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How giant planets sculpt terrestrial exoplanets and debris disks

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Abstract

There exists strong circumstantial evidence from their eccentric orbits that most of the known giant exoplanet systems are the survivors of violent dynamical instabilities. We numerically simulate the evolution of planetary systems around Sun-like stars with three components: (i) an inner disk of planetesimals and planetary embryos, (ii) three giant planets at Jupiter-Saturn distances, and (iii) an outer disk of planetesimals comparable to the primitive Kuiper belt. We calculate the dust production and spectral energy distribution of each system by assuming that each planetesimal particle represents an ensemble of smaller bodies in collisional equilibrium. Our main result is a strong correlation between the presence of terrestrial planets and debris disks. Strong giant planet instabilities that produce very eccentric surviving planets destroy all rocky material in the system, including fully-formed terrestrial planets if the instabilities occur late, and also destroy the icy planetesimal population. Stable or weakly unstable systems allow terrestrial planets to accrete in their inner regions and significant dust to be produced in their outer regions, detectable at mid-infrared wavelengths as debris disks. Stars older than $\sim$ 100 Myr with bright cold dust emission (in particular at $\lambda \sim 70\mu$m) signpost dynamically calm environments that were conducive to efficient terrestrial accretion. Such emission is present around $\sim$16% of billion-year old Solar-type stars. We make two predictions. First, eccentric giant planets should be anti-correlated with both debris disks and terrestrial exoplanets. Second, the presence of debris disks and terrestrial exoplanets should be correlated.

1. Methods

We used the Mercury integrator [2] to simulate radially-segregated planetary systems – with terrestrial planet-forming regions, 3 giant planets on marginally unstable orbits, and outer planetesimal disks – for 200 Myr (details in [3, 4]). We extrapolated the dust fluxes into the future by calculating collisional timescales and assuming that no further dynamical evolution took place. We tested the effect of several system parameters: 1) the mass distribution of the giant planets, 2) the width, 3) total mass and 4) mass distribution of outer planetesimal disks, and 5) the presence of disk gas at the time of giant planet instabilities. We found the same correlations in all sets of simulations, albeit with some interesting differences [3, 4].

2. Results

The system in Fig. 1 went unstable after 55.3 Myr; the instability was mainly restricted to the outer system such that two terrestrial planets survived but the outer planetesimal disk was destroyed. However, in most cases the survival of terrestrial planets and debris disks are closely correlated. All terrestrial material was destroyed in 35-70% of *unstable* simulations but surviving terrestrial planets had typical eccentricities of $\sim$0.1. The ensemble of surviving giant planets matches the observed eccentricity distribution. Weighted combinations of simulations (Cases A and B) match the giant exoplanet mass and semimajor axis distributions and the mass-eccentricity correlation [6]. All simulations show a strong eccentric giant planet-debris disk anti-correlation and a strong debris disk-terrestrial planet correlation (Fig. 2) that holds for

$\lambda \geq 25\mu m$ and ages older than 10-100 Myr [3].

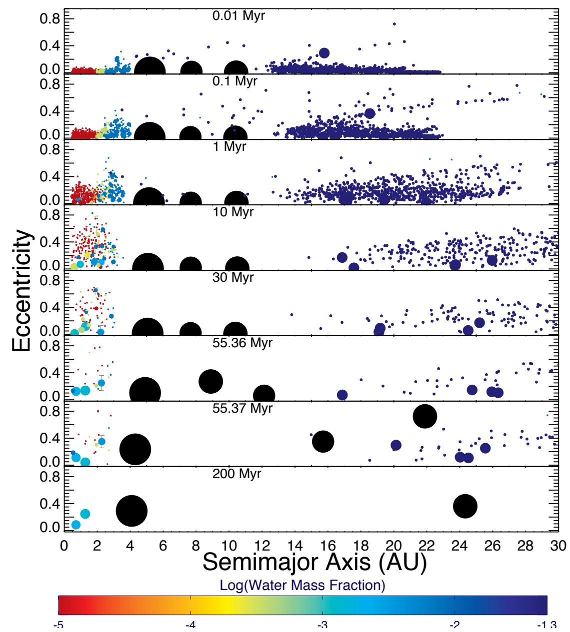

Figure 1: Evolution of a simulation with 5 icy embryos in the outer planetesimal disk [4]. The giant planets are shown as the large black bodies. The two surviving terrestrial planets have a = 0.71 and 1.27 AU, m = 1.3 and 1.58 $M_{\oplus}$, and Myr-averaged e = 0.09 and 0.17, respectively. The two surviving giant planets have a =4.1 and 24.4 AU, m =1.27 and 0.45 M_J.

3. Summary and Conclusions

We predict 1) a strong anti-correlation between eccentric giant planets and debris disks, and 2) a strong correlation between bright debris disks and terrestrial planets. The best stars to search for Earth-like planets are those with bright cold dust and no known giant planets. Combining our simulations with debris disk statistics [5] we predict that at least 27% of stars should host terrestrial planets at any orbital distance and at least 16% of stars should have terrestrial planets in the habitable zone [4].

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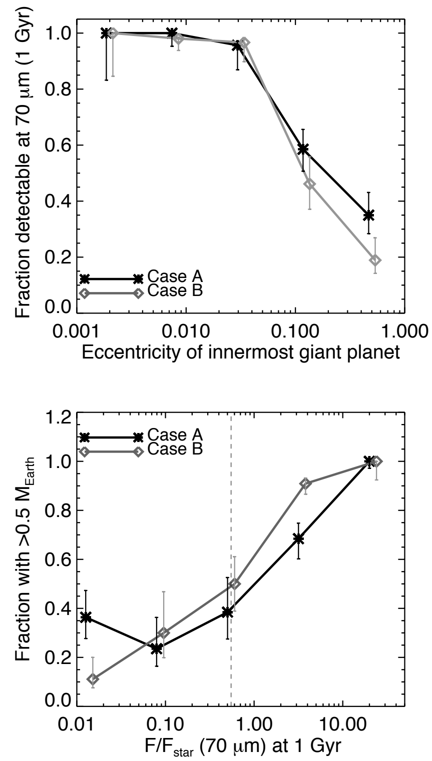

Figure 2: Anti-correlation between the dust flux (at $70\mu m$ after 1 Gyr) and the giant planet eccentricity (top), and correlation between the efficiency of terrestrial planet formation and the dust flux (bottom) [4]. Cases A and B each match giant exoplanets.

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