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Orbital evolution of eccentric, gas-accreting protoplanets

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Distant giant exoplanets with nearly circular orbits have recently been detected by direct imaging observations. The formation of these planets is not accounted for by the standard scenario of planet formation. According to this scenario, a protoplanet is first formed by the accretion of planetesimals. Once its mass exceeds a critical mass, runaway accretion of gas starts and it becomes a giant planet. However, at large distances from the central star, the long timescale for the accretion of planetesimals prevents any protoplanet from reaching this stage before the gas in the disk has disappeared. Another scenario has thus been proposed by Nagasawa (2008): it involves a formation of a giant planet close to the star followed by scattering by another giant planet. The planet that has been scattered outward can thus reach large distances, but not on a circular orbit.

We propose a new scenario for the formation of distant and circular giant planets: We first assume that while still in the gas disk phase, a protoplanet is scattered outward by an inner giant planet. We then show that the orbit of the protoplanet can become circular because of a damping of the eccentricity due to its accretion of gas. Since the sum of orbital and collisional energy is conserved, the semimajor axis must decrease while the planet accretes mass.

We provide an analytical solution to the orbital evolution assuming that the gas accretion rate remains constant along the planet's orbit, but can evolve slowly as a function of the planetary mass. We average the energy and angular momentum provided to the planet by gas accretion over each orbit to obtain differential equations for the orbital elements. The time-evolution of the semimajor axis and eccentricity are obtained by integrating of these equations.

We find that even highly eccentric protoplanets (e=0.99) can evolve into nearly circular orbits by gas accretion. When evolving from a protoplanetary mass of 10 Earth masses to a mass of Jupiter, we find that the final eccentricity is always less than 0.05. The inward migration of the protoplanet directly depends on the eccentricity, and it limited to a semi-major axis of about half its initial value. This scenario therefore can explain the orbits and masses of the giant exoplanets discovered by imaging techniques.

Finally, we examine the orbital evolution of a giant planet in a truncated gas disk. We derive a relation between the disk radius and the final semimajor axis of the giant planet. We will discuss the relation in detail and apply it to various disk model.

Keywords: exoplanet, distant jupiters in circular orbits, planetary formation, gas accretion, orbital evolution