The planet in M4: implications for planet formation in globular clusters

M. E. Beer1, A. R. King1 and J. E. Pringle2

1. Theoretical Astrophysics Group, University of Leicester, Leicester, LE1 7RH, UK
2. Institute of Astronomy, Madingley Rd, Cambridge CB3 OHA, UK

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ABSTRACT

We consider the formation and evolution of the planetary system PSR B1620–26 in the globular cluster M4. We propose that as M4 is a very-low metallicity environment the standard model of planet formation around main-sequence stars through the accretion of gas onto metallic rocky cores should not be applied. Consequently the previously suggested methods for formation are unlikely. We propose that the planet formed through the interaction of a passing star with a circumbinary disc during the common-envelope phase of the inner binary’s evolution. This formation route is favoured by dense stellar systems such as globular clusters.

Key words: planets and satellites: formation - planetary systems: protoplanetary discs - pulsars: individual: PSR B1620–26

1 INTRODUCTION

Extrasolar planets appear to be rare or absent around stars of low metallicity (Gonzalez 1998; Gonzalez, Wallerstein & Saar 1999; Reid 2002; Santos et al. 2003; Fischer, Valenti & Marcy 2004). This has an appealing potential interpretation in terms of the need for a protoplanet to build a metallic core before accreting further (but see Beer et al. 2004). Convincing evidence for a planet in a low metallicity system would clearly offer a challenge to this view.

One potential arena for such a challenge is a globular cluster, where metallicities are far lower than in any star with a known planet. There is one known planetary system in a globular cluster. This is a hierarchical triple with a Jupiter mass planet in a wide non-coplanar orbit with a binary millisecond pulsar (PSR B1620–26) as the inner binary (Backer 1993; Thorsett et al. 1999). We propose that this planet formed through a gravitational instability in a circumbinary disc as a result of an interaction with a passing star.

In Section 2 we summarise the known properties of the planet orbiting PSR B1620–26 as well as the proposed models for how it formed. In Section 3 we suggest how a circumbinary disc may form as a result of equatorial outflows during the common-envelope phase of evolution of the inner binary. Section 4 discusses the likelihood of the disc encountering a passing star and forming planets. Section 5 argues that the neutron star in the inner binary can only have received a small kick during formation. This small kick keeps the binary in the cluster, and the planet bound to it. In Section 6 we discuss this result and its application to planet formation in general as well as summarising our conclusions.

2 THE SYSTEM AND PREVIOUS IDEAS FOR ITS ORIGIN

PSR B1620–26 is a hierarchical triple system in the globular cluster M4. The orbital solution has been found by Thorsett et al. (1999). The inner binary consists of an 11 millisecond pulsar with a white dwarf companion. The period and eccentricity of this binary are 191.4 d and 0.025315 respectively. Observations by Sigurdsson et al. (2003) indicate that the white dwarf is young and undermassive. The age and mass of the white dwarf are $4.8 \times 10^8 \pm 1.4 \times 10^8$ yr and $0.34 \pm 0.04 M_\odot$ respectively. The mass of the pulsar is assumed to be $1.35 M_\odot$.

The white-dwarf mass and binary period are in good agreement with the theoretical predictions for the mass-period relation of Savonije (1987) and Rappaport et al. (1995). These predictions arise from assuming the white dwarf is the core of a giant whose envelope was transferred to the pulsar, spinning it up to millisecond periods. Stellar evolution theory constrains the envelope radius, which is filling its Roche lobe in this model, and hence the binary period as a function of core (white-dwarf) mass. Any model for the origin of the system should not disrupt this relationship significantly.

The third member of this triple is a Jupiter-mass planet whose orbit has a period of order 100 yr (Thorsett et al.
This model we would expect an eccentricity of order $10^{-3}$-centricity. This model fits the observed eccentricity orbital density of convection cells in the red-giant progenitor of the current lowest known metallicity of a main sequence star with a planetary companion is HD 6434 which has an [Fe/H] of $-0.52 \pm 0.08$ (Santos et al. 2003). Fischer et al. (2004) have hypothesised that there is a metallicity dependence on planet formation. They find that at solar metallicity between 5–10% of stars host Doppler-detected planets. As stellar metallicity drops toward [Fe/H] of $-0.5$, however, the occurrence of detected planets declines to a few percent.

**3 THE PROPOSED MODEL**

Figure 1 shows a schematic view of how the system formed in the proposed model. During the formation of the inner binary the progenitor of the neutron star underwent a common-envelope phase (see Bhattacharya & van den Heuvel 1991 for a discussion of likely evolutionary scenarios). A typical scenario consists of a binary with a high-mass component (e.g., $15 \, M_\odot$) and a low-mass component ($1 \, M_\odot$). At the end of core helium burning of the primary its envelope expands until it fills its Roche lobe and enters a common-envelope phase. During this phase the envelope of the neutron star progenitor is ejected while the white dwarf progenitor spirals in. This leaves the core of the massive star which is a helium star and the low-mass companion. The helium star eventually undergoes a supernova leaving a neutron star possibly in an eccentric orbit (due to the supernova kick). This orbit circularizes due to tides and if the companion fills its Roche lobe on the red giant branch then mass transfer occurs. The red-giant envelope is transferred onto the neutron star spinning it up to millisecond periods, eventually leaving a millisecond pulsar.

Possible evidence for the post-common-envelope structure comes from observations of planetary nebulae and pre-planetary nebulae$^1$. In order to explain the shape of many planetary nebulae a slow dense wind confined to a plane is required prior to a final fast spherically symmetric wind which interacts with it (see the review of Balick & Frank 2002). This would form the observed bipolar outflows observed in many planetary nebulae (Gieseking, Becker & Solf 1985; Miranda & Solf 1992; López, Steffen & Meaburn 1997). This slow, dense wind has been directly observed in some pre-planetary nebulae through HCN emission e.g., in the ‘Egg nebula’ (Bieging & Nguyen-Quang-Rieu 1988) and in the ‘Westbrook nebula’ (Sánchez Contreras & Sahai 2004). In the ‘Egg nebula’ there is evidence that this slow wind

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$^1$ Pre-planetary nebulae are also referred to as proto-planetary nebulae, but we do not use the phrase here to avoid confusion with the use of proto-planetary nebulae as being centrifugally supported discs of accreting matter around stars in which planets may form.
has significant rotation (see Pringle 1989). The ‘Westbrook nebula’ (also known as CRL 618) has been interferometrically mapped by Sánchez Contreras & Sahai (2004). They inferred a dense, equatorial torus expanding at 17.5 km s\(^{-1}\). These observations could be of the excited part of a much slower (or even non-moving) torus. This torus extends out to 5.5 arcsec which at their adopted distance of 900 pc corresponds to an outer radius of 3300 AU. They estimate a torus mass of 0.25 M\(_\odot\) (260 M\(_J\)).

The most plausible methods for the formation of this dense, confined gas are either the expulsion of the wind of a red giant by a binary companion in the orbital plane (Morrison 1981) or the emergence from a common-envelope phase (Soker & Livio 1991; Reyes-Ruiz & López 1999). There is a strong resemblance between these winds and protoplanetary discs (Pringle 1989; Kastner & Weintraub 1995). There is no reason why a dense, slow, equatorial wind in the progenitor of a binary millisecond pulsar would not be produced during/after the common-envelope phase. Two- and three-dimensional simulations of common-envelope evolution show that the envelope mass is lost preferentially in directions near the orbital plane (Yorke, Bodenheimer & Taam 1995; Sandquist et al. 1998).

Mastrodemos & Morris (1998; 1999) performed three-dimensional hydrodynamical modelling of gas flows in bipolar nebulae including the formation of accretion discs. We use the term accretion discs loosely here as the matter in them is not centrifugally supported. In fact the discs contain significant rotation but are not strongly unbound. The accretion discs in their simulations extended out to between 100 and 1000 AU and had terminal velocities in the range 10–27 km s\(^{-1}\). If the general wind loss rate in these systems is 10\(^{-4}\) M\(_\odot\) yr\(^{-1}\) (a typical rate for planetary nebulae) then a 10 km s\(^{-1}\) wind would have 5 M\(_J\) within 100 AU. Simulations by Sandquist et al. (1998) found similar results with a disc extending out to 100 AU and a mass > 1 M\(_\odot\) although not all the mass in their simulations was unbound. Such discs have enough mass at large enough radii to form the planet around PSR B1620–26. This planet has a mass of a few Jupiter masses and a periastron distance of ~30 AU (Thorsett et al. 1999).

Planet formation in a post-common-envelope disc could proceed by the standard model for the formation of the solar system giant planets (Wetherill 1980; Mizuno 1980; Stevenson 1982) if the disc is metal rich. This standard model assumes that planets form initially through the agglomeration of dust into grains, pebbles, rocks and thence planetesimals which form the planetary cores. This formation route, however, would not provide the large relative inclination of the two orbits necessary for the Kozai mechanism to produce the high eccentricity of the inner binary. M4 is a low-metallicity cluster but the environment around the primary which loses its envelope during the asymptotic-giant-branch primary could be dust rich (Livio & Pringle 2003). If the planet is to form bound from the initially unbound matter in this disc/wind phase an interaction with a passing star is required (see below).

Gravitational instability in the disc (Boss 2001; Rice et al. 2003; Mayer et al. 2004) provides another possible formation mechanism. This instability requires a change in disc properties on a timescale comparable to or less than the dynamical timescale of the disc. Interaction with a passing star
would provide this and is likely in a globular cluster environment. Any encounter would probably be non-coplanar and so we expect the resulting planets to be non-coplanar as well. Detailed numerical simulations are required, however, to verify if this formation route could indeed produce the planet around PSR B1620–26. Gravitational instabilities typically generate many planetary mass objects (Rice et al. 2003). Some of these may escape from the system as a result of the encounter while others in the case of PSR B1620–26 may not yet be detectable.

Hall, Clarke & Pringle (1996) have investigated the response of a circumstellar accretion disc to the fly-by of a perturbing star on a parabolic orbit. They considered a perturbing star of equal mass to the central star and a disc of non-interacting particles i.e. they did not include hydrodynamical forces in the disc. Their analysis investigated which regions of the disc remain bound after an encounter in addition to whether energy and angular momentum is gained/lost from the perturbing star. They found that for prograde fly-bys matter outside of periastron is lost from the system (i.e. made unbound) while matter within 60 per cent of the periastron distance is not only retained but because of a corotation resonance loses energy and angular momentum to the binary orbit. In retrograde fly-bys there is no corotation resonance and the binary orbit loses energy to the disc principally in the sense of matter outside of periastron becoming unbound from the system.

Boffin et al. (1998) have simulated star-disc encounters using a smoothed particle hydrodynamical approach. They find that the formation of spiral arms and fragmentation occur in the circumstellar disc. The spiral arms have density contrasts of greater than two orders of magnitude compared to the initial disc and it is in these that fragmentation occurs. Pfalzner (2003) has also simulated star-disc encounters and finds formation of spiral arms in the disc. Both of these simulations had a limited number of particles (11,300 and 50,000 particles respectively) and higher resolution simulations of star-disc encounters need to be carried out to investigate the possible fragmentation of the disc due to an encounter further.

In non-coplanar encounters the passing star imparts a perturbation to the accretion disc in its vertical direction (Heller 1993). This tilts the accretion disc compared to its unperturbed orientation. If the disc were to fragment due to this encounter then the planets formed would have inclined orbits relative to the initial disc.

In the model it is easy to envisage a prograde encounter with a periastron greater than the the disc radius in which the planet forms (of order 100 AU) shocking material inside of this radius and extracting energy and angular momentum from this material making it bound. It is in this region that the observed planet can form. Detailed simulations are required to verify this scenario but those already performed demonstrate the overdensities which may be induced in addition to the extraction of energy from the disc matter. Indeed the initial binary is so massive that the primary evolves before the cluster is fully formed. The encounter which forms the planet could occur during this phase.

\[ f(r_{\text{app}} < r_c) = 1 - \cos \left[ \arcsin \left( \frac{r_c}{r_h} \right) \right], \]

\[ r_c = \frac{r_h}{1 - \frac{r_c}{r_h}} \]

2 Here binary orbit refers to the orbit of the two stars which is initially parabolic i.e. has an eccentricity of 1.

![Figure 2. A figure showing a King model for the density profile of the globular cluster M4. The long-dashed line shows the mean density inside the half-mass radius and the short-dashed lines the positions and densities at the core radius \( r_c \) and half-mass radius \( r_h \).](image)

4 DYNAMICAL CONSIDERATIONS

In this section we discuss the possible dynamical history of PSR B1620–26. The aim of this section is to show that the system could be outside the core of M4 and that it would not have sunk into the core of the system within a Hubble time. We start by considering the possible position of the system in the cluster with respect to its observed position which is within the core. We then discuss the relaxation time for an object in M4 to sink into the core using a King profile for the radial number density. We also discuss the encounter timescale for the system and the effects encounters have on the planetary orbit which may initially have been tighter than currently observed.

4.1 Relaxation into cluster core

The observed offset of PSR B1620–26 from the core of M4 (0.767 arcmin) is less than the observed core radius (0.83 arcmin) and considerably less than the half mass radius (3.65 arcmin). This could simply be a projection effect however, with the system actually far outside the core. This is required in both the model described here and that in S93. This would not be unprecedented for globular cluster pulsars e.g. pulsars A and C in NGC 6752, PSR J1748–2444 in Terzan 5 and PSR B1718–19 in NGC 6342 all lie outside the half mass radius (see Freire 2004 for a list of the observed properties of globular cluster pulsars). The chance of the system having a projected distance \( r_{\text{app}} \) less than the core radius \( r_c \) when it is actually at the half-mass radius \( r_h \) is given by

\[ f(r_{\text{app}} < r_c) = 1 - \cos \left[ \arcsin \left( \frac{r_c}{r_h} \right) \right], \]
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Table 1. A table listing the properties of the globular cluster M4.

| Parameter                  | Value          | Reference                  |
|----------------------------|----------------|----------------------------|
| Distance                   | 2.2 kpc        | Harris (1996)              |
| Core radius \(r_c\)        | 0.83 \(r_h\)   | Trager, Dvorgovski & King (1993) |
| Half-mass radius \(r_h\)   | 3.65 \(r_h\)   | Harris (1996)              |
| Tidal radius \(r_t\)       | 32.49 \(r_h\)  | Harris (1996)              |
| Absolute magnitude \(M_V\) | -7.20          | Harris (1996)              |
| Velocity dispersion \(\sigma_{\text{obs}}\) | 3.88 ± 0.64 | Peterson & Latham (1986) |
|                            | 4.44 ± 0.71    | Rastorguev & Samus (1991)  |
| Concentration \((c)\)      | 3.50 ± 0.2     | Peterson, Rees & Cudworth (1995) |
| Metallicity [Fe/H]         | 1.59           | Trager, Dvorgovski & King (1993) |
|                            | -1.20          | Harris (1996)              |

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The relaxation time for an object to enter the core of the globular cluster is inversely proportional to the stellar density (see Djorgovski 1993). The half-mass relaxation time for M4 is of order 1 Gyr (Harris 1996). However, this assumes a stellar density which is equivalent to the mean stellar density inside the half-mass radius. King (1962) finds the density profile of a globular cluster to be

\[
\rho(r) \propto \frac{1}{z} \left[ \arccos \frac{z}{\sqrt{1 - z^2}} \right], \tag{2}
\]

where

\[
z = \sqrt{\frac{1 + (r/r_c)^2}{1 + (r_t/r_c)^2}}, \tag{3}
\]

and \(r_t\) is the tidal radius of the globular cluster. Figure 2 shows the density profile of the globular cluster M4 out to 4 arcmin. Also shown on figure 2 are the mean number density inside of the half-mass radius (calculated below) and the densities at the core and half mass radius respectively. Outside the half-mass radius the stellar density is much less than the mean density inside the half-mass radius (at least an order of magnitude) and so the relaxation time is much greater. Indeed a system outside the half-mass radius would not necessarily enter inside the half-mass radius within a Hubble time. We conclude that if the system was formed outside the half-mass radius of the cluster then the system would still be outside this radius and would not have relaxed into the cluster core.

4.2 Stellar encounters

During the initial formation stages of a globular cluster there occurs a phase of residual gas expulsion which occurs on a timescale of 10^5 yrs (Meylan & Heggie 1997). Irregular mass loss may cause a phase of dynamical mixing - the violent relaxation stage (Lynden-Bell 1962; 1967). This violent relaxation occurs on a timescale of a few crossing times for the globular cluster. The crossing time of the cluster is of order 10^6 yrs so the violent relaxation timescale is comparable to the 15 Myr timescale on which the primary evolves and the planet formed in the model described here. Therefore the encounter required to form the planet in the model may have occurred during this violent relaxation stage (an encounter within ~100 AU is all that is required). Indeed given the number of binary millisecond pulsars in globular clusters it is possible that more have undergone a similar formation route and have planetary mass companions in wide non-coplanar orbits. In low density clusters like M4 these planets may survive without being disrupted by stellar encounters (Davies & Sigurdsson 2001).

We now consider the timescale for the system (including the planet) to encounter another star and what the outcome of this encounter will be. Davies & Sigurdsson (2001) give the timescale for an encounter between a binary and a single star as

\[
\tau_{\text{enc}} = \frac{1}{n\sigma v} , \tag{4}
\]

where \(n\) is the number density of stars, \(v\) is the velocity of the binary (which we take to be the velocity dispersion of M4) and \(\sigma\) is the cross-section for two stars having a relative velocity at infinity of \(v_\infty\) to pass within a distance \(b_{\text{min}}\) of one another

\[
\sigma = \pi b_{\text{min}}^2 \left[ 1 + \frac{2GM}{b_{\text{min}} v_\infty} \right] , \tag{5}
\]

where \(M\) is the total mass of all the components and the second term on the right is due to gravitational focusing and dominates in the low dispersion environment of a globular cluster. We assume that \(v_\infty\) is similar to the velocity dispersion (see Section 3). The encounter timescale may now be written

\[
\tau_{\text{enc}} = 7 \times 10^8 \frac{10^3 \text{ pc}^{-3} \text{ AU} M_\odot}{n} b_{\text{min}}^{-1} \frac{M}{10 \text{ km s}^{-1} \text{ yr}^{-1}} . \tag{6}
\]

We are interested in encounters within 100 AU. These can affect the planet without perturbing the inner binary. Following Djorgovski (1993) and Harris (1996) the mass of the cluster \((M_\text{cl})\) is given by

\[
\log (M_\text{cl}/2) = 0.4 (4.79 - M_V) \tag{7}
\]

where \(M_V\) is the cluster absolute magnitude and a mass to light ratio of 2 has been assumed. Table I contains a list of the properties of the cluster M4. The absolute magnitude is -7.2 which corresponds to a cluster mass of 1.25 \times 10^5 M_\odot. The mean number density \((\overline{N})\) inside the half-mass radius is given by

\[
\overline{N} = \frac{3 M_\text{cl}}{4 \pi \overline{m} r_h} \tag{8}
\]

where \(\overline{m}\) is the mean stellar mass (taken to be 1/3 M_\odot following Harris 1996) and \(r_h\) is the half mass radius which is
2.34 pc using the distance to M4 of 2.2 kpc. This gives a mean number density inside the half-mass radius of \(8 \times 10^5\) pc\(^{-3}\).

If the number density in the region of M4 where the system currently is of order \(10^4\) pc\(^{-3}\) then equation (6) gives the encounter timescale as 150 Myr. The exact distance of the system from the core of M4 is unknown so the timescale may be even larger than this. Indeed the initial orbit of the planet once formed may have been tighter than that currently observed (because of the softening effects of encounters - see below). Consequently the encounter timescale (for an encounter of closest approach comparable to the planetary orbit) may have been larger as well. If the system were at the core radius then the timescale for an encounter would be much less (4.5 Myr) as the number density is higher. This demonstrates that the planet is far more likely to survive if it is outside of the core of M4.

During encounters there is a tendency to equipartition energy between the total kinetic energy of the objects involved and the internal energy of the system (Reggie & Hut 2003). Hard systems have greater internal energy so encounters result in a tighter system and greater kinetic energy. Soft systems have greater kinetic energy which results in a widening of the system. So during encounters, hard systems get harder and soft systems get softer. The boundary between these two regimes is known as the hard/soft boundary \((R_ha)\) and is given by (Bonnell et al. 2001)

\[
R_{ha} = \frac{GM_1 M_2 (M_1 + M_2 + M_3)}{M_3 (M_1 + M_2) v_{enc}^3},
\]

where \(M_1, M_2\) and \(M_3\) are the masses of the inner binary, planet and encountered star respectively and \(v_{enc}\) is the encounter velocity which may be taken to be the same as the velocity dispersion for the cluster. This gives the hard/soft boundary for the planet as a separation of under 1 AU. The planet in this system is consequently always softly bound and encounters/flybys on average lead to it becoming less strongly bound. The outcomes of stellar encounters has been deeply investigated in the case of equal mass components (Hut 1984; Heggie & Hut 1993), but only a few investigations have been carried out for planetary systems (Bonnell et al. 2001; Davies & Sigurdsson 2001; Woolfson 2004).

In their calculations Bonnell et al. (2001) assumed that if a planet was soft it became unbound during an encounter. This is not necessarily the case as Woolfson (2004) has shown when he considered the survivability of planets in wide orbits. Woolfson (2004) considered an open cluster \((v_{enc} \sim 1 \text{ kms}^{-1})\) and integrated for \(10^7\) yrs. For planets with a of order 100 AU he found a large survival probability even for encounters with periastron distances of a similar size. This is because the outcome of an encounter depends on the position of the planet in its orbit and the relative orientation of the planetary orbit and the path of the encountered star. Woolfson (2004) found that encounters tended to soften rather than harden orbits as expected but with little change in energy. Consequently it is possible for the planet to undergo a number of encounters without unbinding it from the system. More numerical simulations are required, however, to verify this scenario before we can authoritatively say what the timescale for disruption of the hierarchical triple is.

In the scenario described above the planet has formed the inner binary evolves to form the binary millisecond pulsar observed today. As this binary is wide (191 d) the accretion onto the neutron star to spin it up to millisecond periods is transient i.e. long quiescent periods during which no accretion occurs and short outburst periods during which accretion occurs but the accretion rate is super-Eddington (see Taam, King & Ritter 2000). During these outbursts of super-Eddington accretion most of the transferred matter is expelled from the system while a small amount is accreted by the neutron star spinning it up to millisecond periods. The ejection of matter from the inner binary results in the planet moving further out. The change in semi-major axis of the planet due to mass lost is given by

\[
a = a_i \frac{M_i}{M},
\]

where \(a\) and \(M\) are the semi-major axis of the planet and total mass of the triple and the subscript i refers to their respective values prior to mass transfer and spin-up of the neutron star. If half a solar mass was ejected from the system to give the pulsar (assumed mass \(1.35 M_\odot\)) and the 0.34 \(M_\odot\) white dwarf then the semi-major axis increased by 30%. Although this only represents a small factor in encounter probability it means that the encounter timescale was longer until recently (as the white dwarf is young) which may help explain its survival.

### 4.3 How radial is the orbit?

In the model described above the system formed outside the half-mass radius of the cluster and has an orbit which does not take it into the core i.e. the orbit does not have a strong radial component. This is a prediction of the model and may be testable in future.

In the model described in S93 the system has been ejected from the core of the cluster due to an exchange encounter. From here the planet describes an orbit which takes it out of the core and back in again. The period of this orbit is similar to a crossing time (of order a Myr). It could be argued that although the system’s orbit takes it back into the core on a Myr timescale the system does not spend much time in the core as it passes through quickly. Consequently it is both more likely to be found outside the core and less likely to have undergone an encounter which unbinds the planet from its orbit.

If the system had a radial orbit, although it is more likely to be found outside the core, we should still expect it to have undergone a number of encounters in the core by now. This can be seen by the following simple argument. Assuming the orbit is entirely radial, in a medium with a density equal to the mean density inside the half-mass radius, and that it orbits between the core and the half-mass radius, the equation of motion is

\[
\frac{d^2r}{dt^2} = -\frac{GM_{cl}m}{2r_{cl}^3} r,
\]

and the system is a simple harmonic oscillator. It is simple to show that the system spends a fraction \(\arcsin(r_c/r_h)\) equal to 13 per cent of its orbit inside the core radius. Using the age of the white dwarf as a lower limit to the interaction timescale this corresponds to 62.4 Myr. As we show above it is probable that the system would have undergone a number of encounters in the core of the cluster within this timescale.

The main motivation for this paper, however, remains...
how the planet could have formed in a low metallicity environment and not whether the model proposed by S93 would have been disrupted in the core.

5 A LOW-KICK VELOCITY FOR THE NEUTRON STAR

Before accepting the picture sketched above, we should check that the system would not be unbound by the natal supernova kick felt by the neutron star. Gnedin et al. (2002) find that the relation between escape velocity ($v_{\text{esc}}$), velocity dispersion ($\sigma_{\text{obs}}$) and concentration ($c$) of a globular cluster is given by

$$\frac{v_{\text{esc}}}{\sigma_{\text{obs}}} = 3.7 + 0.9(c - 1.4) \, .$$

The data shown in Table 1 then give the mean velocity dispersion of 4 kms$^{-1}$ and an escape velocity of 15.25 kms$^{-1}$ from the core of M4. Any kick the neutron star received must have been less than this or the binary would have escaped from the cluster. Consequently the neutron star kick must have been small. Pfahl et al. (2002) have argued that there is a population of neutron-star binaries which receive low kicks. The neutron star in PSR B1620-26 may either have received one of these low kicks or could be at the low-velocity end of the high-kick velocity distribution.

The planet is not strongly bound at formation, so we might expect that a neutron-star kick would unbind it. The neutron-star kick, however, may be towards the planet rather than away from it, making the planet more strongly bound. Consequently, the presence of a planet in a wide orbit around the inner binary does not rule out the formation of the planet prior to the neutron-star kick.

6 DISCUSSION

We have suggested that the formation of the planet in the globular cluster M4 is possible through a gravitational instability in a circumbinary disc caused by an encounter with a passing star. This formation process is metallicity-independent and demonstrates that it is possible to form planets in globular cluster environments. We stress, however, that numerical simulations are required to investigate the possible outcomes of such an encounter. As the formation mechanism requires an encounter with a passing star, which is unlikely outside a cluster, we predict that similar objects are not in the field.

There is one other planetary system known around a pulsar. PSR B1257+12 has three Earth mass planetary companions (Wolczan & Frail 1992). These are thought to have formed through the disruption of the very-low-mass companion of a binary millisecond pulsar through a dynamical instability (Stevens, Rees & Podsiadlowski 1992; King et al. 2004). Once the low-mass companion is disrupted an accretion disc forms around the pulsar from which the planets are formed. Since the companion contained nuclear-processed material of high metallicity, Earth-like planet formation is possible. This process also occurs in a globular cluster although it cannot produce planets with as large an orbit as that in PSR B1620-26 (which has a periastron distance of 30 AU), or as heavy a mass (all the planets orbiting PSR B1257+12 have Earth masses).

To conclude, the globular cluster M4 is a very-low metallicity environment and so the standard model of planet formation should not be applied to the observed planetary system in it. Consequently the previously suggested methods for formation are unlikely. The Jupiter mass planet observed in M4 is a member of a hierarchical triple. When the inner binary underwent a common-envelope phase a circumbinary disc formed as a slow, dense, equatorial wind. This disc extended beyond 100 AU and we propose it underwent an encounter with a passing star. This encounter caused a gravitational instability in the disc and consequent planet formation. This planet was formed in a wide, eccentric, non-coplanar orbit around the inner binary. No other encounters/exchanges are required to explain the formation of this system.

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