How special is the Solar System?

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ABSTRACT

Most mechanisms proposed for the formation of planets are modified versions of the mechanism proposed for the solar system. Here we argue that, in terms of those planetary systems which have been observed, the case for the solar system being a typical planetary system has yet to be established. We consider the possibility that most observed planetary systems have been formed in some quite different way. If so, it may be that none of the observed planetary systems is likely to harbour an earth-like planet.

Key words: accretion, accretion discs - planetary systems: protoplanetary discs

1 INTRODUCTION

Until about ten years ago, theories of planetary formation concentrated, of necessity, on the formation of planets in the solar system (e.g. Lissauer 1993). The theories provide a reasonable explanation, in terms extending back to the ideas of Kant (1755) and others, of why the gas giants form at radii of more than around 5AU from the sun, of why the basic building block of a planet is a rocky core, built up of dust via planetesimals in the solar nebula, and of why the orbits of the planets are essentially coplanar and circular. In the last ten years, over a hundred planetary systems have been discovered, and, at first glance, none of them resembles the solar system (or what the solar system would appear to be when seen from an appropriate distance). In comparing the various systems, it seems sensible as a first step to just consider the properties of the planet which has the largest velocity semi-amplitude in each observed system. In Figure 1 we plot the observed eccentricity, e, against the semi-major axis, a, (measured in AU) for the planet with the largest velocity semi-amplitude in each of the observed systems, including Jupiter as the representative for the solar system. (We discuss the sample used in our analysis in Section 2 and we find no bias in the choice of this as our sample). It is apparent from Fig. 1 that in the observed systems the planets are much closer to the central star (indeed too close to the central star to have formed by the conventional theory – Lin, Bodenheimer & Richardson 1996; Bodenheimer, Hubickyj & Lissauer 2000), and have in general, compared to the solar system, highly eccentric orbits (except for those close enough to the central star that tidal circularization has had time to act – Rasio et al. 1994). Looked at as a distribution in the two-dimensional (a, e)-plane it is immediately apparent that the solar system does not lie within the part of the (a, e)-plane defined by the currently observed distribution of exo-planetary systems.

Thus the natural question arises of whether the solar system is special in some way compared to the majority of planetary systems to be found in the Galaxy (c.f. the discussion in Ford, Havlickova & Rasio 2001). Of course, we know already that it is special in the sense that we are in it, and it is therefore no surprise that all the early models of the formation of planetary systems applied entirely to the solar system. But if the solar system is strongly atypical as a planetary system, in the sense of lying at some extreme in the distribution of properties of all planetary systems, then the more relevant question arises. To what extent we should allow our understanding of the formation of planetary systems, gleaned from observing one atypical and extreme example, albeit at close-range, to bias our understanding of the formation of planetary systems in general?

In Section 2 we quantify the extent to which the solar system may, on current evidence, be considered to be a typical member of the ensemble of planetary systems. We make use of a technique derived in the study of robust statistical procedures in order to determine whether or not to discard some of the observations because they are inconsistent with the rest of the observations and/or with the probability distribution assumed to be the underlying distribution of the data. We show that the solar system is, formally, an outlier

1 Just as almost all models in cosmology apply entirely to the Universe.
2 ROBUST STATISTICS

In this Section we address the formal question of whether the solar system, as represented by Jupiter, is an outlier from the observed distribution of exo-planetary systems. The properties of the known extrasolar planets are distributed non-parametrically (i.e. there is no known underlying distribution for the data). Consequently we require a non-parametric statistical method in order to identify any outliers which may exist in the data. Once any outliers have been identified and removed, the remaining dataset may be described in a statistical sense, as robust. In order to identify outliers in a dataset, a standard procedure is to use a boxplot (see, for example, Hoaglin, Mosteller & Tukey 1983; Madansky 1988). However, in order to quantify the degree to which a particular point is an outlier, the simple boxplot does not suffice. In order to do this, one standard procedure is to transform the data so that it appears more closely to resemble a normal distribution. One class of such transformations is the power transformation as described below. Since the solar system (Jupiter) differs from the bulk of the observed systems both in terms of large semi-major axis, $a$, and small eccentricity, $e$, we apply our statistical considerations to the observed distribution of periastron distance, $a_p = a(1 - e)$.

2.1 Box-Cox power transformation

The Box-Cox power transformation (Box & Cox 1964; see chapter 5 of Madansky 1988 for a detailed discussion) is used to transform a set of observed data points so that they are more normally distributed. The Box-Cox transformation is of the form

$$y_\lambda(x) = \begin{cases} x^\lambda - 1 & \text{if } \lambda \neq 0 \\ \log x & \text{if } \lambda = 0 \end{cases}$$

and $y_\lambda(x)$ will have a normal distribution exactly only if $\lambda \neq 0$ or $1/\lambda$ is an even integer. The aim of the Box-Cox transformation is to find the value of $\lambda$ which gives the best approximation to a normal distribution for the transformed data. If $y_\lambda(x)$ is normally distributed the maximum likelihood estimator of the mean of the transformed data is

$$\bar{y}_\lambda = \frac{\sum_{i=1}^{n} y_{\lambda i}}{n},$$

and the maximum likelihood estimator of the variance is

$$s^2_\lambda = \frac{\sum_{i=1}^{n} (y_{\lambda i} - \bar{y}_\lambda)^2}{n}.$$  

The log likelihood function is

$$l(\lambda) = -\frac{n}{2} \log(2\pi) - \frac{n}{2} \log s^2_\lambda + (\lambda - 1) \sum_{i=1}^{n} \log x_i.$$  

We may vary $\lambda$ to find the value at which this is a maximum and then look for outliers in the transformed distribution.

2.2 Periastron analysis

We perform the Box-Cox analysis on the periastron distribution of the known extrasolar planets. The data for this analysis was taken from the California and Carnegie planet search catalogue (http://exoplanets.org/planet_table.shtml). In this analysis we only consider companions from the extrasolar planet catalogue which have the largest velocity semi-amplitude (i.e. were discovered first in most cases). We have also performed our analysis using both the most massive extrasolar planets in each system and using all the known planets but the significance of Jupiter as an outlier does not vary.

Fig. 2 shows the distribution of periastron distances of the known extrasolar planets plus Jupiter. In Fig. 2 it is clear that Jupiter (with a periastron distance of just under 5 AU) is an outlier but how significant an outlier is unclear as the underlying distribution is unknown.

A Box-Cox transformation finds that $\lambda = 0.185$ gives the maximum for the log likelihood function (equation 4). Fig. 3 shows the transformed data. We can see how well this resembles a normal distribution by measuring the skewness

from the rest the distribution defined by the observed exo-planetary systems. In Section 3 we discuss possible reasons for this result, and address the question of whether it is currently justified to allow the habitability of the solar system to influence our views on planet formation in general. We summarise our conclusions in Section 4.

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and kurtosis of the transformed data. The skewness is given by

\[ S = \frac{1}{n} \sum_{i=1}^{n} \left( \frac{y_{\lambda i} - \bar{y}_\lambda}{\sigma} \right)^3, \]

and the kurtosis by

\[ K = -3 + \frac{1}{n} \sum_{i=1}^{n} \left( \frac{y_{\lambda i} - \bar{y}_\lambda}{\sigma} \right)^4, \]

where \( \sigma \) is the standard deviation of the distribution (see Press et al. 1996, p. 606). The transformed data has a skewness of \(-0.09\) and a kurtosis of \(-1.07\). For a normal distribution of \( n \) data points we would expect a skewness of \( \sqrt{6/n} \) and a kurtosis of \( \sqrt{24/n} \). Our dataset has 98 points so we would expect a skewness and kurtosis of up to 0.25 and 0.49 respectively. Clearly the transformed data is not skewed but it does have a significant kurtosis. This is caused by the well-known spike near the lower end of the distribution, consisting of ‘hot Jupiters’ at small orbital radii (Udry et al. 2003).

The mean and standard deviation of this transformed data are \(-0.71\) and 1.11 respectively. Jupiter is a significant outlier at the 2.31 \( \sigma \) level and is the only two sigma data point in the entire distribution. Jupiter has a transformed periastron measurement of 1.86 while the next largest is that of HD 72659 which has a transformed value of 1.35 i.e. it is half a sigma from its nearest neighbour. Note that the fact that we have used the AU as our unit of measurement, does not affect the outcome. For example, we have also applied the Box-Cox transformation to the periastron distance measured in SI units and to the logarithm of the periastron distance and find that the result is the same in all cases with the transformed data resembling that of Fig. 3 (although with different values for \( \lambda \)).

3 DISCUSSION

We have noted that the solar system is an outlier in the parameter space of known planetary systems. This is already evident from Fig. 1 and we have used a non-parametric statistical test to show that Jupiter lies at about 2.3 \( \sigma \) in the tail of the periastron distribution. Given this, it seems sensible to enquire whether the solar system is a typical planetary system in the sense that it actually belongs to the set of exoplanetary systems observed so far, or whether it might be intrinsically different, or special, in some way. In particular, we address the question of the extent to which it is necessary to assume that all planetary systems formed in the same way as the solar system. The major issue here is whether theoretical models for the formation of exo-planetary systems should just consider minor modifications of the current theory for the formation of the solar system, or whether some quite different ideas might need to be investigated.

3.1 Selection effects

The most obvious point to make is that the way in which the solar system was discovered differs from the rest. Nevertheless, it can be argued that systems similar to the solar system are abundant, but have not yet been discovered due to observational selection effects. This point is made by Lineweaver & Grether (2002, 2003) and by Tabachnik & Tremaine (2002). These authors fit power-law distributions to the properties of extra-solar planets, and then extrapolate them to encompass the properties of the solar system to make deductions about the total number of planetary systems likely to be present, as well as their properties. However, the act of fitting a power-law distribution makes the implicit assumption that the properties of planetary systems are essentially scale-free, and the act of extrapolating...
the distribution to encompass the solar system (and beyond) makes implicit assumptions about the general properties of planetary systems. Lineweaver & Grether (2002) emphasise that overcoming the selection effects is mainly a matter of time. In other words, it may be that all that is required to find systems like the solar system is to observe candidate systems for timescales as long as Jupiter’s orbit. This will take another 5 to 10 years. Thus application of a test of the kind used above to the dataset some 5 to 10 years from now will demonstrate the credibility of this potential solution.

### 3.2 Dichotomy

There is, however, already some evidence that the formation of planetary systems is not a scale-free process. Greaves et al. (2004a) find that there is a dichotomy between those systems which are observed to contain giant planets (at radii typically a few AU or less) and those systems which have a debris disc as evidenced by submillimetre emission at radii typically in the range 20 – 100 AU. They find that those systems with observed giant planets show no evidence for a debris disc, whereas, those systems which display evidence for a debris disc are not directly observed to harbour giant planets. However, as Greaves et al. (2004a) point out, there is evidence that these latter systems contain (currently unobserved) planets at larger radii. This evidence is in two forms. First, the absence of a mid-infrared excess in the debris disc systems points to the absence of planets orbiting at larger radii, which are able to clear a central cavity in the dust distribution, and second, the suggestion of planets at larger radii is given credence by the evidence of internal structure seen in those debris discs which can be imaged, such as clumping, gaps and warping (Greaves et al. 1998; Jayawardhana et al. 1998; Weinberger et al. 1999; Wyatt et al. 1999; Lagrange, Backman & Artymowicz 2000; Augereau et al. 2001; Holland et al. 2003; Wyatt 2003; Kalas, Liu & Matthews 2004). Meyer et al. (2004) recently demonstrated the power of the Spitzer Space Telescope at investigating the properties of debris discs. They note that it is already clear that the interpretation of such discs is likely to be complicated and to involve a number of factors including perhaps a range in primordial disc properties and/or evolutionary histories.

### 3.3 Theoretical models

We therefore consider the implications of this observed break in scale. It might for example be an indication that there are two quite separate mechanisms of planet formation, or it might simply indicate that we are looking at two extremes of a single formation process.

The majority of the current thought (and literature) on the formation of planetary systems (actually giant planets) makes use of the formation model derived for the solar system, modified in some manner. This standard model for the solar system (Wetherill 1980; Mizuno 1980; Stevenson 1982) assumes that planets form initially through the agglomeration of dust into grains, pebbles, rocks and thence planetesimals within a gaseous disc, that these planetesimals coalesce to form planetary cores, and that finally (for the giant planets) these cores use gravity to accrete gas from the ever-present disc. Most of the current theoretical research effort on exo-planets involves devising and justifying suitable modifications of this model, taking the overall view that all planetary systems form a continuous distribution in some suitable parameter space. Even for the solar system, however, this scenario is not without problems (Lissauer 1993; Wuchterl, Guillot & Lissauer 2000). Most notably, the formation of planetesimals from small-scale dust, and the timescales required to accrete the gas onto the protoplanetary cores, encounter difficulties, given possible rapid migration of the cores (Ward & Hahn 2000) and the required core masses for runaway accretion, compared to those observed (see also the discussion by Boss 2000). The main modifications required to make the standard model fit the observed systems, involving planetary migration (e.g. Trilling, Lunine & Benz 2002; Armitage et al. 2002; Alibert, Mardasin & Benz 2004) and the generation of orbital eccentricities (e.g. Rasio & Ford 1996), have difficulties which are not yet fully resolved (see, for example, the discussions by Marcy et al. 1999; Udry, Mayor & Santos 2003; Tremaine & Zakamska 2004).

The main alternative scenario involves the formation of giant planets directly, through gravitational instability in the protostellar gaseous disc (Boss 2001; Rice et al. 2003; Mayer et al. 2002; 2004). Although this model has problems fitting the solar system (for example, the presence of rocky cores in the giant solar system planets, not to mention the existence of terrestrial planets, is more simply explained through the prior formation of the cores from rocky planetesimals), there is no fundamental reason why it, or some modification of it, should not apply to the rest — that is, to the majority of the systems discovered so far. The major problem with the model, as currently constructed, is that, in order to drive strong gravitational instability, it requires a sudden change in disc properties on a timescale comparable to, or less than, the dynamical timescale. This is usually achieved in the simulations by setting the initial conditions appropriately. In reality, this might be achieved either via a sudden change in the cooling rate (e.g. Johnson and Gammie 2003) and/or by a sudden change in the disc density brought about by a dynamical interaction with a low-mass interloper. Note that the mass of such an interloper need only be comparable to the mass of the proto-planetary disc (for example a massive planet or a brown dwarf), and that such collisions might be frequent in the crowded and chaotic conditions in which most stars form (Bate, Bonnell & Bromm 2002a, 2002b, 2003). Black (1997) has noted that the similarity in eccentricity distributions between exo-planets and close binary stars which might indicate that both sets of formation processes are dynamical in origin. There is indeed evidence that planetary properties depend on stellar multiplicity (Zucker & Mazeh 2002; Eggenberger, Udry & Mayor 2003). And such a dynamical mechanism for forming planets is likely to give rise to a wide spread in eccentricities and should be able to give rise to planets at a wide range of orbital radii (Papaloizou & Terquem 2001; Terquem & Papaloizou 2002).

In light of the above discussion, it is possible to take

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3 Such ideas have resonance in the original ideas of Jeans (1928), still being explored, for example, by Oxley & Woolfson (2004).
the view that there are two distinct formation mechanisms for the formation of planets. First, there is the well-trodden path for the formation of the solar system, which produces rocky cores for gaseous planets at radii of several AU as well as terrestrial planets at smaller radii, perhaps on essentially circular orbits. This mechanism would also be able to produce the debris discs at several tens to hundreds of AU. Second, there is the possibility of a more dynamical mechanism for planetary formation, using gravity directly in the formation process. Such a mechanism might be able to produce gaseous planets at a large range of radii, including the observed giant planets at radii less than a few AU, and with a spread of orbital eccentricities. But this mechanism would have difficulty in producing terrestrial-type planets and debris discs. If this mechanism predominates among the observed planetary systems, then few, if any, of the planetary systems detected so far would harbour earth-like rocky planets.

These arguments are reinforced by the following point. Most planetary systems have non-negligible eccentricities, and there is a growing body of opinion that habitability is not very sensitive to orbital eccentricity (Williams & Pollard 2002, 2003; Jones 2003; Jones & Sleep 2003; Asghari et al. 2004). Why, if the solar system is not special, do its planets have essentially circular orbits? One explanation for this might be that terrestrial planets must form through steady core growth in a disc, and such a planet formation mechanism tends to produce circular orbits.

A further piece of evidence that requires explanation is the observation that there appears to be a correlation between the metallicity of a star and the probability of it harbouring a planetary system (Gonzalez, 1998; Gonzalez, Wallerstein & Saar 1999; Reid 2002; Santos et al. 2003; Fischer & Valenti 2003). Fischer & Valenti (2003, and private communication) find that the probability of a star harbouring a planet rises from about 5 per cent when the iron abundance is $\sim 1/3$ that of the sun, to about 20 per cent when the iron abundance is $\sim 3$ times that of the sun.

It could be argued (see, for example, Santos et al. 2003) that this observed correlation can be taken as prima facie support for a model of planet formation which requires the formation of rocky planetary cores as a pre-requisite for forming the gas giants which we observe. The correlation might be an indication that the formation process is a continuous function of metallicity. In this picture, the metal-rich systems would form planetary cores (and hence gas giants) in abundance while there is still enough gas in the disc to cause significant migration, somehow disposing of any excess cores so that there is no debris left. The less metal-rich systems (including the solar system) would be able to form a few cores which barely migrate just as the gas is expelled, leaving a few gas giants at around $\sim 10$ AU and a debris disc at larger radii.

In contrast to this rocky-core formation model, formation through dynamical instability of a disc could lead to the observed giant planets in small and eccentric orbits. Greaves et al. (2004a) find that these systems do not show debris discs. In addition, they find that systems with observed debris discs have suspected gas giants in large orbits (tens of AU). Although systems like the solar system may require some metallicity, this demonstrates the observed exoplanetary systems tend to be favoured by an even higher degree of metallicity even though this is not a requirement of the disk instability model. Indeed, Santos, Israeliian & Mayor (2001) note that the Sun occupies a modest position in the low [Fe/H] tail of the metallicity distribution of stars with planets and go on to suggest that the lack of solar system analogues found so far leads one ‘to speculate about possible different formation histories’.

From a theoretical point of view, there are many reasons, other than core formation, as to why the formation of currently observable planetary systems might be dependent on metallicity. For example, cooling processes in the disc at low temperatures depend mainly on metals (e.g. Johnson & Gammie 2003), as does the shielding of the disc from the X-ray flux generated in the stellar corona/chromosphere (e.g. Alexander, Clarke & Pringle 2004), as well as the cooling rate in the region of the disc subject to evaporation (Hollenbach et al. 1994). Thus, although metal abundance appears to play only a small rôle in the disc timescale for viscous evolution (Livio & Pringle 2004), it may play a significant rôle in the disc dynamics and/or in the timescale on which the disc is dispersed by the central star. In addition, the extra cooling brought about by enhanced metal abundance might mean that the process of star formation takes place in denser environments in more metal-rich systems, perhaps increasing brown dwarf production, and in any case, enhancing the likelihood of close interactions.

4 CONCLUSIONS

There are two main formation scenarios envisaged for planet formation. The model applied to the solar system assumes that planets form initially through the agglomeration of dust into rocks and planetary cores, and that finally (for the giant planets) these cores use gravity to accrete gas. Alternatively, there is the possibility of a more dynamical mechanism using gravity directly in the formation process. The solar system model may not be applicable to the observed extrasolar planets and the dynamical instability model has difficulty reproducing the solar system and debris discs. The metallicity dependence of both models needs to be investigated further.

We conclude that it is still possible that our current understanding of planetary systems is unduly coloured by our intimate knowledge of our own solar system. More observational work is needed if the solar system is to be shown to be a ‘normal’ planetary system. And more theoretical work is required if alternative planet formation scenarios are to shown to be equally viable.

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