The purpose of this paper is to study the combined effects of gas drag and gravitational perturbations by a proto-Jupiter on the orbital evolution of planetesimals, in the solar nebula, near mean motion interior resonances with proto-Jupiter. Our work is motivated by current efforts to explain how an earlier-formed proto-Jupiter can influence the collisional evolution of planetesimals in the primordial asteroid belt and under which circumstances it can prevent runaway growth to bodies of size not larger than the largest observed asteroids [1].

We consider planetesimals in orbits interior to proto-Jupiter, subjected to its gravitational perturbations and experiencing solar-nebula gas drag forces. Secular-perturbation-driven eccentricities might be large, causing a significant enhancement of the drag-induced secular decrease in the semimajor axis. The planetesimals evolve inward and, on a time scale consistent with the solar nebula probable lifetime ($O(10^{6-7})$ years), they may sweep large regions in the asteroid belt and cross a number of mean motion resonances with proto-Jupiter. Passages through resonances, especially for low-order commensurabilities, can result in drastic variations of some orbital elements [2-6]. Our main objectives are to investigate in detail orbital changes induced by resonance passages and to infer their effectiveness in inhibiting the accretion in the asteroid belt.

We performed numerical integrations of planetesimal orbits, influenced by gas drag and perturbed by a proto-Jupiter with the same semimajor axis, eccentricity and inclination as the present Jupiter. The gas drag acceleration was modeled as in [7], with a planetesimal’s radius $r_p$ and bulk-density $\rho_p = 2.5 \text{ g cm}^{-3}$, a dimensionless drag coefficient $C_d = 0.5$, a gas density radial dependence $\rho(r) = \rho_0 r^{-\alpha}$ with $\rho_0 = 2.8 \times 10^{-9} (\text{AU})^{\alpha}$ g cm$^{-3}$ and $\alpha = \frac{11}{4}$, a relative deviation of the gas velocity from the local Keplerian value assumed independent of position in the nebula (consistently with a gas temperature radial dependence $r^{-1}$ [5]) and equal to $-4 \times 10^{-3}$. Planetesimal’s initial eccentricity and inclination were set at $1.0$ and $0.5$ rad, respectively. Integrations were performed by using the Adams-Bashforth predictor-Adams-Moulton corrector multistep method.

Figs. 1+4 show some results of our numerical study near the 2:1 resonance for a proto-Jupiter mass of $15M_\oplus$, a planetesimal’s radius $r_p = 5 \text{ km}$ and semimajor-axis initial values $a_i = 3.33, 3.36, 3.39, 3.42$ and 3.45 AU (symbols for curves as in Fig. 4). The trajectory in the $(e,\dot{\omega})$ plane exhibits a drastic change of the secular evolution of the eccentricity $e$ and perihelion longitude $\dot{\omega}$ at the resonance passage (Fig. 1 with starting point near $(0,0)$ and for $a_i = 3.33$ AU). The jump at the resonance results in a significant increase in the proper eccentricity $e_p$ and shift in $\dot{\omega}$. Fig. 2 shows the time evolution of the $\dot{\omega}$’s, with the sudden breakdown of the phase coherence across the resonance. Fig. 3 shows the variation of the eccentricities in the semimajor-axis regions swept during the orbital decay for the same time interval ($\approx 6.8 \times 10^4$ y) and clearly exhibits steep random increases at the resonance which generally destroy the secular coherent variations. As a consequence, the abrupt change (increase) of the orbital decay rate $-da/dt$, across the resonance, brings planetesimals originating at different $a_i$ to have the same semimajor axis at a given time (Fig. 4).

It is plausible that mean-motion resonance induced orbital-changes, as those depicted in Figs. 1+4, may have significant effects on the collisional evolution and the
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accretion process in the primordial asteroid belt. The induced transition to uncorrelated \( \dot{\omega} \)'s, the induced random increase of eccentricities, the change in the regime of the radial drift of planetesimals may lead to a substantial enhancement of the relative velocities and the collision probability. High, uncorrelated, relative velocities would preclude the runaway growth.

Fig.1. Trajectory in \((e, \dot{\omega})\) plane with the jump across the 2:1 resonance \((a_i = 3.33)\).

Fig.2. Transition from in-phase to out-of-phase \( G(t) \)'s regime across the 2:1 resonance.

Fig.3. Eccentricity variations during the orbital decay and jumps across the 2:1 resonance.

Fig.4. Discontinuous random increase of the orbital decay rate across the 2:1 resonance.