Formation of Extrasolar Planet TOI-849b in a Quiescent Disk. I. Mosqueira[1], [1]San Jose State University, Department of Physics and Astronomy, 1 Washington Square, San Jose, CA 95192 (Ignacio.Mosqueira@sjsu.edu).

Introduction: Recent work reports the observation of the planet TOI-849b with a radius smaller than Neptune's, about forty Earth masses, and located in the so-called Neptune desert [1]. These authors consider a number of possible explanations for the existence of this gas-depleted extrasolar planet that are either fine-tuned or inadequately characterized.

Cause of the fine-tuning: For decades modeling of the formation of planets has relied on the so-called α disk model despite the lack of a mechanism to sustain turbulence (see below). This is the basis of planetary population synthesis models. However, in such models the timing of the removal of the gas disk is fine-tuned. The reason is that disk removal is not an instantaneous event; even in a gas depleted disk there would be enough gas outside the feeding zone of a particular runaway core ultimately to result in the formation of a gaseous planet. That is, disk turbulence and evolution would replenish the feeding zone of the giant planet and result in significant gas accretion. The problem is that the gas disk is responsible for powering the migration and growth of close-in giant planets, but must then be ``switched off'' in order to explain the existence of gas-depleted close-in runaway cores.

Collisional fixes: Recent work discusses additional mechanisms to remove the gas envelope, such as planetary collisions [1, 2]. This claim is based on a previous collisional model indicating that giant impacts may result in gas envelope ejection [3]. However, this study also points out that the envelope is then quickly re-accreted from the nebula. Even if these studies manage to delay the collisions until after gas removal has already taken place, much more work needs to be done to robustly evaluate the outcome of such collisions. In particular, the conditions that must be met for the envelope to be ejected without core erosion or gas re-accretion, either from the nebula or resulting from the impact itself, must be clarified [1]. Indeed, care must be exercised to specify the ultimate sink for the envelope gas that was ejected during the collision. Even though such scenarios have not been ruled out, the issue remains whether more likely alternatives exist. This is the question we explore here. But before we do we are compelled to mention a couple of additional issues in order to motivate our approach.

Is there theoretical support for disk turbulence during planetary formation? While this is not the place to review the status of this field, we do point out that after sustained community effort to identify a hydrodynamic alternative to MRI to keep weakly ionized disks active we are not any closer now to attaining this goal than we were a decade ago. To wit, recently the literature has favored the possibility that the vertical shear instability (VSI) offers a potential hydrodynamic mechanism for angular momentum transport in protoplanetary disks at ~10 AU. However, even discounting issues of numerical convergence, the resulting turbulence is too weak to explain disk accretion, and decreasing the dust opacity by a factor of 10 quenches the VSI at all disk radii [e.g., 4]. Thus, the formation of protoplanets is expected to halt this (already weak) transport process.

Is there tension between extrasolar and solar planetary formation models? In the α paradigm planetary population synthesis models generically produce close-in giant planets [e.g., 2], which is clearly not true for our solar system. But this observation is often set aside based on the flawed supposition that for the solar system the so-called ``grand tack'' model suggests that Jupiter also migrated close-in to around 1.5 AU before turning around [5]. However, this assumption is based on a misunderstanding of the key constraints. The relevant issue is not only to justify the locations of both Jupiter and Saturn but also their **final masses** within a single, self-consistent model of planetary formation. The ``grand-tack'' model focuses on the mass of Mars but fails to consider the resulting mass for Saturn, which is of greater consequence in the extrasolar planet context. The problem here is that only a massive disk can drive the migration of Jupiter. But such a disk would result in the continued growth of Saturn following its proposed (fast) migration, leading to a final mass for Saturn that is much larger than its actual value [6].

Another key source of tension with the α models stems from the fact that for the solar system one must satisfy the constraints of planet and satellite formation together. To date, there are two self-consistent models for the formation of the moons of Jupiter and Saturn [7, 8, 9]. Of the two, the most promising model to explain the observations does not rely on disk turbulence to drive the evolution of the gas component [7, 8].

Planetary formation in a quiescent disk: In a weakly turbulent disk the Type I inward migration of objects of ~ 10 solar masses stalls due to the feedback effect [10, 11]. Since in the core-accretion model of planet formation such objects can form in a time comparable to their migration time, provided that the nebula is enhanced in solids with respect to solar abundances, gap-opening generically explains planet survival. The requisite solids enhancement in planet forming regions of the protoplanetary disk can be readily accommodated using dust/planetesimal inward migration without resorting to model fine-tuning.

Once a stalling core forms gap-opening occurs both due to gas accretion and because of the tidal interaction with the gas disk. The accretion of giant planets is modulated by the depletion of gas in the planet's feeding-zone. In the limit that the core accretes all the gas in its feeding zone, the final mass of the planet (in a weakly turbulent disk) is given by the gaseous isolation mass. In general, there is a competition between the disk clearing due to the planet's tidal torque and that resulting from gas accretion. Thus, in this framework we can expect that gap-opening can result in gas-depleted planetary cores. However, the presence of planetary companions plays a key role in setting the final masses of non-isolated planets, as one planet can replenish the feeding zone of its neighbor, allowing for the formation Jovian planets. In addition, planetary companions can drive planetary migration even in inviscid disks. Unlike Type II evolution powered by a yet-to-be-indentified source of global turbulence, planet-driven disk evolution naturally shuts-off for sufficiently spaced planets, and is thereby able both to migrate planets and also to ``park'' them without invoking gas disk removal fine-tuning [13, 14].

Here we investigate the implications of an inviscid disk for the formation of TOI-849b. Because such a disk would lead to the efficient formation of planetesimals, irrespective of whether the streaming instability operates or not, the growth of the solid core is taken to occur in the classical picture of Safronov. We incorporate standard corrections due to the presence of the gas component, such as drag-enhanced protoplanet capture radii. We use simple parameterized models for the gas accretion rate onto the core [see, e.g., 2], and the tidally-driven evolution of the gas disk [15]. Ultimately the gas accretion terminates on a photoevaporation/wind timescale [16], and not as a result of the viscous evolution of the disk.

Planetary core migration and merging: Even in such a simplified model, there are potentially many processes at play, such as planetary scattering, protoplanet eccentricity excitation and damping, planetary impacts, photoevaporation, hydrodynamic escape and so on. Several of these mechanisms, such as planetary scattering followed by tidal circularization, are potentially of significant interest in the present context. However, we do not intend here to simulate all of the possible pathways resulting in the formation of a gas-depleted planetary core. The goal of this research is not so much to identify the specific pathway leading to the formation of TOI-849b as it is to characterize the likelihood of its occurrence.

Here we begin the necessary task of distinguishing between scenarios that are unlikely versus those that are unrealistic. As a first step, we focus on the migration of planetary cores due to interactions with planetesimals and tidal interactions with the gas disk. To this end, we solve the equation for the gas surface density evolution by combining the equations of continuity and parametrized angular momentum deposition and transport, including parametrized gap-opening. We stress that in the framework of multiple gap-opening planetary cores it is possible for protoplanets to replenish the feeding zone of their neighbors, and also to drive their inward (or outward) migration. This possibility is of particular interest in the present context as it can result in the formation of close-in planets. In order to describe the gravitational interactions and mergers of several protoplanets we employ a statistical approach that lowers the computational cost while still producing fairly realistic distributions of eccentricities and semimajor axes of interacting planets [17].

References:

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