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LETTER

Letter to the Editor

Eccentric giant planets in open star clusters

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Abstract. The discovery of Jupiter–like planets with high eccentricities raises the question of how these eccentricities are produced. We propose that eccentric giant planets (EGPs) could be formed in open star clusters as a result of purely dynamical processes. It is found that at least 3% of the giant planets around stars in open clusters can develop high eccentricities due to multi-body gravitational interactions; this percentage increases to 20% if considering only G-dwarf stars. The formation mechanism implies complex dynamical interactions inside retrograde hierarchical configurations within the cluster core. The percentage of planetary systems leaving open star clusters without changes in their original dynamical properties can be very large, almost 90%.

Key words: celestial mechanics, stellar dynamics – planets and satellites: general – planetary systems – open clusters and associations: general

1. Introduction

Standard theories of planet formation require a disk of gas and dust to form planets by coagulation of small particles due to gas drag and perturbations of the particle orbits (Weidenschilling 1980). The orbits of these particles are almost circular due to viscous dissipation; this fact suggests that newly formed planets should have also small eccentricities.

Very recently, researchers at McDonald and Lick Observatories have independently discovered a planet orbiting the star 16 Cygni B (Cochran at al. 1997; Butler & Marcy 1997; Kamper 1997), which is part of a triple star system about 21.4 pc from Earth. This multiple star consists of an inner binary with two G-dwarf stars separated by about 835 AU. A distant M-dwarf is orbiting the binary in a hierarchical arrangement. The companion to 16 Cygni B has a mass that could be as little as 1.6 times that of Jupiter (M_J = 9.6 $\times 10^{-4} M_{\odot}$), so it is probably a true planet rather than a brown dwarf. It circles the star every 2.2 years in a highly eccentric orbit, e=0.67. Earlier discoveries of eccentric giant planets (hereafter EGPs) are the planet around 70 Vir with e=0.40 (Marcy & Butler 1996), and one orbiting HD 114762 with e=0.35 (Mazeh et al. 1996). Mechanisms for generating EGPs have been considered recently (Artymowicz 1993, 1997; Rasio & Ford 1996; Holman et al. 1997; Katz 1997; Mazeh et al. 1997a; Lin & Ida 1997; Mazeh et al. 1997b).

In this Letter, we consider the possibility of EGP formation around stars in open clusters together with probable parameters of observable systems. In §§ 2 and 3, we present the results of detailed numerical calculations of the dynamical evolution of planetary systems in open star clusters. For simplicity, the planetary systems studied in this work consist of only one giant planet and its host star. The calculations were done with the N-body code NBODY5 (Aarseth 1985, 1994) appropriately modified for our present purpose. This code includes the effect of the Galactic tidal field (Aarseth 1985, 1994) and mass loss due to stellar evolution (Eggleton et al. 1989). The calculations also consider a realistic mass spectrum (Scalo 1986) in the range [0.08, 15.0] $M_{\odot}$. Spherical symmetry and constant density are assumed for generating initial positions, with the rate of the total kinetic and potential energy fixed to 0.25. The initial velocities are random and isotropic. The initial mean radii are in the range [1, 1.5] pc. Multiple interactions are computed by using the Bulirsch-Stoer integrator; numerical errors (relative energy errors) are smaller than 10^{-4} per unit time. The evolution of the models is followed at least for 300 Myr. In § 4 we discuss the feasible observational properties of stellar systems containing a giant planet in open clusters.

2. Planet population evolution

Planets in our solar system show small eccentricities except Pluto and Mercury. Since the eccentricity of the Giant planets in our solar system is small (0.048, 0.056, 0.047, 0.009, respectively, for Jupiter, Saturn, Uranus and Neptune), we have generated a giant planet population orbiting cluster stars with an initial eccentricity of 0.010, semi-major axis in the range [6.3,

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10.3] AU, and masses uniformly distributed in the range 1-6 M_J. All the planetary systems in a given model have the same value of the semi-major axis; i.e. there is no semi-major axis distribution. These are arbitrary but plausible values for newly formed giant planets. They could form by any of the two major giant planet origin mechanisms (Bodenheimer 1982): gravitational collapse of a gaseous sub-condensation until a stage at which a solid core may form; or solid core formation by accumulation of planetesimals, followed by accretion of gas onto the core until collapse instability.

Recently, it has been suggested that most of the stars form in small star clusters (Kroupa 1995a, b, c; de la Fuente Marcos 1997). In this work we consider models with populations in the range [100, 500] stars; the percentage of stars with giant planetary companions is in the range 10-50%. The clusters are situated in the solar neighbourhood. Most of the models have only single stars (except the planetary companions) but two additional models have also very hard (a = 6.4 AU) primordial binaries (binary fraction = 1/3). Double stars do not alter the results significantly. We have studied 500 mono-planetary systems in total.

In spite of the fact that almost circular orbits are harder to perturb, our computations show that both an increase and a diminution of orbital eccentricity is achievable. The eccentricity variations are associated with gravitational encounters. Gravitational circularization events are related to two-body interactions and the eccentricity decrement is in the range 10-40%. The percentage of systems which suffer this process is about 2%. Increase of eccentricity is observed in about 8% of systems with 38% in the range 0.06-0.99. The lowest increments come from simple two-body encounters but for higher increments, complex multi-body interactions are involved. All the largest increments are generated inside hierarchical retrograde configurations. The largest inner eccentricity is computed by using an analytical perturbation equation (Heggie & Rasio 1996) during the evolution of the hierarchical system. The life-time of these hierarchical systems could be greater than 100 Myr and all were formed inside the cluster core. Disintegration of hierarchical systems produce a single star and an EGP; very rarely the planet is ejected after disintegration.

Fig. (1) shows the systems whose eccentricities have changed due to dynamical interactions. It seems that the highest variations are restricted to stellar masses heavier than 0.3 $M_\odot$. For stars with masses in the range 0.5-1.0 $M_\odot$ the biggest number of variations is observed. Only about 2% of systems are disrupted before escaping from the cluster and almost 90% leave the cluster without any major change in their dynamical parameters.

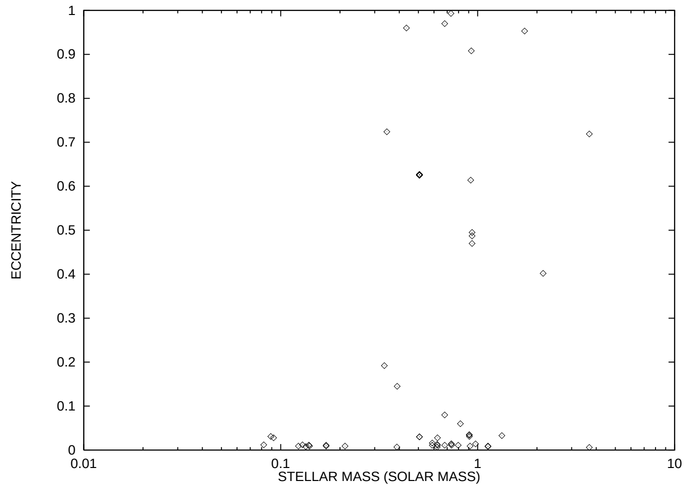

Fig. 1. The relationship between eccentricity and mass of the primary for the systems which changed their initial eccentricity (0.010) after close encounters. The highest eccentricities are produced by four-body interactions (planet–star+two single stars) generating temporary stable hierarchical triple systems.

3. Formation mechanism

Our computations show that high eccentricities can be generated during multi-star gravitational interactions. The main mechanism is connected with the formation of a hierarchical triple or quadruple system. In order to identify stable configurations we use the stability criterion of Mardling and Aarseth (1997a). By using this criterion we select the stable hierarchical configuration to apply the Heggie and Rasio theory to the inner (planetary) orbit. The critical ratio of the outer periastron distance of the mass m_3 to the inner apastron distance of $m_1 + m_2$ is given by

$$Y_0^{min} = \mathscr{C} \left[\frac{1 + e_{out}}{(1 - e_{out})^{1/\alpha}} \frac{1 + q}{(1 + e_{in})^{3-1/\alpha}} \right]^{\alpha/(3\alpha-1)} , \qquad (1)$$

where e_{out}, e_{int} are the outer and inner eccentricities respectively, $q = m_3/(m_1 + m_2)$, $\mathscr{C}$ = 2.8, and α = 2. This criterion has been verified (for mass ratios in range 0.01-100 of the outer body and wide range of values for e_{out}) by systematic calculations (Mardling & Aarseth 1997b).

The characteristic time-scale on which a single star is captured by a mono-planetary system (hereafter MPS) is given approximately by

$$T_c \approx \frac{1}{\mathscr{P} \rho_s \sigma v} , \qquad (2)$$

where $\mathscr{P}$ is the probability that a fourth star (single in this case) also lies within a given distance d, ρ_s is the number density of single stars, σ is the capture cross-section, and v is the root mean square velocity of stars in the system. The cross-section for a single star to pass within a distance d of the centre of mass of a MPS is given by

$$\sigma = \pi d^2 \left(1 + \frac{2G(M_{mps} + M)}{dv^2} \right) , \qquad (3)$$

where M_{mps} is the mass of the MPS and M is the mass of the incoming star. From its point of view, the MPS is a single star-like object, and in order to form an outer binary the velocity perturbation in the encounter must be approximately the RMS velocity of the cluster stars, $\sqrt{GN < M > /2R}$, where R is the half-mass radius of the cluster and $< M >$ is the mean mass of the stars. Considering $M_{mps} + M \approx 2 < M >$ we have

$$T_c \approx \frac{1}{\frac{3n_s^2}{4\pi R^6}\pi d^5 (1 + \frac{4G<M>}{dv^2})v} , \quad (4)$$

where n_s is the number of single star (without planets) and N is the total number of objects (stars+centre of mass of planetary systems). Including the stability criterion we have

$$T_c \approx \frac{4}{3}\frac{\sqrt{2}}{Y_0^5 n_s^2}(\frac{1-e_{out}}{1+e_{in}})^5 \frac{1}{1+(\frac{1-e_{out}}{1+e_{in}})\frac{8R}{Y_0 N a}}\Phi , \quad (5)$$

where $\Phi = \sqrt{R^{13}/G < M > N a^{10}}$, and a is the MPS semi-major axis. According to the stability criterion a typical value for Y_0 can be about 30 (for very eccentric outer body) and using the crossing time ($T_{cross} = 2\ R/v = \sqrt{8\ R^3/G\ N\ < M >}$) we have

$$\frac{T_c}{T_{cross}} \approx \frac{2.8 \times 10^{-8}}{n_s^2}(\frac{1-e_{out}}{1+e_{in}})^5 \frac{1}{1+(\frac{1-e_{out}}{1+e_{in}})\frac{4}{15}\frac{R}{Na}}(\frac{R}{a})^5 . (6)$$

From the calculations these systems only form in the cluster core so we must use the core parameters in Eq. (6). This equation gives $T_c \approx 2000 T_{cross}$ for the typical values of the parameters found in our calculations. The frequency of hierarchical system formation for a cluster with N=300 and 50 mono-planetary systems could be 0.01 per crossing time or about 2 during the typical cluster life-time for the range of N considered in the calculations. If the initial fraction of mono-planetary systems is larger, this process can be very important.

4. Discussion

It is possible to produce EGPs by gravitational interactions between cluster stars starting from giant planets in nearly circular orbits. They can be generated after a four-body interaction among two single stars and a planetary system in which one of the single stars carries away the excess energy, allowing the formation of a hierarchical system. Such a scattering event enables a substantial momentum transfer which permits to change a circular planetary orbit to one with significant eccentricity. From our computations it is clear that a system like 16 Cygni is easily formed by the processes described in this Letter. Observational properties of the 16 Cygni-like systems formed in our calculations appear in Table (1). The systems studied could be easily detected in a long-term Doppler shift survey in nearby open clusters; the minimum period is about 12 yr. The results provide dynamical mechanisms to produce EGPs but they cannot explain the small orbital radius of many of them. Our present calculations do not include the effects of tidal dissipation processes; they could also play an important role as regards diminution of the orbital separation because the periastron of the planet in our calculations can be as small as 0.2 AU. Another interesting fact to point out is the percentage of EGPs from the current planet detections may be about 25% but the percentage of EGPs formed in our computations is about 3%, although our systems have periods greater than 10 yr. This percentage is a lower limit because life-times of poorly populated clusters, as our models, are short. A higher percentage for richer clusters with extended life-times is expected. On the other hand, all the planets discovered until now orbit G or F stars. If we only consider the G-dwarf stars (0.85-1.1 $M_\odot$), our percentage increases (at least) to 20% in the mean. However, the observational statistics is currently too low to make solid conclusions because strong selection effects could be at work. In any case, our numerical work provides significant evidence of a high survival probability of planetary systems in open clusters. Our present results do not depend significantly on stellar evolution because our models disintegrate before significant mass loss from the stars of the MPSs. The Galactic tidal field (i.e. the initial cluster radius) only affects them indirectly, through the cluster life-time.

Table 1. Properties of the 16 Cygni-like systems

M_1^a	M_2^b	e_{in}^c	e_{out}^d	a_{in}^e	a_{out}^f
3.69	2.98	0.661	0.830	10.3	536
0.91	0.87	0.928	0.490	8.2	3506
0.92	2.14	0.614	0.960	7.4	722
0.68	1.34	0.966	0.800	6.4	742
2.14	1.73	0.939	0.400	6.3	722

[a] Mass of the stellar companion of the planet ($M_\odot$).
[b] Mass of the outer star ($M_\odot$).
[c] Planet eccentricity.
[d] Outer star eccentricity.
[e] Semi-major axis of the planet (AU).
[f] Semi-major axis of the outer star (AU).

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