A BRIEF DESCRIPTION OF THE GRAND TACK AND NICE MODELS

The history of giant planets is made of three main phases: (i) the formation phase, which has to occur in a disk of gas, given that most of the giant planet mass is made of hydrogen and helium; (ii) a migration phase, where the giant planet orbits change widely due to the gravitational interaction with the gas; (iii) a late evolution phase, occurring after gas dispersal, during which the orbits of the giant planets can still evolve significantly, mainly due to their interactions with a remnant planetesimal disk and with each other. In the past, we studied the latter two phases, whereas this proposal aims to attack the first one. Here we briefly describe our past results, which build the "picture" illustrated in Fig. 1.

Our "Grand Tack" model (Walsh, Morbidelli, Raymond et al., Nature, 2011) describes the migration of Jupiter and Saturn in the gas disk (often called the Solar Nebula). The model is based on previous hydro-dynamical simulations, which showed that the migration of fully-formed Jupiter and Saturn can be divided into two regimes: (1) Jupiter alone migrates inwards (Type II migration: Lin & Papaloizou, 1986) and (2) Jupiter and Saturn typically migrate *outward*, locked in a 3/2 mean motion resonance (where the orbital period of Saturn is 3/2 that of Jupiter; Masset & Snellgrove, 2001; Morbidelli & Crida, 2007; Pierens & Nelson, 2008; Pierens & Raymond, 2011). The Grand Tack model assumes that Saturn formed later than Jupiter. First, Jupiter migrated inwards from its original birthplace at about 3-4 AU while Saturn was still growing. Next, when Saturn reached a mass close to its current one, it started to migrate inwards more rapidly than Jupiter and became captured in Jupiter's 3/2 resonance; this occurred when Jupiter was at ~1.5 AU. Consequently, Jupiter "tacked" (i.e. its direction of migration was reversed) and the two planets migrated outwards. Outward migration slowed and stalled as the disk dissipated, leaving Jupiter at ~5.5 AU (see Fig. 1).

This model is compelling for several reasons. First, it explains why we don't have a "hot Jupiter" in the solar system, i.e. why our major giant planet did not migrate all the way to the vicinity of the Sun: Jupiter was pulled back by Saturn. Second, it helps explaining the properties of the terrestrial planets: their orbits and masses, accretion timescales, and the presence of water. In particular, it explains, for the first time, the small mass of Mars and its short accretion timescale compared to those of the Earth, because the migration of Jupiter to 1.5 AU strongly depleted the Mars region of its original mass. Third, it explains the structure of the asteroid belt: its mass deficit, its orbital excitation and, most importantly, the co-existence of two broad classes of asteroids (S- and C-types), very different from each other, associated with ordinary and primitive chondrites.

In the Grand Tack model, at the end of the gaseous disk phase the giant planets were in a resonant chain: Saturn was in the 3/2 resonance with Jupiter, and Uranus and Neptune were respectively in resonance with Saturn and with each other (Fig. 1). Their orbits were almost circular and co-planar. Therefore, the giant planets had orbits very different from the current ones, which are non-resonant, more separated from each other and have non-negligible eccentricities and inclinations. The evolution between these two very different orbital configurations is described by the "Nice model".

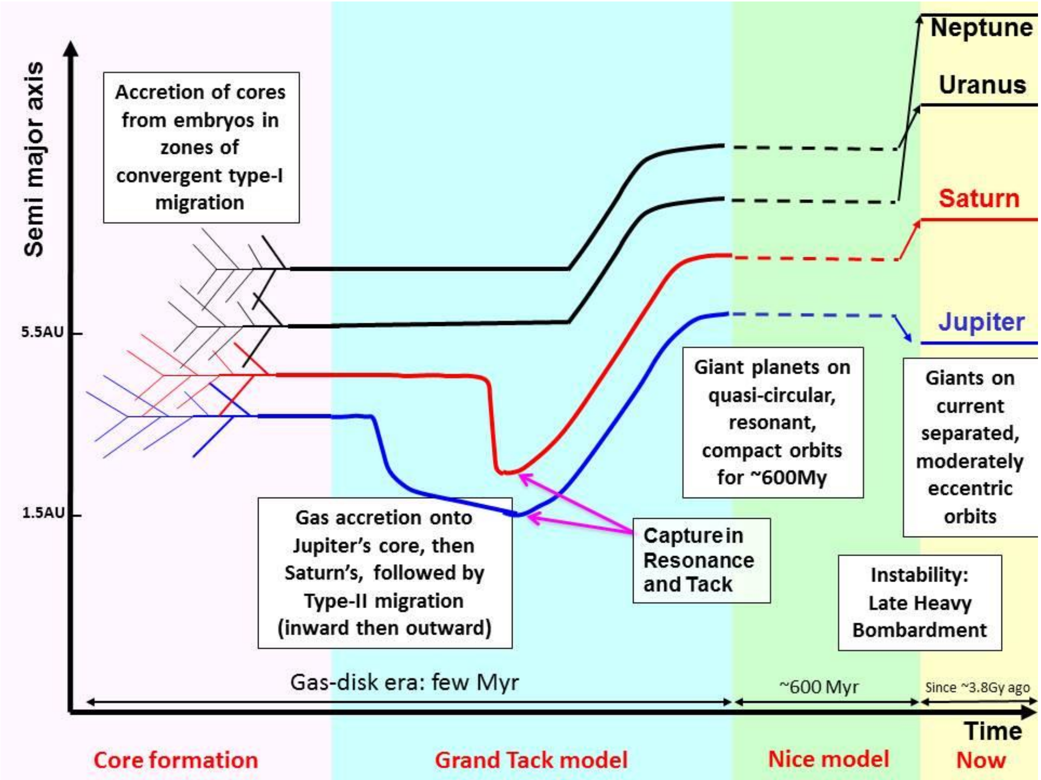

Fig 1.: The "picture" of Solar System evolution provided by the Grand Tack and Nice models. See text for explanations

The Nice model was originally presented in 2005 in a trilogy of Nature papers (Tsiganis et al.; Gomes et al.; Morbidelli et al.). We assumed that the giant planets were originally in a generic compact, circular and co-planar configuration. The Nice model was later completely re-elaborated in Morbidelli et al. (2007) and Levison et al. (2011) once it became clear that the giant planets had to have emerged from the gas-disk phase on mutually resonant orbits (see Morbidelli, 2010 for a review). We describe this more recent version of the model here.

The Nice model assumes the existence of a massive disk of planetesimals extending from a few AU beyond the orbit of the outermost giant planet to about 30 AU (essentially a primitive Kuiper belt). As a result of the gravitational interactions with this disk, after a long time of slow modifications, the giant planets were extracted from their original resonances. Because the orbits of the planets were so close together, they became unstable as soon as they came out of resonance. Consequently, Uranus and Neptune were scattered outward by close encounters with Saturn and Jupiter and penetrated into the planetesimal disk. While the ice giants dispersed this disk, dynamical friction damped their orbital eccentricities and inclinations and parked the planets on stable, well-separated orbits.

The Nice model is compelling for many reasons. First, it explains the current orbits of the giant planets, starting from the original compact and multi-resonant orbits (Tsiganis et al. 2005; Morbidelli et al. 2007; Batygin & Brown 2010). Second, it helps explaining the existence and orbital structure of the Kuiper belt, which is what remains of the primordial trans-Neptunian planetesimal disk (Levison et al., 2008). Third, it explains the origin and orbits of Jupiter's Trojan asteroids and their similarities to Kuiper belt objects in terms of spectral properties and size distribution (Morbidelli et al., 2005; 2009). Fourth, it explains the capture of the irregular satellite populations of all giant planets (Nesvorny et al., 2007). Last and perhaps most important of all, the Nice model explains the origin of the *Late Heavy Bombardment* (LHB) of the inner solar system (see Chapman et al 2007 for a review), an impact spike in the bombardment rate of the terrestrial planets that occurred about 3.9 Gy ago, i.e. about 600 My after the formation of the Earth. In fact, in the model, the instability of the giant planets occurred *late*, i.e. after hundreds of millions of years of evolution (Gomes et al., 2005; Levison et al., 2011) and caused the dispersal of the trans-Neptunian disk and of the asteroid belt (Morbidelli et al. 2010), leading to a heavy bombardment of all terrestrial planets (Morbidelli et al., 2012).

The Nice model has become a new paradigm in planetary science and the Grand Tack model is also imposing itself to the consideration of the international community. Naturally, these models require refinements or extensions as more and more constraints are taken into account (the most exciting development being the idea that the solar system might have had extra planets, ejected during the phase of instability- Nesvorny, 2011; Batygin et al., 2012; Nesvorny and Morbidelli, 2012).

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