Planet-planet scattering alone cannot explain the free-floating planet population

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ABSTRACT

Recent gravitational microlensing observations predict a vast population of free-floating giant planets that outnumbers main sequence stars almost twofold. A frequently-invoked mechanism for generating this population is a dynamical instability that incites planet-planet scattering and the ejection of one or more planets in isolated main sequence planetary systems. Here, we demonstrate that this process alone probably cannot represent the sole source of these galactic wanderers. By using straightforward quantitative arguments and N-body simulations, we argue that the observed number of exoplanets exceeds the plausible number of ejected planets per system from scattering. Thus, other potential sources of free-floating planets, such as planetary stripping in stellar clusters and post-main-sequence ejection, must be considered.

Key words: planetary systems: formation — methods: n-body simulations

\section{INTRODUCTION}

One possible explanation for the existence of free-floating planets (Lucas & Roche 2000; Zapatero Osorio et al. 2000, 2002; Bihain et al. 2009; Sumi et al. 2011) is that they formed in protoplanetary disks around young stars, in systems of multiple planets. These planetary systems subsequently underwent large-scale dynamical instabilities involving close encounters between planets and strong planet-planet scattering events that ejected some planets and left the surviving planets on perturbed orbits (Rasio & Ford 1996; Weidenschilling & Marzari 1996; Lin & Ida 1997; Papaloizou & Terquem 2001; Ford et al. 2001, 2003; Marzari & Weidenschilling 2002). The planet-planet scattering model can reproduce a number of properties of the observed population of extra-solar planets: its broad eccentricity distribution (Adams & Laughlin 2003; Veras & Armitage 2006; Chatterjee et al. 2008; Juric & Tremaine 2008; Ford & Rasio 2008; Raymond et al. 2009, 2010), the distribution of orbital separations between adjacent two-planet pairs (Raymond et al. 2009), and perhaps certain resonant systems (Raymond et al. 2008).

In order for planet-planet scattering to create the free-floating planet population, the following equation:

\[ \frac{N_{\text{free}}}{N_{\text{stars}}} = f_{\text{giant}} \times f_{\text{unstable}} \times n_{\text{ejec}}, \]

must hold, where \(N_{\text{free}}/N_{\text{stars}}\) is the observed frequency of free-floating giant planets of 1.8\(\pm\)0.8 per main-sequence star (Sumi et al. 2011), \(f_{\text{giant}}\) is the fraction of stars with giant planets, \(f_{\text{unstable}}\) is the fraction of planet systems that become unstable, and \(n_{\text{ejec}}\) is the mean number of planets that are ejected during a dynamical instability. The terms on the right-hand side of Eq. (1) are all dependent on stellar mass. We discuss these correlations extensively in Section 3; see also Kennedy & Kenyon (2008).

Exoplanet observations constrain the fraction of stars with gas giant planets to be larger than \(\sim 14\%\) (Cumming et al. 2008; Howard et al. 2010; Mayor et al. 2011) and perhaps as high as 50\% (Gould et al. 2010). The majority of giant planets are located beyond 1 AU (Butler et al. 2005; Udry & Santos 2007), and their abundance increases strongly with orbital distance within the observational capabilities (\(\sim 5\) AU) of radial velocity surveys (Mayor et al. 2011).

Given the difficulty of measuring eccentricities with radial velocity measurements (Shen & Turner 2008; Zakamska et al. 2011), the fraction of planetary systems that becomes unstable is modestly constrained.

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by the eccentricities of surviving planets. In addition, there is a clear positive mass-eccentricity correlation: more massive exoplanets have higher eccentricities (Ribas & Miralda-Escudé 2007; Ford & Rasio 2008; Wright et al. 2009). The simplest way to reproduce the observed distributions is if a large fraction of systems – at least 50% but more probably 75% or more – become unstable, and if the giant planets’ masses within systems with high-mass (\(M \gtrsim M_J\)) planets are roughly equal (Raymond et al. 2010). The typical number of planets ejected per unstable system, \(n_{\text{ejec}}\), must be an increasing function of the number of planets that form in a given system. However, \(n_{\text{ejec}}\) has been addressed only tangentially in previous studies, and we quantify this value in a consistent manner here.

Assuming observationally motivated constraints – \(N_{\text{free}}/N_{\text{stars}} = 1.8, f_{\text{giant}} = 0.2,\) and \(f_{\text{unstable}} = 0.75\) – each instability must eject 12 Jupiter-mass planets (i.e., \(n_{\text{ejec}} = 12\)). For the full range of plausible constraints – \(N_{\text{free}}/N_{\text{stars}} = 1 - 3.5, f_{\text{giant}} = 0.14 - 0.5,\) and \(f_{\text{unstable}} = 0.5 - 1\) – the range of values for \(n_{\text{ejec}}\) is between 2 and 50. At first glance, these values appear implausibly large. As we will show, \(n_{\text{ejec}}\) is indeed so large as to be inconsistent with observational constraints, which means that the planet-planet scattering model, at least in its simplest form, cannot explain the free-floating planet population.

Section 2 is dedicated to placing theoretical constraints on \(n_{\text{ejec}}\) using N-body simulations of planet-planet scattering. We chose initial conditions that we expect to be the most efficient at ejecting planets and tested systems initialized with up to 50 planets. Section 3 incorporates this result into our main argument and discusses additional considerations, such as the contribution from previous generations of main sequence stars which are now stellar remnants, and other potential sources of free-floaters.

2 SCATTERING SIMULATIONS

The dynamical evolution of unstable multi-planet systems leads to planet-planet collisions, planet-star collisions, and/or the hyperbolic ejection of one or more planets. Previous work has shown that ejections comprise the most frequent outcome (Weidenschilling & Marzari 1996; Papaloizou & Terquem 2001; Marzari & Weidenschilling 2002; Adams & Laughlin 2003; Jurić & Tremaine 2008; Veras et al. 2009; Raymond et al. 2010). In an extensive investigation of planet-planet scattering in systems of 10 and 50 planets, Jurić & Tremaine (2008) found that 50%–60% of all planets were ejected from unstable systems with little dependence on the initial planetary distribution. In addition, Raymond et al. (2010) showed that the number of ejected planets is larger in systems that start with unequal-mass planets and in systems with higher-mass planets.

In order to self-consistently assess \(n_{\text{ejec}}\) as a function of the number of planets which have formed in a planetary system, \(N_p\), we performed a suite of planet-planet scattering simulations. Although the phase space of initial conditions is extensive, the results of the investigations referenced above (particularly from Jurić & Tremaine 2008) demonstrate that \(n_{\text{ejec}}\) is largely insensitive to the initial distribution of planetary eccentricity or inclination. Therefore, we consider initially circular and nearly-coplanar (\(i\) chosen randomly from \(0^\circ - 1^\circ\)) sets of \(N_p = 3 – 50\) planets. We tested two different planetary mass distributions: in the \textit{equal} simulations each planet was 1 Jupiter-mass, and in the \textit{random} simulations, the logarithm of the mass of each planet was chosen randomly such that the planet masses took values between 1 Saturn-mass and 10 Jupiter-masses. We assumed that giant planets tend to form at a few AU – close to the ice line – in marginally-unstable configurations. Thus, the innermost planet was placed at 3 AU and for \(N_p = 3, 4, 5, 6, 8,\) and 10, additional planets were spread out radially with a separation of \(K = 4\) mutual Hill radii between adjacent planets (as \(K\) determines the instability timescale: Marzari & Weidenschilling 2002; Chatterjee et al. 2008). For \(N_p = 20\) and 50, \(K\) was decreased to keep the outermost planet at \(\gtrsim 200\) AU (for \(N_p = 20\) and 50, \(K = 2.56\) and 0.99 for the \textit{equal} simulations, and \(K = 2.00\) and 0.70 for the \textit{random} simulations). Each system was integrated for 10 Myr using the Bulirsch-Stoer integrator in the \textit{Mercury} integration package (Chambers 1999). Although slow, this integrator accurately models close encounters. The radius of each planet was taken to be Jupiter’s current radius, and collisions were treated as inelastic mergers. A planet was considered to be ejected if its orbital distance exceeded 10\(^3\) AU, which represents a typical distance at which galactic tides \textit{can} cause escape over a typical main sequence lifetime (Tremaine 1983). We ensured that each simulation conserved energy and angular momentum to one part in 10\(^7\) or better to avoid numerical artifacts (Barnes & Quinlan 2004).

We obtained a sufficiently large statistical measure of \(n_{\text{ejec}}\) by running ensembles of systems for each value of \(N_p\). We integrated 100 sets of initial conditions for each of \(N_p = 3, 4, 5, 6, 8,\) and \(10\), and assigned a random value to each planet’s orbital angles in each instance. We did the same for \(N_p = 20\) and 50, but instead ran 40 and 10 simulations, respectively, for each due to the increased computational cost. Each simulation was run for 10\(^7\) yr. Our results are displayed in Fig. 1.

The figure demonstrates that between 20% and 70% of planets are ejected in each set of simulations. The vertical bars attached to the mean escape percentages for each bin represent ±1 standard deviation values from the mean. For the \textit{equal} simulations (left panel) this mean ejection fraction is roughly constant with \(N_p\), and varies by at most 10%. In contrast, the ejection rate in the \textit{random} simulations (right panel) increases monotonically with \(N_p\). The mean ejection percentage for \(N_p = 10\) is 50%-60%, corroborating the results from the 10-planet simulations in Jurić & Tremaine (2008). The red dashed lines represent the fraction of the initial planetary mass ejected for each value of \(N_p\) (slightly offset to the right of the blue curves for clarity). This value is less than the percentage of planets ejected in all cases, demonstrating that the most massive planets tend to scatter out the smaller ones, corroborating previous results (e.g. Ford et al. 2003).

The effect of varying the initial system configura-
fractions of the random simulations in Fig. 1, and which is subject to the constraint
\[
\sum_{N_p=3}^{\infty} f^{(N_p)}_{\text{giant}} \leq 1. \tag{3}
\]
Now we can simply set \(N_{\text{free}}/N_{\text{stars}} = 1.8\) and take a closer look at Eqs. (2)–(3).

In order to satisfy the constraint in Eq. (3), the vast majority of planetary systems must have \(N_p \geq 5\). If we use the observationally determined upper bound of 0.5 \(\epsilon_p = 0.5\) \(M_\odot\) and \(a_{\text{innermost}} = 30\) AU on the right-hand side of Eq. (3), then the vast majority of planetary systems must have \(N_p \geq 7\). If we use the lower bound of 0.14 \(\epsilon_p = 0.14\) \(M_\odot\) – which applies for Sun-like stars – then the vast majority of planetary systems must have \(N_p \geq 20\). These minimum values of \(N_p\) would be even higher if we instead derived Eq. (2) from the equal simulation results. If, motivated by the monotonicity of the coefficients in Eq. (2), we assume that all systems form a fixed number of planets, then we can calculate a critical giant planet frequency \(f^{(N_p)}_{\text{giant}}\) below which the free-floating population cannot be reproduced. We plot this quantity in Fig. 2 for two different values of \(f^{(N_p)}_{\text{unstable}}\). Here, coefficients for values of \(N_p\) that were not sampled in our simulations were conservatively fixed at the coefficient of the next highest value of \(N_p\) that was sampled. For example, the coefficients of \(f^{(20)}_{\text{giant}}\) and \(f^{(30)}_{\text{giant}}\) are 0.65 and 0.70; hence, the coefficient of \(f^{(21)}_{\text{giant}}\) is taken to be 0.70.

Now that we have determined the relation between \(N_p\) and \(f^{(N_p)}_{\text{giant}}\), we can assess the constraints on forming \(N_p\) giant planets in a single system. A simple first consideration is the outermost planet’s semimajor axis before any scattering occurs. For simplicity, assume \(N_p\)
1-Jupiter-mass planets all orbit a 1M$_\odot$ star, and that the planets are formed close enough to be on the verge of instability ($K = 4$). Then, with an adopted innermost semimajor axis of 3 AU, $a_{\text{outermost}} = 3$ AU $\cdot (1.415)^{N_p-1}$. Therefore, for $N_p > 13$, $a_{\text{outermost}} > 200$ AU. Core accretion cannot form planets beyond $\approx 35$ AU (Dodson-Robinson et al. 2009), gravitational instability has not yet been demonstrated to produce planets beyond 200 AU (Boss 2006), and only in the most extreme cases may planet-disc interactions cause planets to migrate outward beyond 200 AU (Crida et al. 2009). If giant planets were all formed by core accretion, then the $a < 35$ AU restriction implies $N_p \leq 8$, implying that at least 40% of systems, all with 8 giant planets, all must have become unstable in order to produce the free-floating planet population by planet-planet scattering alone. Alternatively, if giant planets were all formed by gravitational instability, even in extended “maximum-mass” discs (Dodson-Robinson et al. 2009), there are not more than a few giant-planet-mass clumps form (Boley 2009; Boley et al. 2011).

Radial velocity observations suggest that, within a few AU, giant planets are far more common around higher-mass stars (Johnson et al. 2007; Lovis & Mayor 2007; Bowler et al. 2010). However, low-mass stars outnumber higher-mass stars by a large factor (Parravano et al. 2011 and references therein). If $f_{\text{giant}}$ does indeed decrease as $M$ decreases, then explaining free-floaters via planet-planet scattering proves to be more difficult simply because fewer total stars would form giant planets. Consider, for example, the observed lower-bound frequencies of giant planets for different stellar masses deduced from radial velocity surveys for three categories of stars: M dwarfs (3%, Bonfils et al. 2011), Solar-like stars: (14%, Mayor et al. 2011), and A-type stars (20%, Johnson et al. 2010). The total integrated value of $f_{\text{giant}}$ depends on the mass ranges adopted for these stellar types and the particular initial mass function assumed. At minimum, the relative frequency of stars in these three bins should differ by a factor of a few (e.g., in the ratio 4:2:1), which yields an integrated $f_{\text{giant}}$ of $\leq 8.5%$. If, however, there exists at least one order of magnitude more M dwarfs than Solar-type stars, then the integrated $f_{\text{giant}}$ must be $\leq 4.5%$. If this value is adopted as the true value of $f_{\text{giant}}$, then Fig. 2 demonstrates that giant planet systems must be extremely crowded, with at minimum 25 giant planets per system. This value is almost certainly unrealistic given the arguments presented above and current observational constraints. However, we note that microlensing surveys suggest that giant planets on more distant orbits may actually be very common around low-mass stars (Gould et al. 2010), in which case a typical giant planet system need only contain 4-10 planets (Fig. 2).

To what degree do stars that have already evolved off the main sequence contribute to the free-floating planet population? In order to estimate this contribution, we need only count the current population of white dwarfs, as stars that underwent supernovae or/and formed a black hole comprise a negligible fraction (< 1%) of the total stellar population (Parravano et al. 2011). One of the most complete and least-biased samples of white dwarfs represents the local population (within 20 pc of the Sun), which is estimated to have a space density of $4.8 \pm 0.5 \times 10^{-3}$ pc$^{-3}$ (Holberg et al. 2008). The space density of stars in the Galactic Disc is $\approx 6 \times 10^{-1}$ pc$^{-3}$ (Binney & Tremaine 2008, Pg. 3), implying that the fraction of the free-floating population which has arisen from dynamical instability soon after formation in already-dead stars is on the order of 1%. This value is not great enough to change the results here unless $N_p$ is orders of magnitude higher for high-mass stars than for the lower-mass stars that dominate the current galactic population.

If the planet-planet scattering model can reproduce the free-floating planet population in a realistic framework, then the following observational predictions must hold. First, the frequency of giant planets around low-mass stars must be high (>50%), in agreement with microlensing results (Gould et al. 2010) and in disagreement with radial velocity surveys (Johnson et al. 2007; Lovis & Mayor 2007; Bowler et al. 2010; Johnson et al. 2010). However, low-mass stars outnumber higher-mass stars by a large factor (Parravano et al. 2011 and references therein). If $f_{\text{giant}}$ does indeed decrease as $M$ decreases, then explaining free-floaters via planet-planet scattering proves to be more difficult simply because fewer total stars would form giant planets. Consider, for example, the observed lower-bound frequencies of giant planets for different stellar masses deduced from radial velocity surveys for three categories of stars: M dwarfs (3%, Bonfils et al. 2011), Solar-like stars: (14%, Mayor et al. 2011), and A-type stars (20%, Johnson et al. 2010). The total integrated value of $f_{\text{giant}}$ depends on the mass ranges adopted for these stellar types and the particular initial mass function assumed. At minimum, the relative frequency of stars in these three bins should differ by a factor of a few (e.g., in the ratio 4:2:1), which yields an integrated $f_{\text{giant}}$ of $\leq 8.5%$. If, however, there exists at least one order of magnitude more M dwarfs than Solar-type stars, then the integrated $f_{\text{giant}}$ must be $\leq 4.5%$. If this value is adopted as the true value of $f_{\text{giant}}$, then Fig. 2 demonstrates that giant planet systems must be extremely crowded, with at minimum 25 giant planets per system. This value is almost certainly unrealistic given the arguments presented above and current observational constraints. However, we note that microlensing surveys suggest that giant planets on more distant orbits may actually be very common around low-mass stars (Gould et al. 2010), in which case a typical giant planet system need only contain 4-10 planets (Fig. 2).
thought to cause disruption for semimajor axes of 1987) or galactic tides (e.g. Tremaine 1993), which are long-term effects from passing stars (e.g. Weinberg et al.

Veras et al. (2011) show that planets at several hundred AU are unlikely to disrupt their host star’s disc. Recent cluster simulations have shown that planets with orbital radii of 5-30 AU are likely to disrupt or transfer through close stellar passages within their birth clusters at a rate of up to 10% (Parker & Quanz 2011). The cluster disruption rate is much higher than the long-term effects from passing stars (e.g. Weinberg et al. 1987) or galactic tides (e.g. Tremaine 1993), which is thought to cause disruption for semimajor axes of 10^6 AU. Free-floating Jupiter-mass objects can also be formed by collisions between high-mass protoplanetary discs (Lin et al. 1998), but extremely dense stellar conditions are needed to cause such collisions. Other potential sources of free-floating planets may arise from dynamical ejection due to mass loss from high-mass protoplanetary discs (Lin et al. 1998), but extremely dense stellar conditions are needed to cause such collisions. Other potential sources of free-floating planets may arise from dynamical ejection due to mass loss during post-main-sequence evolution. Veras et al. (2011) show that planets at several hundred AU can be dynamically ejected due to mass loss from stars with progenitor masses greater than ~2 M☉; these planets may reach such wide distances through scattering over the main sequence lifetime of the system.

The interaction of planetary systems with localized Galactic phenomena such as the tidal streams, passage into and out of spiral arms from radial stellar migration, Lindblad resonances with the bar, and passing molecular clouds represent other, largely unexplored, possible sources of free-floating planets. Also, we cannot rule out the possibility that Jupiter-mass objects could simply represent the low-mass tail of the stellar initial mass function, and that free-floating planets could help constrain the presence or extent of a planet-star gap in the initial mass function (e.g. Chabrier 2003; Parravano et al. 2011).

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