Large Scattering Events and the Formation of Planetary Systems

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Abstract. In the nucleated instability picture of gas giant formation, the final stage is the rapid accretion of a massive gas envelope by a solid core, bringing about a tenfold or more increase in mass. This tends to trigger the scattering of any nearby bodies, including other would-be giant planet cores; it has been shown in past work that the typical outcome is an outer planetary system very similar to our own. Here, we show that the gravitational scattering accompanying the formation of gas giant planets can also produce, in some cases, outer planets with semimajor axes much larger than those in the Solar System, and eccentricities which remain high for tens of millions of years. Rings, gaps and asymmetries detected in a number of circumstellar dust disks, which hint at the presence of embedded planets at stellocentric distances far beyond where planet formation is expected to occur, may be connected to such a scenario.

1. The model

During the lifetime of the nebular gas, a protoplanetary disk with the profile of the standard Hayashi (1981) model, and a surface density several times the minimum, will tend to produce bodies large enough to serve as the solid cores of giant planets, i.e. around 10 M⊕ in mass, in an annulus roughly corresponding to the the Jupiter-Saturn region (Thommes, Duncan and Levison, hereafter TDL, 2002b). The inner bound results from the increase of the isolation mass (e.g., Lissauer 1987) with stellocentric distance; inside some radius, the final protoplanet masses are too small. The outer bound comes about from the increase of accretion timescale with stellocentric distance; beyond some radius, protoplanets cannot grow large enough during the lifetime of the nebular gas (~10 Myrs, e.g., Strom, Edwards and Skrutskie 1993).

In a system which forms gas giant planets by nucleated instability (e.g., Pollack et al. 1996), one of the giant protoplanets will eventually acquire a massive gas envelope. Using numerical simulations, TDL (1999, 2002a) demonstrated that this sudden mass increase of one of the protoplanets (by an order of magnitude or more over ~10⁵ years) tends to destabilize the orbits of its neighbours, scattering them outward onto eccentric orbits. With most of its orbit now embedded in the still accretionally unevolved outer planetesimal disk, a scattered protoplanet then experiences dynamical friction (e.g., Stewart and Wetherill 1988), which damps its eccentricity down again. The end result is
most often a protoplanet on a nearly circular orbit, albeit with a semimajor axis significantly larger than it originally had. In this way, a planetary system resembling the configuration of the giant planets of the Solar System is commonly produced, with the scattered and recircularized protoplanets standing in for Neptune, Uranus, and Saturn; the latter needs to acquire its own (less) massive gas envelope before the dispersal of the nebular gas, in order to match the Solar System.

In some of the simulations performed in the above work, protoplanets were so strongly scattered after “Jupiter”’s gas accretion phase that that they ended up with apocenter distances of hundreds of AU and ultimately became unbound from the Sun. However, in all these runs the planetesimal disk was only modeled out to a radius of 60 AU. Here, we investigate the possibility that, given a larger (and thus likely more realistic) planetesimal disk, such bodies might be retained on stable orbits. This would result in planetary systems with giant planets at stellocentric distances far beyond where significant accretion ought to have taken place.

2. Numerical simulations

The simulations performed here are very similar to those described in TDL (1999, 2002a). Four bodies, each of mass 10 M⊕—thus large enough to serve as giant planet cores—are initially placed on stable, circular orbits between about 5 and 10 AU. Beyond this is a disk of small planetesimals, each of mass 0.1 M⊕. Though such (Mars-mass) planetesimals are unrealistically large, the eccentricity damping rate due to dynamical friction depends principally on the overall density of the disk, rather than on the mass of the individual bodies which make it up, as long as the protoplanet eccentricities are high (details are given in TDL2002a). The main difference with respect to the earlier simulations is that the planetesimal disk extends not to 60 AU, but to 200 AU. Once the simulation commences, the mass of the innermost protoplanet is increased to 310 M⊕, approximately the mass of Jupiter, over 10⁵ years, simulating the accretion of a massive gas envelope to form the first gas giant. Fig. 1 shows the end states, after 10 Myrs, of a set of ten simulations. Initial conditions differ only in the orbital phases of the four protoplanets, which are randomly generated. The simulations disk is initially given the surface density of the minimum-mass protosolar disk, 30(r/1 AU)⁻³/₂ g/cm² (Hayashi 1981). In four of the cases, the end result is a system qualitatively similar to the outer Solar System: three protoplanets (gasless proto-Saturn, Uranus and Neptune) are on well-spaced, low-eccentricity orbits between about 10 and 30 AU. In three other cases, one of the protoplanets has been lost, either by becoming unbound, or by merging with another body. However, there are two cases, Runs C and G, where one protoplanet has been scattered much further, ending up with a semimajor axis greater than 200 AU, and between 100 and 200 AU, respectively. In both instances, the protoplanet retains a high eccentricity (0.7 - 0.8) even after 10 Myrs. This is because the dynamical friction timescale is inversely proportional to the density of the planetesimal disk, which falls off with stellocentric distance. For this same reason, simulations with more massive planetesimal disk show a lower incidence of such large scattering events; the higher density of planetes-
imials makes for stronger dynamical friction, and thus a stronger tendency for planetary systems to be relatively compact, like our own.

3. Discussion

A number of spatially resolved debris disks show features which may result from the influence of unseen (giant) planetary companions. The problem is, these features are seen at large stellocentric distances, far beyond where giant planet formation is expected to have occurred. Examples are the dust disks around HD 141569 (Weinberger et al. 1999), HR 4796A (Schneider et al. 1999), and HD 163296 (Grady et al. 2000). These systems possess, respectively, a 40 AU wide gap centered at a radius of 250 AU, a dust ring of radius 70 AU, and a 50 AU wide gap at a radius of 325 AU. A seemingly less extreme case is Vega, which displays two dust emission peaks 80 AU from the star. These have been successfully modeled as concentrations resulting from the trapping of dust particles (which spiral inward due to radiation pressure and Poynting-Robertson drag) in exterior mean-motion resonances with an eccentric gas giant (Wilner et al. 2002). A model with a 3 M_{Jupiter} planet having a semimajor axis of 40 AU and an eccentricity of 0.6 has been demonstrated to give a good match to the observations.

Large scattering events like the ones described here constitute a mechanism by which giant planets might, after forming at orbital radii similar to those of Jupiter and Saturn, be transported out to distances comparable to those of the disk features described above. This offers one way to avoid the difficult problem of explaining the formation of giant planets at 100 AU or more, just as the original model avoids the formation timescale problem of Uranus and Neptune in our Solar System. However, extending the model in this way introduces two principal problems. First, the mechanism works for “ice giants”—Uranus/Neptune
mass bodies—not for bodies the mass of gas giants. In the latter case, one
would be dealing with a scenario more akin to that described by Rasio and Ford
(1996), in which multiple gas giants scatter each other. Eccentricities of any
strongly-scattered planets would likely remain high indefinitely, since at $\gtrsim 100$
AU the mass in planetesimals is very small compared to that of a gas giant.

The other problem is that, as stated above, the probability of a very large
scattering event decreases with the mass of the exterior planetesimal disk. A
minimum-mass disk allows scattering of ice giants to semimajor axes of order
100 AU to occur readily, but a minimum-mass disk is also unlikely to produce
giant planets in the first place. This will be a problem if giant planets at large
stellocentric distances turn out to be ubiquitous. The above-described features
do seem to be common, given that they appear in a significant fraction of the
(small number of) disks that have been directly imaged thus far. In order to
simultaneously form such large bodies and allow them to be readily scattered
to large distances, one must invoke a steep density profile, or a local density
enhancement where the giant planets form.

The above considerations provide ways in which the scenario proposed here
can, in the near future, be observationally tested. First, newly-formed gas giants
at large stellocentric are hot enough to be detectable, in principal, by current
searches (e.g., Macintosh et al. 2000). Positive detections would immediately
rule out the above mechanism as the sole source of planets at large orbital
radii. Conversely, the continued absence of such detections would suggest that
whatever is producing the features we see is smaller than a gas giant. Or,
indeed, the features may have nothing to do with planets at all. Secondly, future
observations will give us a better idea of the typical masses and density profiles of
dust disks and, by extension, of the characteristics of the underlying planetesimal
disks. It will then be easier to assess the likelihood of large scattering events. In
particular, it will be interesting to see what correlations, if any, exist between
disk mass and the occurrence rate of rings, gaps and asymmetries at large radii.

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