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Rotation of the Solar system planets and the origin of the Moon in the context of the tidal downsizing hypothesis

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ABSTRACT

It has been proposed recently that the first step in the formation of both rocky and gas giant planets is dust sedimentation into a solid core inside a gas clump (giant planet embryo). The clumps are then assumed to migrate closer to the star where their metal poor envelopes are sheared away by the tidal forces or by an irradiation-driven mass loss. We consider the implications of this hypothesis for natal rotation rates of both terrestrial and gas giant planets. It is found that both types of planets may rotate near their breakup angular frequencies at birth. The direction of the spin should coincide with that of the parent disc and the star, except in cases of embryos that had close interactions or mergers with other embryos in the past. Furthermore, the large repository of specific angular momentum at birth also allows formation of close binary rocky planets inside the same embryos. We compare these predictions with rotation rates of planets in the Solar system and also question whether the Earth–Moon pair could have been formed within the same giant planet embryo.

Key words: accretion, accretion discs – Moon – planets and satellites: formation.

1 INTRODUCTION

Recently, a 'tidal downsizing' hypothesis (Nayakshin 2010a) for planet formation was advanced (see also Boley et al. 2010; Nayakshin 2010b,c). Planets, both rocky and gas giants, are built in this hypothesis very early on, while the gaseous disc is still comparable in mass with the star. In brief, the disc is expected to fragment on gaseous clumps with mass ∼10 Jupiter masses at ∼100 au scales, where radiative cooling is sufficiently fast. The gas clumps then contract due to radiative cooling. The contraction process may be protracted enough (Nayakshin 2010c) to allow the dust to sediment inside the embryos to make terrestrial planet cores (as proposed by Boss 1998, earlier). Finally, embryos (gas clumps) migrate closer to the star, where their gaseous envelopes are tidally and possibly irradiatively disrupted, leaving behind either rocky cores of terrestrial planets or more massive gas giants.

Numerical simulations of massive gas discs by e.g. Vorobyov & Basu (2006), Boley et al. (2010) appear to support the embryo migration part of the hypothesis, while the recent simulation by Cha & Nayakshin (2010) has actually resulted in a 'super-Earth' solid core being delivered from ∼100 to ∼8 au. Nevertheless, the numerical simulations of this kind are in their infancy, and it also remains unclear how robust the results are given that the embryo evolution strongly depends on assumed dust opacity and other parameters of the problem.

A supplementary way to test a hypothesis is to consider its least model dependent predictions and contrast them to observations. In this paper we make one such comparison by considering the spins of the planets at birth in the context of the tidal downsizing scheme. We point out that gas clumps born in the disc by fragmentation are usually found to rotate in prograde direction with the spin tightly aligned to that of the parent disc. We show below that rotation of the giant embryos endows both rocky and giant planets born inside the embryos with prograde rotation at high, potentially near breakup, rates. The offsets of planet's direction of spin from the disc rotation in this scenario is due to embryo–embryo interactions. We also note that rapid rotation of the inner zones of the embryos implies that rocky planets born there by gravitational instability may not form single but be in binaries or even multiples.

These predictions are consistent with the observations of the Solar system planets rotation pattern, e.g. relatively rapid and mainly prograde. We also note that the Earth and the Moon would have to be born inside the same giant planet embryo if the tidal downsizing hypothesis is correct.

We conclude the paper by noting that despite these encouraging results, there is a whole list of observations (compiled partly due to the anonymous referee of this paper) that the tidal downsizing hypothesis needs to be further tested upon.

2 SIMULATED ROTATING GIANT PLANET EMBRYOS

Although our arguments are analytical, we find it useful to illustrate our points with numerical simulations that were recently presented

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by Cha & Nayakshin (2010), who simulated fragmentation and evolution of a massive, $M_{\rm d} = 0.4\,{\rm M}_{\odot}$, gas disc around a parent star of mass $M_* = 0.6\,{\rm M}_{\odot}$. The gas component was modelled with a 3D SPH code utilising an analytical approximation to the radiative cooling, whereas the dust was treated as a second fluid under the influence of gravity and the drag force from the gas. The grains were allowed to grow via a stick-and-hit mechanism saturated at a maximum impact velocity of 3 m $\rm s^{-1}$.

As expected, the disc fragmented on a dozen or so gaseous clumps with masses between 5 and 20 M_J at a distance of $\sim$70 to $\sim$150 au. Some of the clumps merged with one another, others interacted strongly gravitationally. Several clumps made it into the inner few tens of au. The less dense ones were destroyed by tidal shear releasing their dust content at $\sim$15 au. One particular embryo was dense enough to spiral in closer before being completely destroyed. By virtue of its higher density the embryo also contained larger dust grains and a gravitationally collapsed dust core of mass $\sim 7.5\,{\rm M}_{\oplus}$. The 'super-Earth' core was deposited in a low eccentricity orbit with the semi-major axis of 8 au.

Fig. 1 shows the face-on gas column density map centred on a typical undisturbed embryo at a large distance from the star at time $t = 4880$ yr (same as the left-hand panel of fig. 2 in Cha & Nayakshin 2010). The collection of cyan dots in the centre of the figure is the dust grain particles with size greater than 10 cm. The grain concentration is not yet high enough to yield a collapsed solid core at the time of the snapshot. Black arrows show the velocity field of the gas with respect to the velocity of the densest part of the embryo. The spin direction is the same as that of the parent disc around the star, save for offset by about 5°. The origin of prograde rotation of the embryo may be in the shape of streamlines on the 'horse-shoe orbits' of gas near the location of a massive planet (see Lubow, Seibert & Artymowicz 1999). The magnitude of velocity

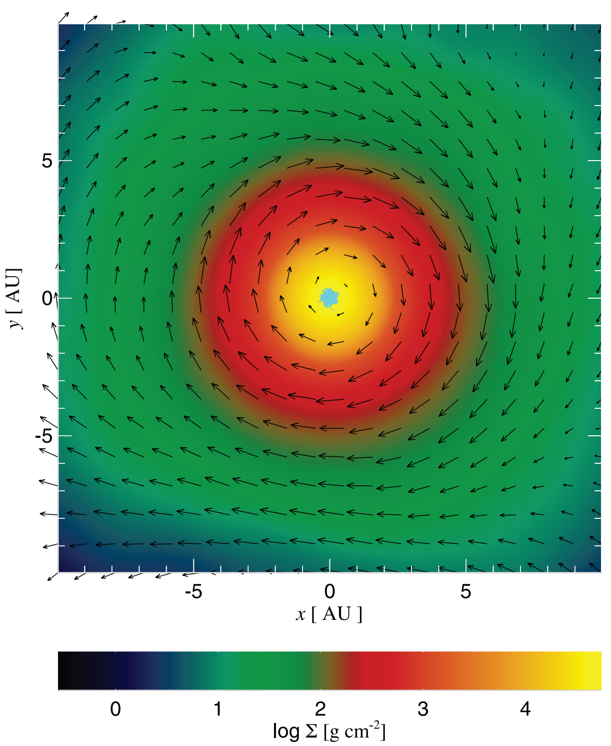

Figure 1. The top projection of a typical 'undisturbed' embryo at a large ($\sim$100 au) distance from the star. The central cyan colour points show dust particles with size greater than 10 cm.

vectors in the figure first increase with distance from the centre (to the distance of a few au), and then stay roughly constant or perhaps decrease slightly further out.

A sufficiently viscous gaseous body may be expected to rotate at a constant angular frequency, e.g. as a solid body. For a constant density embryo model (Nayakshin 2010c), the maximum breakup angular frequency of rotation is

$$\Omega_{\rm break} = \left(\frac{4\pi G\rho_0}{3}\right)^{1/2}, \quad (1)$$

where ρ_0 is the density of the embryo. We define the rotational breakup velocity of the embryo as

$$v_{\rm break} = \Omega_{\rm break} r, \quad (2)$$

where $r = \sqrt{x^2 + y^2}$ is the projected distance to the embryo's centre. To analyse the rotation pattern of embryo in Fig. 1 further, we normalize the velocity field on $v_{\rm break}$, taking ρ_0 to be the mean gas density in the embryo. The left-hand panel of Fig. 2 shows the embryo in the same face-on projection as in Fig. 1, whereas the right-hand panel of the figure shows the projection of the embryo along the y-direction (e.g. in the plane of the disc). The velocity vectors in the right-hand panel are exaggerated (compared with the left-hand panel) for visibility.

It is clear from the left-hand panel that the embryo spins nearly as a solid body in the central few au, as the normalized velocity vectors are of almost a constant length. Furthermore, the right-hand panel shows that the rotation is significant enough to deform the embryo's shape from a spherical shape to that of an oblate spheroid flattened along the spin vector. The amplitude of rotation Ω is close to $0.1\Omega_{\rm break}$.

Our final example of rotating embryos found in simulations is shown in Fig. 3 which shows the face-on projection of an embryo closest to the star in the left-hand panel of fig. 4 of Cha & Nayakshin (2010). The embryo is within slightly less than 40 au from the parent star (located south-west in the figure) and has just interacted with another embryo outside of the figure and located north-west. This is an example of an embryo significantly perturbed by the tidal field of the star and other interactions in the disc. The central dot in the left-hand panel of the figure is the super-Earth solid core (we do not show grains smaller than 100 cm in this figure). The right-hand panel of Fig. 3 shows the central part of this embryo, centred on the solid core. Note that the rotation pattern of the gas component is offset by about 0.15 au from the solid core in this case. The velocity vectors are not normalized on $v_{\rm break}$ in this figure.

The spin axis of this embryo is more strongly inclined away from the disc axis of symmetry; the inclination angle for the embryo is slightly larger than 30°. This large inclination is very likely to be the result of at least two interactions that the embryo has had earlier. In particular, it had merged with another smaller one; there were also a close passage of a massive embryo (see Cha & Nayakshin 2010).

3 NATAL SPIN OF ROCKY PLANETS

We now assume that the embryos are roughly in a solid body rotation with angular frequency $\Omega_0 = \xi_{\rm rot}\Omega_{\rm break}$, where $0 < \xi_{\rm rot} < 1$ is a parameter. From our numerical simulations to date, and also Boley et al. (2010), $\xi_{\rm rot} \sim 0.1$. $\xi_{\rm rot} = 1$ corresponds to the maximum rotation frequency. We write the mass of the embryo $M_{\rm emb} = 10\,M_J m_1$ and use the fiducial parameters for the embryo model in paper III, which yields $R_{\rm emb} = 0.8$ au $t_4^{-1/2}$, where $t_4 = t/10^4$ yr is the age of the embryo. We thus have that the minimum rotation

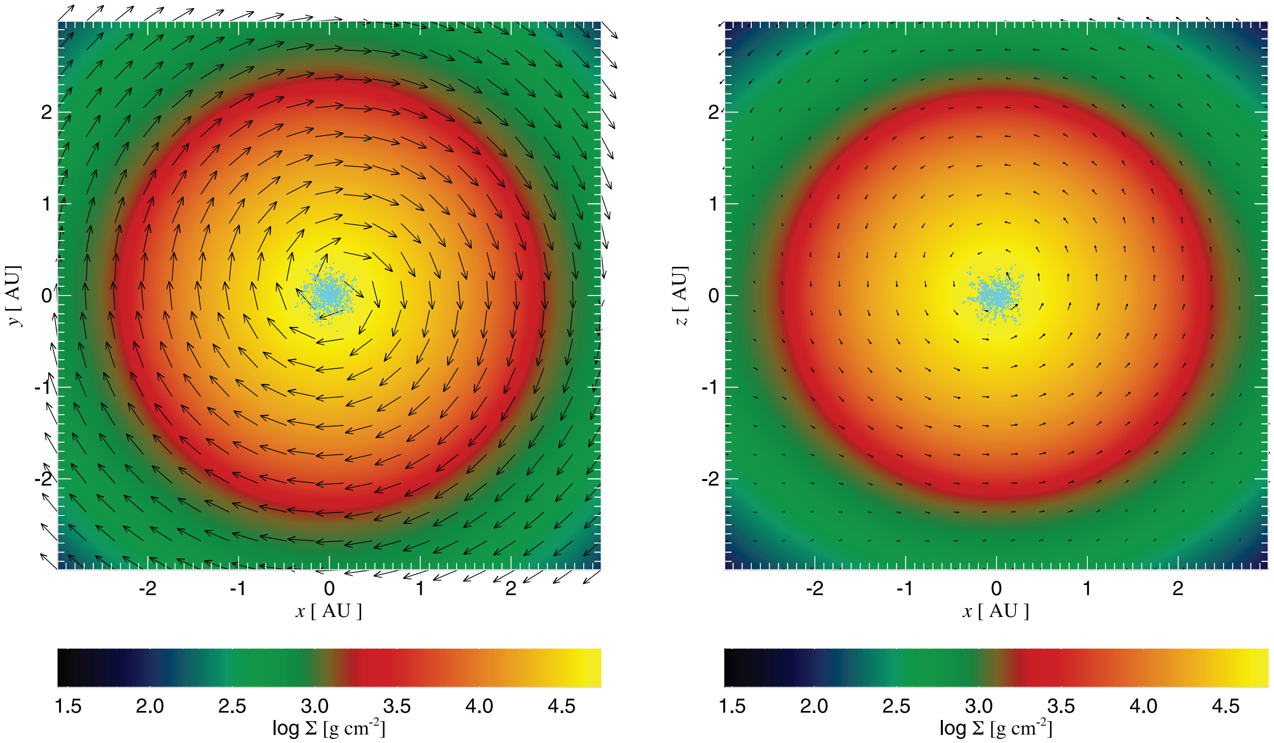

Figure 2. Left: same embryo at same time as in Fig. 1 but at smaller scales and using 'solid body rotation' normalization for velocity vectors. The near constancy of the magnitude of the velocity vectors indicates that the embryo rotates as a solid body. Right: edge-on projection of same embryo. Note the flattened Saturn-like shape of the envelope. The scaling of velocity vectors in this panel is slightly increased for improved visibility of the flow directions.

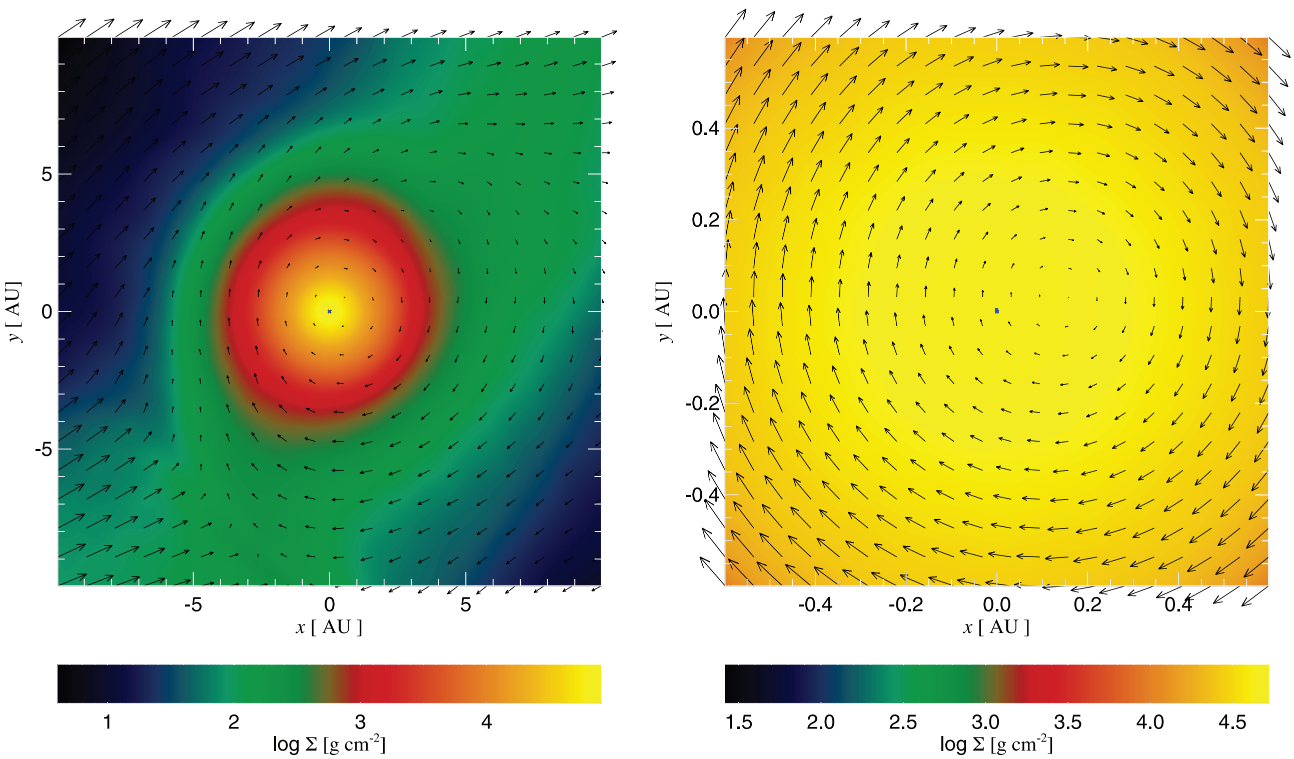

Figure 3. Top projections of the embryo closest to the star (located about 40 au in the south-west direction in the figure). Left: extended view, showing that the embryo is disturbed by the interactions with the parent star and other embryos. Right: zoom in on the same embryo. The figure is centred on the 'super-Earth' core (see Cha & Nayakshin 2010). Note the offset between the gas envelope's centre of rotation and the super-Earth location.

period of an embryo is

$$T_{\min,0} = 2\pi\Omega_{\rm br}^{-1} = 7 t_4^{-3/4} m_1^{-1/2} \ \text{yr}. \tag{3}$$

The minimum angular frequency is likely to be the angular frequency of disc rotation at the location where the embryos are born. This corresponds to the maximum spin period of

$$T_{\max,0} = 10^3 \ R_{100\,\rm au}^{3/2} \ \text{yr}. \tag{4}$$

Typical rotation period of an embryo is then $T_{\rm rot,0} \sim 100$ yr.

Now let a rocky planet of mass $M_{\rm p}$ to be formed by a direct gravitational collapse of a solid-dominated region, such as the 'grain cluster' (Nayakshin 2010c). The dust density, $\rho_{\rm d}$, of such regions may be higher than that of the gas by the factor of up to $f_{\rm g}^{-1/2} \sim 10$, where $f_{\rm g}$ is the mass fraction of dust in the embryo. For typical opacity values this implies the dust densities in the range of 10^{-9} to 10^{-7} g cm^{-3}. The specific angular momentum of the collapsing fragment is $\sim \xi_{\rm rot}\Omega_0 \ R_{\rm fr}^2$, where $R_{\rm fr} = (3M_{\rm p}/4\pi\rho_{\rm d})^{1/3}$ is the linear dimension of the fragment.

The specific angular momentum of a rocky planet at birth is that of the material that made it, and thus the rotation rate of the rocky planet is

$$T_{\rm p} = T_{\rm rot,0}\left(\frac{\rho_{\rm d}}{\rho_{\rm p}}\right)^{2/3} . \tag{5}$$

As $T_{\min,0} < T_{\rm rot,0} < T_{\max,0}$, we arrive at the following estimate of the natal rotation period of rocky planets:

$$0.25 \ t_4^{-3/4} m_1^{-1/2} \left(\frac{\rho_{-8}}{\rho_{\rm p}}\right)^{2/3} < T_{\rm p} < 41 \ R_{100\,\rm au}^{3/2} \left(\frac{\rho_{-8}}{\rho_{\rm p}}\right)^{2/3} , \tag{6}$$

in hours, where $\rho_{\rm d} = 10^{-8}\rho_{-8}$ g cm^{-3}. Alternatively, writing $T_{\rm rot,0} = T_{\min,0}\,\xi_{\rm rot}^{-1}$,

$$T_{\rm p} = 2.5 \ \frac{0.1}{\xi_{\rm rot}} \ t_4^{-3/4} m_1^{-1/2} \left(\frac{\rho_{-8}}{\rho_{\rm p}}\right)^{2/3} . \tag{7}$$

Now the shortest possible rotation period for a planet of density $\rho_{\rm p}$ is actually

$$T_{\rm break} = 2\pi(3/4\pi G\rho_{\rm p})^{1/2} \approx 1.5 \tag{8}$$

hours for $\rho_{\rm p} = 5$ g cm^{-3}. This is longer than the minimum period estimated in equation 6. This implies that for the most rapidly rotating embryos the direct gravitational collapse formation route for rocky planets is limited by the angular momentum effects. The initial configuration of rocky planets may thus be oblate spheroids, or fragmentation may result in binaries (see Section 5.2).

So far we considered formation of the solid core by a single gravitational collapse episode of a large dust reservoir. If further core growth continues by accretion of small (cm-sized) solids well coupled to the gas (as in the 1D models of Nayakshin 2010b), then that process could slow down the planet's rotation. If the core's growth is dominated by collisional impacts of larger solids, say 10 km or more, then these may be shown to be decoupled from the gas, as the gas-solid friction is unimportant for such large objects. The result – a spin-up or spin-down – would then depend on the balance of the flows of solids striking the planet with prograde or retrograde angular momentum (as in 'standard theory', see Giuli 1968; Harris 1977). In general we would expect further solid accretion to slow down the initially high spin of rocky planets.

4 ROTATION OF GIANT PLANETS

We now assume that for gas giant planets the solid core's mass is small compared with the total planet's mass. If core's mass is a significant contributor then the arguments of the previous section apply and hence the planet is likely to be rapidly rotating at birth.

The maximum specific angular momentum of gas accreting on to the growing giant planet of mass $M_{\rm p}$ can be estimated as $J_{\rm p} \sim \Omega_0 R_{\rm A}^2$, where Ω_0 is the angular frequency of the giant planet's embryo, and $R_{\rm A}$ is the accretion radius defined by $R_{\rm A} = 2GM_{\rm p}/c_{\rm s}^2$, where $c_{\rm s}^2$ is the sound speed in the embryo. This estimate would be correct if gas accretes on to the planet in a Bondi (1952)-like manner, so that beyond $R_{\rm A}$ the gas moves radially inward subsonically, with gas density and pressure deviating little from its values at infinity, whereas gas inside the accretion radius plunges on the accretor in a free fall. If the flow is deterred by angular momentum barrier at intermediate radii or by thermal effects due to energy release by the planet, then viscous torques are likely to carry some angular momentum away as in an accretion disc (Shakura & Sunyaev 1973).

Accordingly, we estimate that the minimum spin period of gas giants at birth is

$$T_{\rm giant} \geq T_{\rm rot,0}\frac{R_{\rm p}^2 c_{\rm s}^4}{(2GM_{\rm p})^2} = 3.3 \ T_3^2 m_{\rm p}^{-4/3}\rho_{\rm p}^{-2/3}\frac{T_{\rm rot,0}}{100 \ \rm yr} , \tag{9}$$

where T_3 is the embryo's temperature in 10^3 K, $T_{\rm rot,0}$ is the embryo's rotation period, $m_{\rm p}$ is the planet's mass in Jupiter masses, and $\rho_{\rm p}$ is the planet's mean density. The fastest rotation is again comparable to the he breakup period (for Jupiter, $T_{\rm br} \sim 2.9$ h). Hence the gas accretion estimate also predicts a rather fast initial rotation, although with a range of uncertainties possible due to a non-linear physics of envelope accretion (e.g. Pollack et al. 1996).

5 CONSTRAINTS FROM THE SOLAR SYSTEM

5.1 Rotation of planets

Five out of nine Solar system planets rotate rapidly in the prograde fashion, that is, in the direction of their revolution around the Sun (the Sun spins in the same direction too). The exceptions are: the two inner rocky planets, Mercury and Venus, whose spins are thought to have been strongly affected by the Sun; Pluto, the dwarf planet with a weight of just a fifth of the Moon; and Uranus, whose orbit is inclined at more than 90° to the Sun's rotational axis. Therefore, out of the major eight planets not strongly affected by the Solar tides, the only exception to the prograde rotation is Uranus. With exception of the two inner planets, the rest spin with a period of between about half a day and a day. These spin rates are large: increasing them by a factor of a few to a few ten would tear the planets apart by centrifugal forces.

The origin of these large and coherent planetary spins is difficult to understand (e.g. Dones & Tremaine 1993) in the context of the 'classical' Earth assembly model (e.g. Wetherill 1990). In this model rocky planets grow by accretion of smaller rocky fragments. As terrestrial planets are physically very small, e.g. $R \lesssim 10^9$ cm, compared with dimensions of the disc (their orbits), one expects that the accretor should receive nearly equal amounts of positive and negative angular momentum. The final spin is a result of a delicate cancellation of these positive and negative angular momentum impacts. Not surprisingly, the result is highly sensitive to the assumptions about the orbits of the bodies accreting on the protoplanet Giuli (1968), Harris (1977). For this reason, the large spins of Earth and Mars are most naturally explained by one or a few 'giant' planetesimal impacts (Dones & Tremaine 1993). However, such impacts would have to be very special to give the Earth and the Mars similar spin directions also closely matching that of the Sun.

In the context of the tidal downsizing scenario, as we argued above, most of the planets would rotate coherently, with exception of those whose parent embryos have undergone direct collisions or close passages of other embryos. Therefore the rotation rates and directions of the Earth and the Mars would be the norm rather than exception in this picture. The rotation pattern of gas giants in the Solar system may be explained in a similar fashion but due to accretion of gas on to the solid cores (see Section 4).

5.2 The origin of the Moon

The subject of planetary rotation closely sides with that of formation of planetary satellites. By the ratio of the mass to that of the primary planet, the Moon is the heaviest satellite amongst the major Solar system planets. The Moon is generally believed to have been formed due to a giant impact of a large solid body on the Earth (Hartmann & Davis 1975; Canup & Asphaug 2001). Numerical simulations of giant impacts indicate that the Moon would have been mainly ($\sim$80 per cent, see Canup 2008) made of the impactor (named Theia).

Various composition measurements indicate that the mantle and the crust of the Earth and the Moon are very similar (see a list of references in de Meijer & van Westrenen 2009). In fact, even the oxygen isotope composition of the two bodies were measured to be similar which initially appeared to be consistent with the idea of Theia forming very nearby to Earth (Wiechert et al. 2001). However, more recent oxygen isotope ratio measurements of lunar samples reveal an oxygen isotope composition that is not just similar but is indistinguishable from terrestrial samples, and clearly distinct from meteorites coming from Mars and Vesta, which motivated suggestions of complicated and highly efficient mixing processes during the hypothesised Earth–Theia collision (Pahlevan & Stevenson 2007).

We shall now consider these observational facts in the context of the tidal downsizing scenario. Perhaps Theia, the body that struck the proto-Earth, could have been formed inside the same giant planet embryo that formed the Earth, explaining the compositional similarities.

In addition, tidal downsizing picture also allows for a more optimistic look at the the famous fission hypothesis by George Howard Darwin (see e.g. Binder 1974). There is not enough angular momentum for the proto-Earth for fission to occur (e.g. for a review see Boss & Peale 1986) in the standard planetesimal accretion theory. The tidal downsizing hypothesis does have enough angular momentum, as we argued in Section 3. On the other hand, we calculate that the natal angular momentum of the Earth rotating near the breakup limit would be about a factor of 3 higher than the present day value in the system. A mechanism to get rid of the angular momentum would then be required in this picture. Assuming that the excess angular momentum is carried away by rocky bodies or gas with angular momentum (with respect to the Earth) equal to that at the Hill's radius of the Earth would require as much as 1/3 Earth masses of material. This is however not large with respect to the original giant envelope mass, and thus should not be ruled out outright.

Finally, fast rotation of the 'grain cluster' of solids (see Nayakshin 2010c) may prevent its condensation into a single body. Additionally, referring back to Fig. 3 where the super-Earth is offset from the rotational centre of the gas embryo, it is not impossible that in such a case a second core is born in the rotational centre, creating a binary solid-core system. Further work is needed to test which of the three points of view, if any, could explain the data, but it appears that forming the parent bodies of the Earth and the Moon inside the same embryo would help to explain the extraordinary degree of oxygen isotopes similarity between them.

5.3 Other constraints from the Solar system

The referee of this paper has pointed out that tidal downsizing hypothesis does not currently have explanations for at least the following observations of the Solar system: the Late Heavy Bombardment event, the exact chemical composition of the rocky inner planets, and the orbital evolution of the outer giant planets. These issues are outside of the scope of this paper, but we hope to clarify them in our future work.

6 CONCLUSIONS

In this short article we estimated the rotation rate of planets, both terrestrial and giant, in the context of the tidal downsizing hypothesis for planet formation. We showed that such planets could potentially be rotating near their breakup limit at formation, although there are mechanisms for lowering the initial spins. The default direction of the spins coincides with that of the parent disc. This may explain the fast and coherent rotation pattern of most of the Solar system planets. Exceptions to the coherent rotation may be due to embryo–embryo interactions that appear to occur frequently in the simulations. We also argued that the Moon could have formed inside the same parent embryo as the Earth, explaining compositional similarities between the two bodies.

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REFERENCES

Binder A. B., 1974, Moon, 11, 53
Boley A. C., Hayfield T., Mayer L., Durisen R. H., 2010, Icarus, 207, 509
Bondi H., 1952, MNRAS, 112, 195
Boss A. P., 1998, ApJ, 503, 923
Boss A. P., Peale S. J., 1986, in Hartmann W. K., Phillips R. J., Taylor G. J., eds, LPI Conf. Proc., Origin of the Moon. LPI, Huston, TX, p. 59
Canup R. M., 2008, Icarus, 196, 518
Canup R. M., Asphaug E., 2001, Nat, 412, 708
Cha S.-H., Nayakshin S., 2010, preprint (arXiv:1010.1489)
de Meijer R. J., van Westrenen W., 2009, LPI Sci. Conf. Abstracts Vol. 40, LPI Technical Report. LPI, Huston, TX, p. 1847
Dones L., Tremaine S., 1993, Icarus, 103, 67
Giuli R. T., 1968, Icarus, 8, 301
Harris A. W., 1977, Icarus, 31, 168
Hartmann W. K., Davis D. R., 1975, Icarus, 24, 504
Lubow S. H., Seibert M., Artymowicz P., 1999, ApJ, 526, 1001
Nayakshin S., 2010a, MNRAS, 408, L36
Nayakshin S., 2010b, preprint (arXiv:1007.4165)
Nayakshin S., 2010c, MNRAS, 408, 2381
Pahlevan K., Stevenson D. J., 2007, Earth Planet. Sci. Lett., 262, 438
Pollack J. B. et al., 1996, Icarus, 124, 62
Shakura N. I., Sunyaev R. A., 1973, A&A, 24, 337
Vorobyov E. I., Basu S., 2006, ApJ, 650, 956
Wetherill G. W., 1990, Annu. Rev. Earth Planet. Sci., 18, 205
Wiechert U. et al., 2001, Sci, 294, 345

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