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Formation of TRAPPIST-1

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Abstract

We present a model for the formation of the recently-discovered TRAPPIST-1 planetary system. In our scenario planets form in the interior regions, by accretion of mm to cm-size particles (pebbles) that drifted from the outer disk. This scenario has several advantages: it connects to the observation that disks are made up of pebbles, it is efficient, it explains why the TRAPPIST-1 planets are ∼Earth mass, and it provides a rationale for the system's architecture.

1. Introduction

TRAPPIST-1 is an M8 main-sequence star located at a distance of 12 pc. It has recently been observed to harbor seven planets, all within 0.1 au and all with radii inferred to be around $\sim 1\,R_\oplus$ [1]. From transit timing analysis the planets are consistent with a rocky composition, although solutions where planets harbor significant amounts of H_2O (ice) are also possible.

Since the stellar mass is only 8% of solar, and typical disk masses are a fraction of stellar, the TRAPPIST-1 protoplanetary disk very efficiently converted solid material into planets. TRAPPIST-1 presents a puzzle for planet formation theories, because both the *in situ* model and the *migration model* do not work very well or need extreme conditions. For *in situ* formation a very massive disk is needed. Such disks would likely be unstable and the classical formation model cannot easily explain the packed configuration. The migration scenario – where planets assemble in the outer disk, then migrate in – would fare slightly better since the disk can have a more standard size. But it offers no good explanation for the fact that the TRAPPIST-1 planets are ∼1 Earth mass, why there are seven of them, and can only produce icy planets.

2. Our model

Figure 1 sketches our model for the formation of the TRAPPIST-1 planets [7]. Pebbles form in the outer disk by coagulation of dust grains, until they start to drift by aerodynamical drag. However, this growth+drift occurs in an inside-out fashion, which does not result in strong particle pileups needed to trigger planetesimal formation by, *e.g.*, the streaming instability [3]. (a) We propose that the H_2O iceline ($r_{\rm ice} \approx 0.1$ au for TRAPPIST-1) is the place where the local solids-to-gas ratio can reach ∼1, either by condensation of the vapor [9] or by pileup of ice-free (silicate) grains [2, 8]. Under these conditions planetary embryos can form. (b) Due to type I migration, embryos cross the iceline and enter the ice-free region. (c) There, silicate pebbles are smaller because of collisional fragmentation. Nevertheless, pebble accretion remains efficient and growth is fast [6]. (d) At approximately Earth masses embryos reach their *pebble isolation mass* – the mass where a shallow gaps in the gas disk is opened that arrests further pebble accretion [4]. The planet then migrates further to the inner disk edge r_c, the stellar magnetospheric cavity radius. Meanwhile a second embryo forms at the iceline, which undergoes an evolution similar to its elder sibling. Stages (a)–(d) repeat until the pebble flux from the outer disk subsides.

(e) Convergent migration of planets in dissipative media like gas-rich disks, causes them to be trapped in resonances. We assume that planets get trapped in first order mean motion resonances, close to the period ratios in which they are presently observed. The system remains in this state until the disk starts to decay.

However, the period ratios of planets b/c and c/d are currently not close to any first-order integer commensurability. We propose that the current architecture is set during the disk clearing phase through a processes named *magnetospheric rebound* [5]. Simply put, it means that the inner disk edge (r_c) expands as the disk loses mass. In principle, disk-planet interaction causes the inner planet to be tied to the expanding r_c, but this coupling will break when the expansion of r_c is too rapid. We have tuned the parameters of the magnetospheric rebound model in order to match the architecture of TRAPPIST-1. This implies that there are two dispersion phases: (f) an initial phase where r_c stalls between planets c and d, after which the system mi-

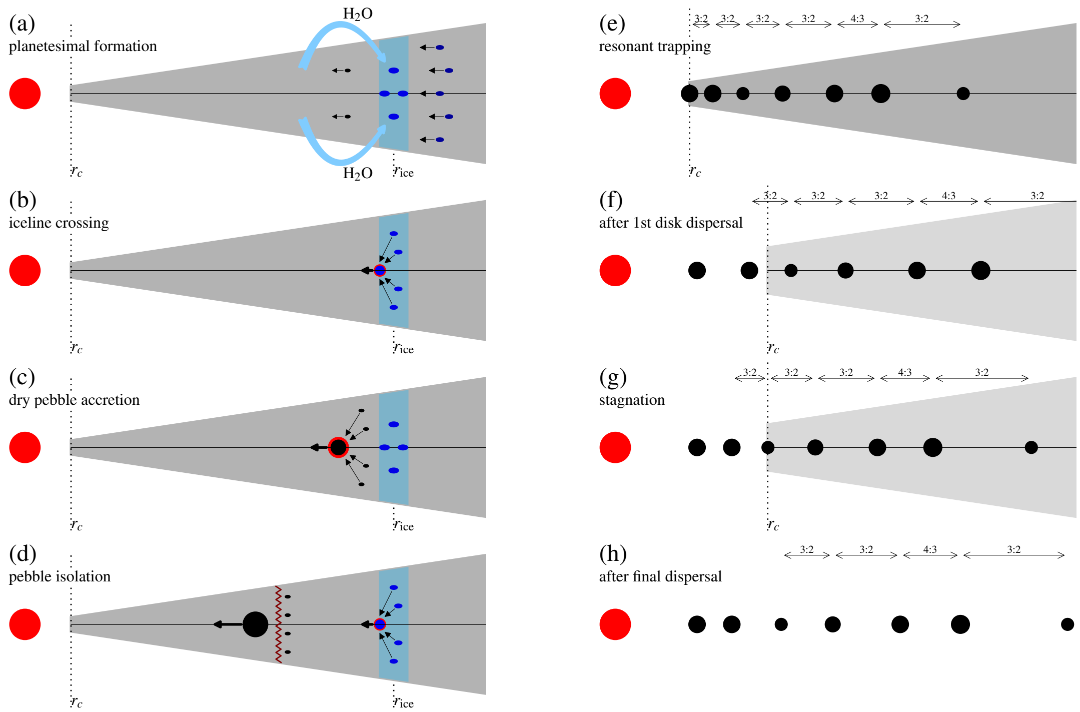

Figure 1: Sketch of the formation of TRAPPIST-1. Described in the main text.

grates in again, such that planet d now coincides with r_c (g); and a final dispersion phase, which moves c/d out of resonance, because of divergent migration, resulting in a configuration that by-and-large resembles the present one (h).

3. Implications and Outlook

In our proposed scenario it is not the planets but the planetary building blocks that migrated. Many M-stars observed with *Kepler* feature such a concentration of close-in planets, similar to TRAPPIST-1. However, such a scenario would be hard to envision when the pebble flux is blocked by, for example, a giant planet *beyond* the H_2O iceline. Hence, within the context of the proposed scenario, close-in planets would preferentially form in systems that failed to form a gas giant. On the other hand, in systems where a giant planet did form early planet formation proceeded towards outer gas and ice giants.

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