What does the PDS 70 system tell us about planet-satellite formation? 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: High-resolution (~20 mas) ALMA observations at a wavelength of 855 μm reveal the presence of a detached dusty circumplanetary disk (CPD) at the location of planet PDS 70 c ~34 au from the star [1]. Assuming the disk is optically thin, the authors estimate the CPD dust mass for several grain size distributions as a function of the maximum grain size from submicron to cm sizes and find a lower bound of about 0.005 $M_\oplus$ (see their Fig. 9). Earlier observations had uncovered the presence of an additional planet at ~22 au [1 and references therein], making this planetary system reminiscent of the Jupiter-Saturn pair.

PDS 70 and satellite formation: The first thing to emphasize is that the interpretation of the CPD around PDS 70 c as a moon-forming disk is likely to be correct. Therefore, it is fair to ask whether the observations can be used to rule out any of the satellite formation models in the literature. While the gas constraints derived from the ^{12}CO and HCO^+ lines remain to be published, the disk dust mass as well as the radial extent of the disk definitively rule out the compact, low surface density ``starved'' disk model. Conversely, the observations offer strong support for the quiescent solids-enhanced minimum mass (SEMM) regular satellite formation model we submitted in 2001 [2, 3, 4].

It is significant that the giant planet architecture of the solar system and that of the PDS 70 planets fits well with our **quiescent** disk models. In contrast, the α disk planetary population models generically produce close-in giant planets [e.g., 5]. Although there is an ongoing effort to allow for outward planetary migration, these scenarios are not applicable either to the solar system or to the PDS 70 planets (see below). In addition, recent observational constraints derived from the settling of mm sized grains to the disk mid-plane [e.g., 6], as well as ALMA observations of CO emission [e.g., 7] argue in favor of quiescent disks.

It is also noteworthy that the PDS 70 planets are embedded in a large-scale gap. At its inception, this framework is equally applicable to the solar system. As stated in multiple publications [e.g., 8, 9], the formation timescale of the CPD is controlled by the creation of a large scale Jupiter-Saturn gap, as are the final masses of the two giant planets themselves. Thus, the satellite systems of the giant planets should not be viewed in isolation. Likewise, in a quiescent disk model, the final masses of gaseous extrasolar planets are controlled by large scale gap formation [10, 11, 12].

Moreover, the age of the PDS 70 stellar system, the lack of an observed CPD around planet PDS 70 b, the estimated dust mass of the observed CPD around planet PDS 70 c, as well as the radial extent of the CPD dovetails with our SEMM satellite formation model [3, 4]. In this regard, it is instructive to compare the formation timescale and masses of the outermost regular satellites of Jupiter (Callisto) and Saturn (Iapetus) to the system age and to the CPD dust mass, respectively. Our SEMM model gives a formation time for Callisto of $\sim 10^6$ yrs and for Iapetus of $\sim 10^7$ yrs. The longer timescale for Saturn is due to its larger Hill radius and its smaller mass. These timescales fit very well both with the absence of an observed CPD at the location of PDS 70 b and also with the presence of a CPD around PDS 70 c. Given a stellar system age of ~5.4 Myr [13], the simplest explanation of the observations is that most of the dust mass around PDS 70 b has already been incorporated into satellites, but the CPD around PDS 70 c is still in the process of forming moons. In addition, the estimated CPD dust mass is roughly consistent with the mass of Callisto. Lastly, the radial extent of the CPD out to a fraction of the planet's Hill radius also matches our SEMM model.

However, we stress that the gas to dust ratio of the CPD is largely unconstrained at present. Therefore, it is difficult to rule out a planetesimal collisional model in which most of the mass of the disk is in the form of solids [14]. In this model, the reason for PDS 70 c to exhibit a CPD is because of the continued delivery of planetesimal fragments resulting from a giant planet induced collisional cascade. We must also point out that the SEMM model itself allows for the delivery of solids by the ablation of disk-crossing planetesimal fragments. Indeed ablation of icy and rocky planetesimal fragments provides the leading explanation for the ice-rich composition of Iapetus when compared to other regular satellites and outer solar system objects [15]. Iapetus is of interest here because it formed in the outer regions of the outer planet disk.

Finally, we draw attention to a key difference between the two planetary systems that is likely to have significant consequences for the formation of moons. Namely, the outer disk locations of the PDS 70 planets significantly lengthens the time it takes for the formation of a large scale gap. This in turn means that gap formation takes place concurrently with the formation of moons and of the CPD itself. This is in contrast with the Jupiter-Saturn system wherein gap formation takes place faster than satellite accretion, allowing for the separation of timescales [e.g., 9]. This is the subject of future work as we discuss below. But before we do we must first address the following outstanding issues.

Concerning the continued use of the α−model: Despite the lack of observational or theoretical support for intrinsic global disk turbulence at the time of planet or satellite formation the α−model prescription remains a staple of numerical studies. Consequently, in [1] there is misguided discussion of: a) a steady state attained between the gas inflow to the CPD and the accretion rate onto the planet [16]; b) a viscous disk heating contribution to the CPD; c) dust traps caused by a balance between a sub-Keplerian headwind and a viscous outflow; and d) the giant planets migrating outward in a grand-tack like scenario [16, 17]. However, these ideas are not justified. Taken in turn: a) there is no steady state attained in the process of opening a large-scale gap between the two giant planets, rather the process is dynamic; b) the inclusion of a viscous heating term leads the authors to overestimate the temperature of the disk and to underestimate the dust disk mass; c) there is no evidence that a quiescent disk is in need of such dust traps to form satellitesimals, instead gravitational instabilities [18] could be implicated; d) we turn to the proposed migration scenarios next.

Grand-tack style outward migration scenarios: A number of works have considered the possibility that the giant planet pair may have migrated inward and then outward in a viscously evolving disk [16, 17, 19]. However, the migration scenarios outlined in those studies are flawed. First, a source of turbulence that can drive the late-stage migration of fully formed gap-opening giant planets has yet to be identified. Second, the grand-tack models fail to consider the final masses of the giant planets. For the solar system, the continued growth of Saturn following its proposed migration would result in a final mass for this planet that is much larger than its actual value [20]. Third, in quiescent disks Jupiter sized giant planets can open a deep gap, thereby cutting-off the inner disk from the outer disk. Since a fully formed gap prevents the outer disk from replenishing the inner disk there would not be enough angular momentum available to propel the outward migration of Jupiter mass planets from ~1 au out to ~20 au. Fourth, even in turbulent disks self-consistent treatment of the problem requires inclusion of concurrent giant planet gas accretion. This is because planet accretion decreases the amount of gas that flows from the outer disk to the inner disk, and also because it increases the mass of the planets, thereby exacerbating the angular momentum budget issue we raised above. Fifth, such a scenario is **not** supported by the observations: a model in which the gas turbulence is strong enough to transport gas from the outer disk to the inner disk would also result in the formation of CPDs around **both** planets, not just the outer planet as observed.

Disk turbulence driven by gas inflow onto the CPD: In a Keplerian disk the stress tensor couples to both the Coriolis force and to the background shear. It is the stabilizing effect of the Coriolis term that causes the turbulence fluctuations to decay [e.g., 21]. However, in the presence of rapid inflow onto the CPD, the inflow itself provides an additional local source of free energy that can sustain the turbulence. This can be treated using LES numerical techniques. In this approach there is a subgrid model taking into account turbulence production and dissipation terms [e.g., 22]. During an early phase of CPD evolution a fraction of the energy of infall would be available as a source of free energy to sustain the turbulent kinetic energy of the disk. However, it must be stressed that this treatment is distinct from and should not be conflated with the α−model prescription. While the gas inflow onto the CPD may power an early dynamical phase of turbulent disk evolution, it can not be used to dissipate the CPD. This is the basis of our SEMM models [8].

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