 0.07$ disc with $m_p = 5 M_\oplus$ for different eccentricities. Thermal relaxation and viscosity were optimized to prevent entropy/vortensity corotation torque saturation. The density within the horseshoe region has the characteristic structure for a disc that exerts a positive unsaturated corotation torque: a positive density perturbation leading the planet and a negative perturbation trailing it. The black lines delineate the horseshoe region, and we see that the width of this region diminishes as eccentricity increases, owing to the material in this region experiencing an effective softening of the gravitational acceleration due to the planet.

The corotation torque experienced by the planet is shown in figure 1(b), as a function of orbital eccentricity. As reported by Bitsch & Kley [18], the torque drops off with increasing eccentricity. We ascribe this effect as being due in large part to the decrease in the horseshoe width displayed in figure 1(a). Fendyke & Nelson [27] provide a fit to the results from their full suite of simulations.
covering different values of $h$, $e$ and $m_p$, and find that the fully unsaturated corotation torque can be fitted by

$$
\Gamma_c(e) = \Gamma_{c,0} \exp \left( -\frac{e}{\Delta} \right),
$$

where $\Delta = h/2 + 0.01$ and $\Gamma_{c,0}$ is the corotation torque at zero eccentricity. An important result is that the parameter that determines the magnitude of $\Delta$ is the disc scale height $h$ and not the horseshoe width, as has been suggested in previous work. Given that the horseshoe width varies inversely with $h$, the realization that $\Delta$ scales with $h$ will be particularly important where large-scale migration occurs in discs where $h$ varies significantly with orbital radius.

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**Figure 1.** (a) Time-averaged surface density for simulations with increasing values of eccentricity in a disc with $h = 0.07$ and $m_p = 5 M_\oplus$. The superimposed black lines show the circulating streamlines that lie closest to the planet, and thus delineate the horseshoe region. (c) Corotation torque measured for a $5 M_\oplus$ planet embedded in a disc with $h = 0.07$ as a function of eccentricity. (Online version in colour.)
5. Planet formation simulations

We now present the results of N-body simulations of planet formation. These are initiated during the oligarchic growth stage when the system consists of embryos and planetesimals. The basic model is similar to that described in Hellary & Nelson [19] but incorporates numerous improvements.

(a) The gas disc model

In previous work, a disc model was adopted with fixed power laws for the radial surface density and temperature distributions. This has been replaced with a thermodynamically evolving viscous disc model that photoevaporates. We solve the standard surface density diffusion equation [28] using explicit finite differences, including tidal torques from embedded planets, so that gaps may form self-consistently [21]. The equilibrium temperature is calculated iteratively through a balance between radiative cooling and heating due to stellar radiation, accretion luminosity and viscous dissipation [29]. Rosseland mean opacities from Bell & Lin [30] are employed. The prescription from Dullemond et al. [31] leads to photoevaporation. This removes gas primarily from beyond the radius where it becomes unbound from the star ($r_g = 10$ AU here). The flux of EUV ionizing photons is $f_{41} \times 10^{41}$ s\(^{-1}\), and we consider values $f_{41} = 1, 10, 100$. The gas disc runs between 0.1 and 40 AU.

(b) The solid component

Disc solids consist of planetary embryos with mass $0.2 M_\oplus$ immersed within a large number of ‘super-planetesimals’. Protoplanets interact gravitationally with each other and with planetesimals. Planetesimals interact only with protoplanets. Protoplanets accrete through collisions with other protoplanets and planetesimals. Planetesimals experience gas drag, with an acceleration appropriate for bodies of radius 1 or 10 km (assuming an internal density of 3 g cm\(^{-3}\)). Super-planetesimal masses equal one-tenth of the initial protoplanet masses. Simulations are initiated with approximately 40 protoplanets distributed between 1 and 20 AU, and between approximately 2000 and 12 000 planetesimals, depending on the particular run (higher-mass discs include more planetesimals).

The surface density of solids falls initially as $r^{-3/2}$. For a disc with solar metallicity, the surface density of solids equals 7.1 g cm\(^{-3}\) at 1 AU, unit and increases by a factor 30/7.1 beyond the snow line, where the initial steady disc temperature falls below 160 K. The $N$-body components of our simulations were conducted using MERCURY-6 [32].

(c) Gas-disc-driven migration

We incorporate migration of low-mass planets using the prescriptions for type I migration presented in Paardekooper et al. [17]:

$$\Gamma_{\text{tot}} = \Gamma_{\text{LR}} + \Gamma_{\text{VHS}} G_v F_v + \Gamma_{\text{EHS}} F_v G_d + \Gamma_{\text{LVCT}} (1 - K_v) + \Gamma_{\text{LECT}} (1 - K_v) (1 - K_d).$$

The total torque $\Gamma_{\text{tot}}$ is composed of the Lindblad torque, $\Gamma_{\text{LR}}$, vortensity and entropy contributions to the horseshoe drag ($\Gamma_{\text{VHS}}$ and $\Gamma_{\text{EHS}}$, respectively) and vortensity and entropy contributions to the linear corotation torque ($\Gamma_{\text{LVCT}}$ and $\Gamma_{\text{LECT}}$, respectively). The factors $F_v$, $G_v$, $F_d$, $G_d$, $K_v$ and $K_d$ determine the level of saturation of the corotation torque contributions through estimates of the relative time scales between thermal/viscous diffusion across the horseshoe region and the horseshoe libration period (see [19] for a description of how these terms are incorporated). Eccentricity and inclination damping are included [33], with reduction factors accounting for eccentricity/inclination [26]. A similar reduction factor is applied to the Lindblad torque, and the corotation torque is multiplied by the reduction factor described in Hellary & Nelson [19]. Note that this is not the same prescription as described in §4 because the result
described there was obtained after the simulations described here were performed. Future work will adopt this new reduction factor. Migration transitions to type II when a planet forms a gap. It is noteworthy that the disc can become very thin near to the star, $H/r < 0.02$, such that planets with masses approximately $10 \, M_{\oplus}$ can open gaps there.

(d) Gas accretion onto planets

We include gas accretion in our simulations through the implementation of a fitting formula to the detailed envelope accretion calculations presented in Movshovitz et al. [34]. Coagulation and settling of grains in the atmosphere decrease the opacity and shorten the envelope accretion time to 2.6 Myr for a planet with a $3 \, M_{\oplus}$ core and to 0.6 Myr when a $10 \, M_{\oplus}$ core is present, substantially shorter than earlier estimates obtained without grain evolution [9]. Gas accretion is mass-conservative, as we remove gas from the disc in an annulus surrounding the planet as it accretes onto the planet. Gas accretion onto planets is only initiated once the core mass reaches $3 \, M_{\oplus}$.

Once the gaseous planet reaches $30 \, M_{\oplus}$, accretion transitions to a mode where the rate is controlled by viscous supply to its neighbourhood. Based on the local surface density, we estimate the gas mass within a putative circumplanetary disc, and the planet accretes on the viscous time scale of this subdisc. This mode of accretion is effective at dramatically slowing the accretion rate onto the planet when it forms a gap in the disc. We note that the mass-conservative routine also limits the accretion rate for planets with $m_p < 30 \, M_{\oplus}$, so, if deep gap formation occurs for such planets, their masses are also limited.

(e) Enhanced planetesimal accretion

The presence of a gaseous envelope gives a planet an increased cross section for accreting planetesimals owing to aerodynamic drag. We adopt the prescription given in Inaba & Ikoma [35], which incorporates expansion or contraction of the envelope due to increased or decreased accretion of solids. The accretion rate obtained in the simulations is used to compute the envelope structure.

(f) Initial conditions

We have performed more than 100 $N$-body simulations covering time periods up to 5 Myr. For each parameter set, we used two different random number seeds for defining initial protoplanet and planetesimal positions. We have considered discs with mass in the range 1–6 MMSN (where MMSN is the minimum-mass solar nebula model that contains approx. 0.015 $M_\odot$ (solar masses) within 40 AU). We have also considered two metallicity factors (1 and 2, the factor 2 is only used for discs with masses in the range 1–3 MMSN), two effective planetesimal sizes (1 and 10 km) and three EUV photon fluxes ($f_{41} = 1, 10, 100$). We emphasize that our aim at the present time is to examine the interplay between accretion, migration and planet–planet interactions during planet formation. It is not to undertake a study of planetary population synthesis, as exemplified in the studies by Ida & Lin [36] and Mordasini et al. [37]. It is for this reason that we do not choose our initial conditions by drawing them from a distribution based on observations or theoretical considerations.

6. Simulation results

Space constraints prevent us from presenting a full set of results, so instead we present two cases that illustrate some of the more common modes of evolution observed.
Figure 2. The locations and masses of the planets (dots, blue online) in run 1 plotted against the planetesimal (rapidly varying curve, red online) and gas (smoothly varying curve, green online) surface densities at various times. Plotted gas surface densities are reduced by a factor of 10 to allow concurrent plotting. (Online version in colour.)

(a) Run 1

Run 1 has an initial disc mass equal to twice the MMSN, metallicity factor unity, $f_{41} = 1$ and planetesimal radius of 10 km. Snapshots of the simulation results showing protoplanet masses, and planetesimal and gas disc surface densities are shown in figure 2. Mass growth as a result of planetesimal accretion and planet–planet collisions begins slowly, as the solid disc mass is comparatively low in this run. During the first 0.5 Myr, no planets greater than 1 M$_{\oplus}$ have formed, and the gas-driven migration has not been effective. By 1.5 Myr, the gas disc mass has halved. Some Earth-mass planets have formed and migrated to regions where they experience zero net torque from the gas disc. The contours in figure 3 indicate the direction of migration for planets on circular orbits as a function of planet mass and semi-major axis at different times during the evolution. A value of +2.5 indicates strong outward migration and −2.5 indicates inward migration. For a given planet mass, there may exist disc regions where the thermal and viscous time scales are approximately equal to the horseshoe libration time, giving a maximally positive value to the corotation torque that drives outward migration. As the planet migrates outwards, however, the disc surface density and opacity decrease, and the thermal time scale becomes short, reducing the corotation torque. Eventually, the corotation and Lindblad torques cancel, creating a zero-torque zone for the planet. Planets outside of this zone will tend to migrate inwards towards it, and planets inside will tend to migrate outwards to it, creating a convergence point. In figure 3, this region corresponds to the terminus between dark grey (blue online) and mid-grey (red online) areas, where the dark grey (blue online) area is inward of a mid-grey (red online) area. A number of bodies with $m_p = 1–2$ M$_{\oplus}$ are seen to straddle this region at 1.5 Myr. These planets do not grow substantially over the following 1.5 Myr but remain in regions of zero torque and move inwards, as the gas disc accretes onto the star (the zero-torque zone moves inwards, as the disc surface
density and opacity decrease). By 3 Myr, the gas disc has almost completely dispersed. Note the characteristic dip in surface density in figure 2c due to photoevaporation. This dip soon grows into a wide hole in the disc, after which the remainder of the gas in the disc rapidly photoevaporates.

After the disc is completely dispersed (after 3.25 Myr), evolution is driven entirely by solid-body interactions. Accretion is limited to planet–planet collisions and planetesimal accretion. As the eccentricities and inclinations of bodies can no longer be damped by the gas disc, a sharp increase in these quantities is observed from this point onwards in figure 4, which shows the time evolution of masses, semi-major axes and eccentricities for all planets in this run.

This run failed to produce any gaseous planets, because none exceeded 3 M⊕ (required for gas accretion) during the disc lifetime. All remaining planets lie between 0.4 and 6.4 AU. units and undergo a final stage of giant impact growth that can last for tens of million years, longer than our simulation evolution time.

(b) Run 2

Run 2 has an initial disc mass equal to three times the MMSN, metallicity factor unity, f_{41} = 100 and planetesimal radius of 1 km. Snapshots of the simulation results showing protoplanet masses, and planetesimal and gas disc surface densities are shown in figure 5. The more massive disc and smaller planetesimals in this case lead to swifter planetary accretion than that observed in run 1, and we see the growth of approximately Earth-mass bodies after 0.1 Myr in figure 5a. Figure 5b shows that numerous bodies with masses in the range 8–20 M⊕ have grown after 1.5 Myr. The contour plots in figure 6 show the regions of outward and inward migration in the planetary mass–semi-major axis plane. At 1.5 Myr, the more massive bodies cannot migrate outwards through corotation torques because their associated horseshoe libration times are short.
Figure 4. The evolution of masses, semi-major axes and eccentricities for all protoplanets in run 1. (Online version in colour.)

Figure 5. The locations and masses of the planets (dots, blue online) in run 2 plotted against the planetesimal (rapidly varying curve, red online) and gas (smoothly varying curve, green online) surface densities at various times. Plotted gas surface densities are reduced by a factor of 10 to allow concurrent plotting. (Online version in colour.)

relative to the local thermal and viscous time scales. These protoplanets migrate inwards because of Lindblad torques. Lower-mass planets located at approximately 2 AU are located in zero-torque regions, and so migrate inwards slowly, as the gas disc accretes onto the central star.
The temperature in the disc inner regions leads to the disc scale height to radius ratio $H/r \lesssim 0.02$, allowing relatively low-mass planets with $m_p \gtrsim 10 \, M_{\oplus}$ to form gaps and transition to slower type II migration, as illustrated in figure 5c. Nonetheless, the large quantities of gas lying exterior to these five gap-forming planets drives them into the central star. After 2.5 Myr, we are left with only two sub-Earth-mass planets in the disc, and these remain until after the gas disc fully disperses.

**7. Discussion and conclusion**

We have shown the results from two simulations drawn from a suite of 108 runs in total. These two simulations are quite representative of the outcomes of all simulations because they result in populations of low- and intermediate-mass planets, but no surviving gas giants because they or their precursors always migrate into the central star before gas disc dispersal. Examples of the following types of planets are formed in our simulations: gas giant planets with substantial solid cores (i.e. $m_{\text{core}} \geq 10 \, M_{\oplus}$); gaseous planets with modest core masses (i.e. $m_{\text{core}} \sim 3–5 \, M_{\oplus}$); Neptune-like and super-Earth-mass planets with significant core masses and moderate envelopes that account for approximately 10% of the total planet mass; and terrestrial planets whose masses remain less than $3 \, M_{\oplus}$ and so did not accrete significant gaseous envelopes. All gas giant planets that emerged from the simulations (with high- or low-mass cores) formed gaps in the disc and experienced type II migration into the central star, leaving no long-term survivors. Significant numbers of the other classes of planet described above formed and survived long term in the runs. The maximum mass of any surviving planet was approximately $15 \, M_{\oplus}$.

The formation of gas giants was favoured in runs either where the initial total disc mass was $5–6 \times \text{MMSN}$, or in discs with a total gas mass $3 \times \text{MMSN}$ and a metallicity enhancement factor of 2, and in models where the planetesimal radii were equal to 1 km, as this enhanced the rapid growth of cores. The rapid formation of cores followed by runaway gas accretion typically formed Saturn-mass bodies within 1 Myr whose further mass growth was retarded by gap formation. The existence of a substantial gas disc lying outside the planet orbit essentially guarantees migration into the central star in our models because the photoevaporative wind is unable to remove such a large amount of mass within the type II migration time scale. No giants formed late in the disc lifetime such that photoevaporative loss of the disc could prevent migration into the central star. Adoption of an inner magnetospheric cavity close to the star would lead to the formation of hot Jupiters, but this cannot account for the long-term survival of the numerous extrasolar gas giants that are seen to orbit at large or intermediate distances from their stars, and so we have not implemented this in our models. Improved statistics in terms of a larger sample of simulations are required to determine whether or not the basic model adopted here is
capable of producing surviving giants, or if instead some substantial improvement in the model components is required. Simple back-of-the-envelope estimates suggest that the formation of surviving giant planets requires that their cores begin accreting gas at large distance from the central star (i.e. $\gtrsim 20$ AU) in order that the migration, gas accretion and disc removal time scales are all favourable, and in our models this almost never happens because corotation torques in the disc are incapable of pushing cores out to such a large distance. This suggests that significant model modifications are required for successful formation of gas giant planets.

Comparing the results with our previous model [19], we note the large numbers of super-Earths and Neptune-like planets that are formed in the new runs versus the complete dearth of such planets in the earlier models. This improvement arises in part because gap formation in the thinner regions of the disc close to the star reduces gas accretion onto these planets and prevents them from growing out of the super-Earth to Neptune mass range. Numerous examples of these planets also arose, however, by forming late in the runs when the gas disc was close to dispersing. Often the planets would be stranded out beyond a few astronomical units after disc dispersal.

It is difficult to compare the planetary population we generate with the full set of observational data given space restrictions. The fact that we have not undertaken a serious attempt at population synthesis, by drawing initial conditions from an observationally motivated sample of disc models, would render such a comparison as meaningless. We simply note, however, that the diverse types of planets being found by radial velocity and transit surveys, for example the Kepler mission, are formed in the simulations, even though the more massive planets do not survive migration into the star. Low-mass and low-density planets arise when small cores begin to accrete gas and migrate close in to the central star where the disc is thin and gap formation choked off further gas accretion. Systems of super-Earths and Neptune-like bodies arise quite naturally and small terrestrial bodies are also formed in abundance, often as the debris left over from the formation of larger bodies. One area of disagreement, however, is that the maximum mass of a surviving planet in our simulations is approximately $15 M_\oplus$, close to that of Uranus and Neptune, but substantially lower than the masses of the numerous sub-gas giant planets that have been detected observationally. Improvements to the model, for example implementation of a self-consistent model for gas envelope accretion and a more sophisticated disc model, will allow simulations of higher fidelity to be produced and these will form the basis for future comparison with observational data to test whether or not the basic paradigm of planet formation based on oligarchic growth and disc-driven migration can explain the diversity of the known planets.

A paper describing the simulations presented here in more detail is currently in preparation.

References


