have struggled to explain how Uranus and Neptune formed at their present locations in the Solar System, because at such distances from the Sun the nebular disk density would have been low, and so the time required for these planets to grow is thought to be longer than the age of the Solar System.

The Thommes *et al.*[1] model postulates that the four giant planets started out as rocky cores in the Jupiter–Saturn region, and that the cores of Uranus and Neptune were violently tossed out by gravitational scattering from Jupiter and Saturn, which had already accreted large amounts of gas. In the simulations, the ejected planets remain in highly chaotic orbits for a short period of time (a few hundred thousand years), after which they settle down (by means of friction with the nebular disk) and gradually migrate out to their present, nearly circular orbits. The authors start their simulations with four cores embedded in a narrow zone of the solar nebula, and find that in 50% of their trials the giant planets end up more or less where they are now.

The model is unusual in suggesting that all four giant planets originated in the same region of the solar nebula — within a ring 5–10 astronomical units from the Sun (1 AU = Sun–Earth distance). This is substantially narrower than previous estimates of 10–20 AU for the birthplace of Uranus and Neptune[3], and far inside their current orbits at 19 and 30 AU, respectively. Because the nebular disk density and orbital rotation is much higher at 5 AU than at 30 AU (ref. 4), the timescale for growing planetary cores is much reduced in this model, and so provides a solution to part of the mystery of how Uranus and Neptune formed. The solution is only partial because one still needs to explain how the Jupiter and Saturn cores accreted large amounts of gas whereas Uranus and Neptune did not.

The biggest remaining question is how realistic is the initial state. For example, it is likely that the violent character of the migration would be damped by gas-drag effects and the self-gravity of the nebular disk, both of which have been neglected in the numerical model. I find it conceivable that a process leading to the formation of a system of planetary cores embedded in a protoplanetary disk would self-regulate to remain 'marginally stable' throughout its evolution as the disk mass is gradually exhausted. This means the planets would separate relatively slowly rather than through violent dynamical instabilities as proposed by Thommes *et al.*[1]. Further advances in numerical and analytical modelling of the evolution of protoplanetary disks will be needed to address this uncertainty.

Armitage and Hansen[2] consider the evolution of giant protoplanetary disks around other stars — disks much more massive than our solar nebula is thought to have been — in which a giant planet forms quickly, possibly by means of a gravitational instability in the disk[5]. Using computer simulations of disk–planet interactions, the authors find that starting with a marginally stable disk, the embedded giant planet quickly clears a partial gap and also creates a spiral density pattern in the surrounding disk material. The planet accretes mass rapidly through the spiral arms, and when the planetary mass reaches four-to-five times Jupiter's mass the disk rapidly fragments around sites of orbital resonances (these are especially unstable orbits in the disk due to the planet's perturbation). Such 'triggering' of planet formation by Jupiter at its orbital resonances has been suggested previously for our Solar System[6]; the work by Armitage and Hansen represents the first demonstration of this process in a self-consistent computer simulation.

In this simulation, the disk fragments also accrete mass rapidly to become giant planets, with final masses greater than Jupiter. This process yields several giant planets in close proximity to each other, starting out in nearly circular orbits at large distances from the star (several astronomical units). The authors suggest that such a system would subsequently evolve by way of mutual gravitational scattering and eventually result in a planetary system consisting of one or more massive planets in eccentric orbits (although this latter process is not modelled in their simulation). Examples of such systems have been found in recent extrasolar planet searches[7,8].

As with the Thommes *et al.* model, the overriding uncertainty in these computer simulations is the plausibility of the initial state, in this case a single giant planet embedded in a massive protoplanetary disk. Are there reasonable evolutionary paths during star formation that lead to such systems? We also don't yet know whether the disk fragments produced by the simulations actually grow into planets rather than breaking up again; the simulations need to be carried out for longer (with all the necessary physics included) to address this question. Nonetheless, our understanding of planet formation is so limited that plausible new ideas are always welcome. ■

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Daedalus

Citing to infinity

Lev Landau once proposed a logarithmic ranking for physicists. Einstein he placed in class 0.5, Dirac and Heisenberg in class 1.0, and Landau himself, modestly, in class 2.5. These days we have an objective ranking tool, the citation index. Each scientist is judged by the citations his papers gain in other scientists' papers. This criterion dominates the struggle for grants, tenure, promotion and reputation. Daedalus argues that Internet publication now permits an even greater step forward.

When all scientific papers are stored in, and accessed from, one vast computer database, it will be easy to extract all the citations attracted by a paper at any moment. Even better, the citations credited to each of the citers could also be extracted. Clearly it is more prestigious to be cited by a prolific author with many citations to his own credit, than to be cited by a citationless nobody. And these second-order citations could be judged in their turn by the quality of their third-order citers. So Daedalus is refining the business of citation scoring. His 'multi-order citation score', MOCS, will trace the citation tree of a paper to notional infinity, giving each successive order of citations a decreasing weighting.

The mathematical form of MOCS will need careful thought. It must be well-behaved, immune from strong perturbations propagated from distant anomalies in the citation tree, or instabilities from tangles of self or mutual citation. Such citations will be given, if not quite zero, at least a low weighting. The eccentric theorist who cites only himself, the author who builds endlessly on one little finding, the small, mutually back-scratching clique, cannot be allowed to gain unduly from their efforts. And logical tricks like citing a paper within itself, which might generate an infinite MOCS, will need to be identified and excluded. A multi-authored paper will divide its total MOCS among the authors, possibly in accordance with weightings declared within that paper.

Once properly optimized, MOCS will transform the struggle for scientific fame and recognition. Sadly, it will also give ammunition to those wicked sociologists who claim that science is merely a game for distributing prestige and grants among competing players. **David Jones**

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