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Turning solar systems into extrasolar planetary systems in stellar clusters

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Abstract. Many stars are formed in some form of cluster or association. These environments can have a much higher number density of stars than the field of the galaxy. Such crowded places are hostile environments: a large fraction of initially single stars will undergo close encounters with other stars or exchange into binaries. We describe how such close encounters and exchange encounters will affect the properties of a planetary system around a single star. We define singletons as single stars which have never suffered close encounters with other stars or spent time within a binary system. It may be that planetary systems similar to our own solar system can only survive around singletons. Close encounters or the presence of a stellar companion will perturb the planetary system, leading to strong planet-planet interactions, often leaving planets on tighter and more eccentric orbits. Thus, planetary systems which initially resembled our own solar system may later more closely resemble the observed extrasolar planetary systems.

Keywords. planetary systems, open clusters and associations: general, binaries: general

1. Introduction

As of November, 2010, a little over 500 planets have been discovered orbiting around other stars. A large fraction of these extrasolar planetary systems are different from our own Solar System: planets as massive as Jupiter are found on much tighter, and eccentric orbits compared to the wider, and essentially circular, orbits of our own gas giants. Interactions between Jupiter and Saturn cause their orbits to change slightly, tilting their planes and changing their eccentricities, but the changes are *oscillatory*: their amplitudes do not grow over time or cause the planets to scatter strongly off each other. If left alone, the gas giants of our Solar System will tick for ever. Is this *Solar–System–like* behaviour common, or rare, throughout the entire population of planetary systems? It could be rare, if planetary systems tend to form with more–massive planets arranged more closely together. Planet–planet interactions would then often lead to strong scatterings between planets, ejecting some whilst leaving others on more bound and eccentric orbits. Indeed such a mechanism is found to match the observed distribution of exoplanet orbits (eg Juric & Tremaine 2008). However, there are some certainly some known multiple planet systems beyond our own Solar System where the planets are seen to be on relatively circular orbits (eg see Fig. 11 of Lovis *et al.* 2011). In these systems, migration has almost certainly brought in the massive planets to orbits substantially closer than the case for our own Jupiter. It is possible that a subset of these systems are solar–system–like by my above definition, in that they are stable if left alone.

In this contribution, we consider what would happen to solar–system–like planetary systems within stellar clusters. This is an important question as all stars form in some sort of stellar cluster or association. Indeed there is evidence that the Sun was formed in a cluster containing about 1000 stars (Adams 2010). We consider two processes which may transform these stable planetary systems into unstable ones, where planets can be ejected. Firstly, close, fly-by encounters with other stars will perturb planetary orbits and even, sometimes, directly eject planets during an encounter. Secondly, if a single star encounters a binary system, it may exchange in to the binary replacing one of the original binary components. The stellar companion within a binary may, over time, perturb the orbits of any planets. How often do fly-by encounters and binary companions de-stabilise planetary systems? What fraction of Solar–System–like planetary systems could survive intact?

We introduce here the idea of a *Singleton*, which is defined as

1) a star which has not formed in a binary,

2) a star which has not later spent time within a binary system,

3) a star which has not suffered close encounters with other stars.

Thus, if we consider for now planetary systems formed around only single stars, the question of solar-system survival within a stellar cluster becomes one of singleton fraction. The frequency of encounters will depend in part on how long a particular star spends within a stellar cluster. Some clusters will break up very quickly as gas is driven out by supernovae or winds from massive stars unbinding the system. Other clusters will survive this early phase of mass loss but the stars will escape from the cluster over a few hundred million years or so, driven by the combined effects of two–body scattering and tidal stripping, populating the field of the Galaxy.

Below we first review what can happen to stars, binaries, and planetary systems within stellar clusters. We then consider in more detail the effects of close encounters and stellar companions on planetary systems, concluding with an estimate of the likely fraction of solar systems which will be affected by being formed in a clustered environment.

2. What happens within a cluster

Young stellar clusters contain a few hundred to about one thousand stars within a radius of about 1pc. One can compute the time required for a particular star to undergo an encounter with another star passing within some distance, rmin, which may be approximated by:

$$\tau_{\rm enc} \simeq 3.3 \times 10^7 {\rm yr} \left(\frac{100 \ {\rm pc}^{-3}}{n} \right) \left(\frac{v_\infty}{1 \ {\rm km/s}} \right) \left(\frac{10^3 \ {\rm AU}}{r_{\rm min}} \right) \left(\frac{{\rm M}_\odot}{m_{\rm t}} \right) . \qquad (2.1)$$

Here n is the stellar number density in the cluster, v_∞ is the mean relative speed at infinity of the stars in the cluster, $r_{\rm min}$ is the encounter distance and $m_{\rm t}$ is the total mass of the stars involved in the encounter. The cross–section for an interaction is increased greatly by what is known as gravitational focusing, where stars are deflected towards each other because of their mutual gravitational attraction. This effect is has been included. The terms in the above equation are of order unity for a typical cluster of a few hundred stars. In other words, for the clusters we consider here, a star will have another star pass within 1000 AU every 30 Myr or so. Encounters can therefore play an important role in the evolution of a planetary system formed in stellar clusters.

We have performed N–body simulations of stellar clusters for a range of masses and radii, modelling the evaporation of the clusters in the Galactic tidal field (Malmberg *et al.* 2007). We followed the histories of all stars considering how many of the stars which were initially single had close encounters or exchanged into binaries. Close encounters here are defined as any encounter within 1000 AU. This is also the typical size of the widest binaries that can survive in the stellar clusters we consider. We find that the singleton fraction (ie those stars having no fly-bys and not exchanging into binaries) can be as low as 10–20% for solar–like stars. Most stars will have at least one encounter within 1000 AU with another star, and about 10% will have spent time in binaries, although most of these stars are single again by the end of the simulation as many binaries are broken up during binary-binary encounters.

3. The effects of fly-bys on planetary systems

We consider now the effects of the flybys. We have simulated flyby encounters between intruding single stars of various masses and a solar–mass star with a planetary system (Malmberg, Davies & Heggie 2011). We find that 20–40% of encounters within 100 AU lead to the direct ejection of at least one planet from a system containing the four gas giants of the solar system. In addition, we find a further 20–40% of encounters lead to the ejection of at least one planet within 100 Myr of the encounters as the planetary systems became unstable due to perturbations in the planetary orbits during the flyby.

As planetary systems become unstable, planet–planet scattering leaves some planets on more bound orbits, whilst others are left on wider orbits. These latter planets will be ejected after several scatterings. However, a snap–shot of all planetary systems some time after encounters would reveal a population of planets on very wide, eccentric orbits (100–1000 AU). This is also the case for planetary systems which are unstable from birth (Scharf & Menou 2009; Veras *et al.* 2009). We also find that planets are sometimes grabbed by the intruding star. We find that these planets are typically on orbits of between 10 and 100 AU and a broad range of eccentricities. This planet could destabilise a planetary system around the intruding star.

4. The effects of binary companions on planetary systems

We consider now the situation where a star with a planetary system has had an encounter with a stellar binary and exchanged into the binary. The stellar companion may now perturb the planetary system. If the orbit of the stellar companion is relatively highly inclined with respect to the plane of the planetary system, the Kozai mechanism may operate (Kozai 1962). For a single planet, this will lead to so–called Kozai cycles where the eccentricity of the planet is seen to oscillate. In the case of planetary systems containing multiple planets, the outer planet will undergo Kozai oscillations on the shortest timescale. Providing the orbit of the stellar companion is sufficiently inclined, the orbit of the outer planet may, periodically, cross the orbit of planets which orbit more closely to the host star. This leads to a period of strong scattering between the planets, with some being ejected and others left on more bound, and eccentric, orbits (Malmberg, Davies & Chambers 2007 ; Malmberg & Davies 2009). In some cases, one is left with a single planet orbiting around the star, undergoing Kozai oscillations. In other cases, mutual planet–planet interactions may protect the planetary system from the effects of the Kozai mechanism, providing the timescale for the changes in planetary orbital elements due to planet–planet interactions is shorter than that due to the Kozai mechanism caused by the stellar companion.

In addition, if the orbit of the stellar companion is extremely inclined (ie within a few degrees of 90 degrees) then the Kozai effect will place the planet on extremely eccentric orbits, with maximum eccentricities close to unity. In this case, tidal interactions between the planet and the host star may circularize the orbit, leaving the planet on a much tighter orbit, which may also be rather inclined compared to its initial orbital plane (eg Fabrycky & Tremaine 2007; Wu, Murray & Ramshai 2007). Indeed observations of the so–called Rossiter-McLaughlin Effect in transiting planets suggests that at least some systems are highly inclined (eg Triaud *et al.* 2010).

5. The likely fraction of planetary systems affected

We have performed N–body simulations of stellar clusters to measure the rate of close encounters and exchanges into binary systems. Subsequently, we have performed simulations of close encounters and their subsequent effects on planetary systems to calculate the cross section to significantly alter a planetary system (eg to eject planets). We have also modelled the effects of stellar companions on planetary orbits via the Kozai effect.

We can now combine all of these results to estimate the fraction of planetary systems which are likely to be affected by either flybys or stellar companions within stellar clusters. We consider here only solar–mass stars, having the four gas giants of our own Solar System. Based on the results of our calculations for clusters initially containing 700 stars, we estimate that some 15% of systems will lose at least one planet due to flyby encounters. Stellar companions will account for planetary losses in about 5% of planetary systems. These figures will change with the initial number of stars in the cluster but only relatively slowly (Malmberg, Davies & Heggie 2011). We therefore conclude that stable planetary systems can be made unstable by flybys or stellar companions interestingly often.

We should also recall that here: 1) we have assumed that planetary systems are only formed around single stars, and 2) taken a relatively modest binary fraction within our stellar clusters (one third). Relaxing either of these constraints would increase the number of systems effected within binaries.

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