Are there brown dwarfs in globular clusters?

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ABSTRACT

We present an analytical method for constraining the substellar initial mass function in globular clusters, based on the observed frequency of transit events. Globular clusters typically have very high stellar densities where close encounters are relatively common, and thus tidal capture can occur to form close binary systems. Encounters between main sequence stars and lower-mass objects can result in tidal capture if the mass ratio is $>10^{-2}$. If brown dwarfs exist in significant numbers, they too will be found in close binaries, and some fraction of their number should be revealed as they transit their stellar companions. We calculate the rate of tidal capture of brown dwarfs in both segregated and unsegregated clusters, and find that the tidal capture is more likely to occur over an initial relaxation time before equipartition occurs. The lack of any such transits in recent HST monitoring of 47 Tuc implies an upper limit on the frequency of brown dwarfs ($<15\%$ relative to stars) which is significantly below that measured in the galactic field and young clusters.

Key words: stars: formation – stars: brown dwarfs – stars: luminosity function, mass function – globular clusters and associations: general.

1 INTRODUCTION

Brown dwarfs have recently been shown to exist in significant numbers in the nearby galactic field (Nakajima et al. 1995; Rebolo, Zapatero-Osorio, & Martin 1995; Reid et al. 1999), young open clusters such as the Pleiades, M 35, and α Per (Bouvier et al. 1998; Barrado y Navascues et al. 2001, 2002) and star-forming regions including the Orion Trapezium Cluster, Taurus-Auriga, ρ Ophiuchi (McCaughrean et al. 1995; Hillenbrand & Carpenter 2000; Luhman et al. 2000; Muench et al. 2002; Briceño et al. 2002; Luhman & Rieke 1999; Muench et al. 2003; Preibisch, Stanke, & Zinnecker 2003). Analyses show that brown dwarfs may well be as frequent as stars (Chabrier 2002), and thus although they are insignificant in terms of their mass contribution, their existence and numbers pose significant constraints on theories for the origin of the Initial Mass Function (IMF).

One standard theory for the origin of the IMF is that the masses are determined by the local thermal Jeans mass coupled with dynamical processes during the star formation process (e.g. Bonnell et al. 1997; Klessen, Burkert & Bate 1998; Bonnell et al. 2001; Larson 2002; Bate, Bonnell & Bromm 2003). In this scenario, the low-mass end of the IMF arises due to dynamical interactions that eject forming stars from their natal environments, thus truncating their accretion and limiting their mass (Reipurth & Clarke 2001). A recent numerical simulation has shown that this process can occur in dense stellar environments, such that objects that would otherwise accrete sufficiently to become stars are reduced to being brown dwarfs (Bate, Bonnell, & Bromm 2002). Establishing the low-mass end of the IMF in differing environments is therefore important, in order to establish whether or not the IMF is universal, and if not, which physical parameters play the dominant role in defining its form. In particular, globular clusters may yield important clues, as their low-metallicity environment should result in lower cooling rates and thus larger Jeans masses (e.g. Larson 1998). In fact, observations of the low-mass stellar component in globular clusters yields IMFs similar to young stellar clusters and the Galactic field (Paresce & De Marchi 2000). This

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would imply that globulars should have similar numbers of brown dwarfs as have been found in nearby regions.

In this letter, we discuss an analytical method for constraining the brown dwarf population of a globular cluster, based on observations of transits. In Section 2, we show that if significant numbers of brown dwarfs are present in a globular cluster, tidal capture would lead to a population of close binary systems comprising a normal main sequence star and a brown dwarf, and that some fraction of these systems should then exhibit transits. In Section 3, we examine how the frequency of transit events in a given cluster can be used to quantify the imposed constraint on the substellar mass function in the cluster. In Section 4, we look at the results of a recent HST monitoring study of 47 Tuc searching for planetary transits (Gilliland et al. 2000), and argue that the complete lack of transits in their data implies a dearth of brown dwarfs as close companions.

## 2 TIDAL CAPTURE

Tidal capture occurs when two objects pass close enough together to raise tides with energy equivalent to the excess kinetic energy of their mutual orbits. In order for the capture mechanism to operate, the gravitational perturbation from this passage should be large, implying in turn that the mass ratio of the two stars should not be too small: very low-mass perturbers do not raise large tides. An additional requirement is that both objects should be single, as hard binaries would repel any perturbers. Finally, to be efficient in a statistical sense, the frequency of close interactions should be significant, as is easily satisfied in a globular cluster.

Tidal capture was initially conjectured as the source of low-mass X-ray binary systems found in globular clusters (Fabian, Pringle & Rees 1975). The energy raised in a tide (Press & Teukolsky 1977; Lee & Ostriker 1986) by an object of mass $M_p$ passing within a distance $R$ of a star of mass $M_*$ and radius $R_*$ is

$$E_{\text{tide}} \approx \frac{GM_*^2}{R_*} \left( \frac{M_p}{M_*} \right)^2 \left( \frac{R}{R_*} \right)^6,$$

where $G$ is the gravitational constant. The detailed model analysis of Lee & Ostriker (1986) showed that, for $n = 3/2$ polytropes appropriate for low-mass main-sequence stars, including the roughly equal contributions from the quadrupole and octopole terms results in a similar expression for the tidal energy. Here we consider only the tides raised on the primary by a low-mass perturber, as the smaller radius of the secondary would necessitate a direct collision before sufficient energy was raised in its tides.

Comparing this tidal energy to the excess kinetic energy over that of a bound orbit at a separation of $R$, Fabian et al. (1975) showed that in order for the star to capture the perturber, it must pass within a periastron distance $R = a_c$ of the star,

$$a_c = \frac{\left( \frac{GM_*}{R_* v_q} \right)^2 (1 + q)}{\sqrt{q}},$$

where $v_q$ is the velocity dispersion of the system and $q = M_p/M_*$ is the mass ratio (see also Lee & Ostriker 1986). It is evident from these equations that if the mass ratio of the encounter is too extreme, the tidal energy is very low and the capture radius $a_c$ becomes comparable to or smaller than the stellar radius $R_*$. This effect is illustrated in Figure 1, which plots the capture radius as a function of the mass ratio, assuming a fixed primary star with mass $M_* = 0.5M_{\odot}$ and radius $R_* = 0.57R_{\odot}$ (i.e. assuming $R \propto M_0.8$ for main sequence stars), and a cluster velocity dispersion of $v_d = 10\, \text{km}\, \text{s}^{-1}$. We see that as the mass ratio of the encounter decreases, the capture radius decreases dramatically until, for $q \leq 10^{-3}$, the capture radius becomes smaller than the stellar radius. For example, the capture radius of a mass ratio of $q = 0.1$ is $a_c \approx 2.4R_*$ while for a mass ratio of $q = 0.02$, the capture radius decreases to $a_c \approx 1.8R_*$. In more detail, the capture radius in fact needs to exceed the sum of the radii of the two interacting objects, i.e. the distance at which the two sources would collide. For our fiducial $0.5M_{\odot}$ primary, perturbers with $q \geq 0.16$ will be stellar (i.e. $\geq 0.08M_{\odot}$), and we use

$$R_p \approx q^{0.9} R_*,$$

while for lower-mass, brown dwarf perturbers, we use

$$R_p \approx 0.1R_{\odot},$$

as the radius is roughly independent of mass for these low-mass objects supported by electron degeneracy pressure. Figure 1 then also plots the collisional radius

$$R_c = R_* + R_p.$$
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...is, in the gravitationally focused regime, simply proportional to the difference between $a_c$ and $R_c$ (see Section 3). The essential result from Figure 1 is that perturbers with mass ratios of $q \geq 10^{-2}$ have a non-negligible chance of being tidally captured if they undergo a close encounter with a low-mass main sequence star in a globular cluster environment.

As a check, we can compare this capture radius to that found in numerical simulations of encounters between objects with unequal masses. Encounters in a globular cluster with $v_d \approx 10 \text{ km s}^{-1}$ are well approximated as having a low relative velocity at infinity. In this situation, Benz & Hills (1992) (for $q = 0.2$) and Lai, Rasio, & Shapiro (1993) ($q = 0.1$) found that capture occurred when the two stars pass within twice the sum of their radii. This is in good agreement with Figure 1 where, for mass ratios of $q \approx 0.1$, $a_c \approx 2R_c$.

In the following analysis, we assume that the typical star in a globular cluster has a mass and radius of $0.5M_\odot$ and $0.57R_\odot$, respectively, while any brown dwarfs present have fiducial masses and radii of $0.03M_\odot$ and $0.1R_\odot$ respectively. Once a brown dwarf is captured to form a binary, the system will circularise on a relatively short timescale (Mardling 1996). In the case of a high eccentricity binary circularising at constant angular momentum, the resultant binary separation is then $\approx 2a_c$. (Mardling 1996). Thus we take the mean binary parameters to be a separation of $2a_c \approx 4R_c \approx 2R_\odot$, and an orbital period of $\approx 14$ hours.

In our approach, we are implicitly assuming that the deposition of the tidal energy has little effect on the primary’s structure. This is justified in that the total energy dumped into tides is but a small (2.5 %) fraction of the binding energy of the star and that most of this is in the form of bulk motion of the star’s spin. The deposition of this energy is sufficiently deep in a $n = 3/2$ polytope and the damping sufficiently long such as to have minimal effect on our result (Ray, Kembhavi & Antia 1987; Kochanek 1992).

3 CLOSE BINARIES WITH BROWN DWARF SECONDARIES

Next, we need to calculate the expected number of tidally-captured close binary systems containing brown dwarfs from the total population of brown dwarfs present in the globular cluster. Including gravitational focussing the timescale, $\tau_c$, for a star of mass $M_*$ to pass within a distance $R$ of another star is found from (Binney & Tremaine 1987)

$$
\frac{1}{\tau} = 16\sqrt{\pi n(r)v_{\text{disp}}R^2}\left(1 + \frac{GM_*}{2v_{\text{disp}}^2R}\right),
$$

where $n(r)$ is the density of stars in the cluster as a function of the distance $r$ from the cluster centre. For a globular cluster with a velocity dispersion of $v_d \approx 10 \text{ km s}^{-1}$ (e.g. 47 Tuc; Gebhardt et al. 1995), the second (gravitationally focussed) term of the parentheses is much larger than unity and thus dominates, and the rate is then proportional to $R$ rather than $R^2$. Thus, the rate of encounters that result in capture (but not in collisions) is proportional to $a_c - R_c$, which we henceforth define as $R_\text{c}$. We can then write Equation (6) as

$$
\tau_c \approx 7 \times 10^{10} \frac{10^5 \text{pc}^{-3}}{n(r)} \frac{v_d}{10 \text{ km s}^{-1}} \frac{R_c}{R_\text{c}} \frac{M_\odot}{M_*} \text{ years.}
$$

Finally, if we assume the age of the cluster, $t_{\text{age}}$, to be $\approx 10^{10}$ years, then $\tau_c \gg t_{\text{age}}$, and we can then estimate the probability of capture as

$$
P_{\text{capt}} = \frac{t_{\text{age}}}{\tau_c}.
$$

A difficulty arises in that, in addition to the actual numbers of brown dwarfs, we do not know their spatial distribution $n(r)$. At one extreme, there is the possibility that the brown dwarfs simply follow the stellar distribution. However, it is much more likely that the cluster is relaxed and that there is mass segregation, with the other extreme scenario being that the brown dwarfs are in a state of energy equipartition with the stars.

These two extremes are illustrated in Figure 2. The solid line represents the $W=9$ King profile (or concentration level of $c = \log(R_{\text{tidal}}/R_\text{core}) \approx 2$; Binney & Tremaine 1987), appropriate for 47 Tuc (Trager, King, & Djorgovski 1995), assuming an equal number of brown dwarfs and stars in the cluster, and normalising to a central stellar number density of $10^5 \text{ pc}^{-3}$ (Webbink 1985). For the first of our extremes, the brown dwarf distribution would follow this curve too.

The dashed line is then the brown dwarf distribution under the assumption of equipartition of energy, computed from a multi-mass King model (da Costa & Freeman 1976). We have simplified the construction of this model by considering just two mass bins (‘stars’ and ‘brown dwarfs’), and by neglecting the contribution of the latter population to the cluster potential. Since the brown dwarfs are on average about an order of magnitude less massive than the stars, we assign a $\sigma$ (the 1D velocity dispersion) in the King distribution function for the brown dwarfs that is three times the corresponding $\sigma$ for the stars. Again, we normalise the resulting brown dwarf profile in Figure 2 such that the total number of brown dwarfs is equal to the total number of stars. As expected, the equipartition model is significantly depleted in brown dwarfs in its inner regions.

Pending N-body models of globular clusters that include a realistic number of stars and binaries, it is unclear which of the profiles shown in Figure 2 is more appropriate over the balance of the cluster lifetime. To date, Monte Carlo simulations (which omit binaries; Fregeau et al. 2002) and N-body simulations of less populous clusters (Hurley & Shara 2002) show a marked decrease in the number of low-mass objects in the cores of clusters. The segregation occurs over a number of relaxation times, but does not appear to reach the level of equipartition. Our two extreme scenarios are therefore likely to bracket the actual brown dwarf density profile. What remains undetermined is the total number of brown dwarfs in globular clusters, i.e., the normalisation of the distribution.

Proceeding, we next estimate the capture rate using the stellar distribution plotted in Figure 2, sampling stars that appear (in projection) to be located between the centre of the cluster and the half-mass radius, as was the case for the HST observations of 47 Tuc (Gilliland et al. 2000).

For each of the stars in the sample, we select orbital parameters from the King distribution function and follow their orbits in the fixed King potential. At each instantaneous location of each sampled star, we compute a capture rate based on Equation (8) and an assumed brown dwarf profile, whose shape is given by either of the extremes shown.
Figure 2. The radial density distribution of stars (in stars $\text{pc}^{-3}$) is plotted using a King model with $W = 9$ (solid line). The density is normalised to the core density of 47 Tuc (Djorgovski & Meylan 1993). The distribution of brown dwarfs following energy equipartition is also plotted (dashed line), assuming equal numbers of brown dwarfs and stars in the cluster.

Figure 3. The fraction of systems with brown dwarf companions as a result of tidal capture plotted against the relative number of brown dwarfs to stars in the cluster. The upper curve (open squares) assumes that the brown dwarfs follow the same density distribution as the stars over the full lifetime of the cluster. The middle curve (pentagons) shows the fraction of systems captured within an initial cluster relaxation time ($t_{rh} \approx 3 \times 10^9$ yrs; Harris 1996), before mass segregation becomes important. The lower curve (filled triangles) shows the capture probability assuming that the brown dwarfs are always in equipartition with the stars over the cluster lifetime. The dashed line shows the upper limit of $4 \times 10^{-4}$ stars with close brown dwarf companions implied by the lack of transits seen in the 47 Tuc data of Gilliland et al. (2000) (see text).

in Figure 2, and whose normalisation is adjustable. In this way, we accumulate a probability that the star has captured a brown dwarf, for both assumptions about the (time invariant) brown dwarf distribution.

Figure 3 then shows the resulting fraction of stars with a tidally-captured brown dwarf companion, as a function of the ratio of the total number of brown dwarfs to stars in the cluster. The open squares correspond to the assumption that the brown dwarf density distribution follows that of the stars over the entire lifetime of the cluster, while the filled triangles illustrate the case where the brown dwarfs follow an equipartition distribution over the entire lifetime. Predictably, the capture rates are much lower in the latter case. Lastly, the filled pentagons correspond to the case where the brown dwarf distribution follows the stars for the first relaxation time of the cluster ($\approx 3 \times 10^9$ years; Harris 1996), and that the capture rate is negligible thereafter, as justified by the lower capture probabilities seen once equipartition is achieved.

For example, assuming that the stars and brown dwarfs follow the same distribution and are equal in number, then 1% of the stars should have brown dwarf companions after $10^{10}$ yrs. Conversely, for equal numbers of brown dwarfs and stars in a fully segregated distribution, roughly only 0.05% of the stars should have brown dwarf companions. Finally, for the scenario with a cluster equal in number of stars and brown dwarfs, unsegregated for an initial relaxation time of $t_{rh} \approx 3 \times 10^9$ yrs, and segregated thereafter, $\approx 0.3\%$ the stars end up with brown dwarf companions.

The above estimates neglect the possibility that the cluster is undergoing core collapse. In such a scenario, the core density would have increased in the recent past and thus the core number densities throughout much of the lifetime of the cluster would have been smaller. This scenario appears unlikely considering the relatively low concentration level of the density profile and the size of the core (Howell, Guhathakurta & Gilliland 2000). We can make a crude estimate of such a scenario by taking the segregated distribution of the brown dwarfs as being the initial distribution for both stars and brown dwarfs. This results, as above, in only 0.05% of the stars having brown dwarf companions.

4 THE CASE OF 47 TUC

Gilliland et al. (2000) used the Hubble Space Telescope to monitor the globular cluster 47 Tuc continuously over 8.3 days, obtaining imaging photometry every few minutes, searching for transits. The HST WFPC2 field-of-view spanned a region from the core out to the half-mass radius of the cluster and contained $\approx 34000$ stars. No transit events were detected during the monitoring campaign.

The goal of the campaign was to detect hot Jupiters (i.e. in close orbits, cf. 51 Pegasi et al.) in orbits of 2–4 days around main sequence stars in the cluster. However,
if present as close companions, brown dwarfs would also have been readily detectable via transits. The radius of a brown dwarf is essentially the same as that of Jupiter, so brown dwarfs should have cooled to temperatures of less than 1000 K (Burrows et al. 1997), rendering them effectively black when viewed against a stellar disk.

The probability of a transit in a given system depends on \(\sin(i)\), the orbital inclination with respect to the line-of-sight, and the orbital separation, with a transit requiring \(\sin(i) < (R_\ast + R_{BD})/a\). For the hot Jupiters hoped for by Gilliland et al. (2000), typical orbital parameters would have predicted a 10% probability that any given system would be inclined such that the planet would transit the stellar disk, leading Gilliland et al. (2000) to conclude that \(\lesssim 10^{-3}\) of the stars in 47 Tuc have hot Jupiters. This fraction is significantly lower than seen for nearby galactic field stars, and one plausible explanation is that the low metallicity in globular clusters makes planet formation there a very inefficient process.

For tidally-captured brown dwarfs, however, the orbital separation would be just \(\approx 4R_\ast\), orbit, and thus the chance of a transit in a given system rises to 25%. Thus, the same null result can be used to infer that \(\lesssim 4 \times 10^{-3}\) of the stars in 47 Tuc have close brown dwarf companions today. Therefore, in the unlikely case where the stars and brown dwarfs are in equipartition for the full lifetime of the cluster, Figure 3 shows that the total number of brown dwarfs in 47 Tuc must be less than the number of stars. For the more probable scenario, where the cluster is initially unsegregated for the first relaxation time, Figure 3 implies that the number of brown dwarfs is \(\lesssim 15\%\) of the number of stars.

Our fiducial calculations presented above assumed 0.579 \(M_\odot\) stars with 0.579 \(R_\odot\) radii, while in their analysis of 47 Tuc, Gilliland et al. (2000) assumed typical parameters of 0.81 \(M_\odot\) and 0.92 \(R_\odot\) for the stars in their 47 Tuc sample. For the sake of consistency, it is thus worth estimating the difference their assumptions would have on our calculations. The higher-mass and larger-radius stars have higher rates of tidal capture, and working through our analysis again, we find the expected fraction of stars with tidally-captured brown dwarf secondaries to be a factor 2 higher than estimated for our fiducial case. This translates into an increase by a factor 2 for the predicted fraction of systems with close brown dwarf companions: in the scenario where the cluster contains equal numbers of brown dwarfs and stars, and where captures occur only during an initial relaxation time when the brown dwarfs follow the stellar distribution, the expected fraction of stars with brown dwarf companions would increase from 0.3% to 0.6%, and the expected number of transits would double. Thus, the absence of transits in 47 Tuc would imply a factor of 2 lower brown dwarf frequency, i.e. \(\lesssim 7.5\%\) of the stellar frequency.

It is also worth considering what would happen if the typical brown dwarf mass was decreased from 0.05 \(M_\odot\) to 0.01 \(M_\odot\), with a constant radius of \(\sim 0.1R_\odot\). The cross section for capture reduces to \(\approx 60\%\) of its former value and thus the fraction of stars with brown dwarf companions then decreases from 0.3% to 0.18%. The number of expected transits would decrease by 60%, and thus the lack of transits would imply a 60% higher upper limit on the number of brown dwarfs than in our fiducial case, i.e. the total brown dwarf population is constrained to be \(\lesssim 25\%\) of the stellar population. However, even though the total number of brown dwarfs has gone up, their contribution to the total cluster mass remains negligible.

In conclusion, taking the most plausible model for the dynamical evolution of 47 Tuc and thus of the brown dwarf capture rates, the lack of any detected transits in the cluster implies a significantly lower ratio of brown dwarfs to stars (\(\lesssim 15\%\)) than has been found in nearby clusters and the solar neighbourhood (\(\sim \) unity). This in turn implies that the initial mass function is not in fact universally constant below the hydrogen burning limit.

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