A Simple Dynamical Model for \( \omega \) Cen

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ABSTRACT
We construct a simple dynamical model of the massive globular cluster \( \omega \) Cen. The model includes simple treatments of dynamical evolution in a galactic tide, and evolution of single stars. Binary stars and rotation are neglected. The model approximately fits observational data on the surface brightness profile, the profile of radial velocity dispersion, and the main sequence mass function at two radii.

Key words: stellar dynamics – methods: miscellaneous – stars: luminosity function, mass function – globular clusters: individual: \( \omega \) Cen

1 INTRODUCTION

Dynamical modelling of individual globular clusters has a long history (see, for example, the review by Meylan & Heggie 1997). For the most part the models used have been variants of the King-Michie model. While incorporating essential aspects of stellar dynamics they have nothing to say about dynamical evolution, which has been the focus of theory for many years.

Dynamical evolutionary models, based on Fokker-Planck codes, have been constructed for a number of individual clusters by members of Cohn’s group (Grabhorn et al 1992, Dull et al 1997, Drukier 1995). These models were tested against available observational data on the surface brightness profiles, individual stellar radial velocities, sometimes ground-based mass functions, and even data on the exotic stellar components in a cluster (Phinney 1993).

In the meantime a wealth of high quality data on the main sequence mass function down to near the H-burning limit has been acquired, thanks mainly to the high resolution of HST (e.g. Elson et al 1995, Cool et al 1996, Santiago et al 1996, von Hippel et al 1996, Piotto et al 1997, King et al 1998, Marconi et al 1998, Pulone et al 1999, Paresce & De Marchi 2000, De Marchi et al 2000, Andreuzzi et al 2001, where we have restricted the credits to one citation per lead author). Though static (King-like) models have been constructed which incorporates some of this data (Anderson 1997, Sosin & King 1997, Saviane et al 1998, Piotto & Zoccali 1999, in addition to some of the foregoing references), we are not aware of any evolutionary models which do so.

Our aim in this paper is a first step in this direction, i.e. to construct a dynamical evolutionary model of a well observed, old, galactic globular cluster, so as to represent

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it might well be better to treat the two kinds of data separately, but we have followed Meylan in treating the surface brightness profile as a single data set. The surface brightness has been adjusted approximately for interstellar absorption. Much doubt was cast on the reliability of this surface brightness profile by van Leeuwen et al. (2000), on the basis of a proper motion study, but more recently the results have been reconciled (van Leeuwen & Le Poole 2002).

Our radial velocity data is taken from Meylan et al. (1995). We have used the binned data presented in this paper, rather than individual values in Meylan’s catalogue. This implies that the largest radius is at about 28pc, compared with a nominal tidal radius of about 70pc (Meylan 1987). Therefore at large radii the surface brightness profile is the only constraint.

For the mass function we have used the luminosity functions presented by De Marchi (1999), converted to a mass function using the model of Baraffe et al. (1997) for metallicity $[M/H] = -1.5$. We have assumed that the data of De Marchi give the numbers of observed stars per magnitude bin in the two fields (with his stated adjustment by 0.1 dex for the outer field). This assumption is consistent with the stated numbers of objects in each field. The two fields for which mass functions are given are stated to be at radii of about 7′ and 4.6′, and these are the values we have adopted. Nevertheless, from an inspection of the image fields in relation to ω Cen, we consider that the outer field is centred more nearly at 7.4′. We have also corrected these radii for the ellipticity, using values from Geyer et al. (1983). A more recent determination of the ellipticity (van Leeuwen & Le Poole 2002) suggests that the ellipticity is even larger.

### 2.2 Features of the Monte Carlo code

The Monte Carlo code (Giersz 1998, 2001) models a spherically symmetric stellar system by a number of spherical shells characterised by radius, energy and angular momentum. As described in these papers the number of such shells equals the number of stars in the real system. In the present application, however, the number of shells is much smaller than the number of stars, just as in the earlier formulations by Hénon (1971) and Stodolakiewicz (1982), and so each shell is referred to as a superstellar shell. Each superstellar shell represents a large number of stars of the same stellar mass, energy and angular momentum. In this investigation the initial number of shells was chosen in the range from 1024 to 16384. Where individual models are discussed below, 16384 shells were used.

Very briefly, the code chooses the radius of each star in a manner appropriate to its energy and angular momentum. The energy and angular momentum are adjusted in a manner dictated by the theory of two-body relaxation. These processes are repeated until the required evolution time (which we assume to be 12 Gyr) has elapsed.

For dynamical purposes, stellar evolution is treated in a very simple manner. At the start, each star is assigned an evolution time (depending on its initial mass) according to the prescription adopted by Chernoff & Weinberg (1990). At this time the star is replaced by a degenerate remnant whose mass is also determined as in Chernoff & Weinberg, except for one point: for an initial mass in the range $4.7M_\odot < m < 8.0M_\odot$ the remnant is assumed to be a neutron star of $1.4M_\odot$. Neutron stars are given no kick, and so all are retained, except those which may escape by relaxation or tidal overflow; see also Sec.3.3.

Now we discuss briefly the data output from the Monte-Carlo code. At any time a model is defined by the radius, energy, angular momentum and mass of its supershells. The resulting surface brightness and radial velocity dispersion profiles may be very noisy, for two reasons. First, each shell gives a cusp in surface brightness at its edge. Secondly, these profiles are dominated by the relatively small number of evolving stars. It is better, therefore, to represent each superstellar by a space density, corresponding to its orbital motion. As a compromise, we represented each superstellar by 100 radii, chosen with the correct radial distribution for a superstellar with given energy and angular momentum.

### 2.3 Conversion to observational data

Each shell of nominal radius $r$ is taken to represent a uniform spherical shell of radii $0.9r$ and $1.1r$, to further reduce the effects of the cusp which would exist at the projected edge of a thin shell. This shell also corresponds to known values of the radial and transverse velocity. It is therefore easy to compute a density-weighted velocity dispersion along a line of sight. Because the observed radial velocities are obtained for giants, only shells corresponding to non-degenerate stars above $0.7M_\odot$ were included. (Though not all such stars would be giants, it was assumed that mass segregation in the range of masses from $0.7M_\odot$ to the turnoff mass could be ignored.)

The mass functions were obtained in a similar way. The most problematic area is creation of the surface brightness profile, which requires computation of the luminosity of each star from its mass and age (12 Gyr). For main sequence stars we used the formulae of Eggleton et al. (1989), but scaled the evolution time (i.e. the time for the end of non-degenerate phases of evolution) to coincide with those used in the Monte Carlo code (i.e. those of Chernoff & Weinberg 1990).

Applied to evolving stars, this approach led to the occurrence of a very few shells with very high luminosity, which produced a very rough (“bumpy”) surface brightness profile. Therefore we computed the time-averaged luminosity during these phases of evolution, and assigned this luminosity to each evolving star (i.e. post-main sequence but non-degenerate stars). For this purpose we used the code of Hurley et al. (2000). We checked that the mean luminosity of stars brighter than $m_V = 16$ in the catalogue of Lyngá (1996) is approximately consistent with what would be obtained from the code.

The surface brightness was corrected for extinction. A simple bolometric correction was also applied (Reed 1998).1

### 3 FINDING A MODEL OF ω Cen

#### 3.1 Initial conditions

Our initial model is a King model (King 1966), specified by its total mass, $M$, and scaled central potential, $W_0$. The

1 Note that, in his formula (5), $T$ should be replaced by $10^{-4}T$
initial tidal radius was set from observational estimates of current values \( (M = 3.9 \times 10^4 M_\odot) \) [Pryor & Meylan 1993], \( r_t = 63.9 \text{pc} \), from data in Trager et al (1993) and Peterson (1993)), assuming that \( r_t \propto M^{1/3} \).

Guided by recent observational data (Kroupa 2001) we adopted an initial mass function in the form of a continuous broken power law

\[
    f(m) \propto \begin{cases} 
        m^{-\alpha_1}, & \text{if } m_1 < m < m_2; \\
        m^{-\alpha_2}, & \text{if } m_b < m < m_2.
    \end{cases}
\]

We quickly realised that \( \alpha_1 \) was quite tightly constrained near \( \alpha_1 = 1 \) by the mass functions, and adopted this value. We also fixed \( m_1 = 0.1 M_\odot \) and \( m_2 = 15 M_\odot \). The value of \( m_1 \) is a little lower than the lowest mass included in the mass functions. Specification of the upper mass limit \( m_2 \) is relatively unimportant in our models: because the number of superstars is so modest, all shells have masses considerably below \( m_2 \), unless \( \alpha_2 \) is rather low. The mass function is therefore specified by the mass at the break point between the two power laws, \( m_b \), and the slope of the initial mass function for higher masses, \( \alpha_2 \).

In summary, each initial model is specified by the four parameters \( M, W_0, \alpha_2, m_b \).

3.2 Exploration of initial conditions

Using 4096 shells, the computation of a single model takes a few minutes on a 400MHz Sun workstation. After the Monte Carlo code has run, the output can then be compared with the three kinds of data, i.e. the profiles of surface brightness and velocity dispersion, and the mass functions at two observed radii. This was done both visually and by a calculation of \( \chi^2 \). For the latter purpose, estimates of the errors of the observational data were adopted. Because of the Monte Carlo nature of the code, the predictions of each model are subject to statistical uncertainty, but no attempt was made to quantify this for purposes of computation of \( \chi^2 \).

After preliminary examination of a number of models, the parameter space was explored somewhat more systematically, but still manually, by considering the effect of variation in each of the parameters. The conclusions are summarised in Table 1, which also gives the ranges of values of the four parameters outside which the fit was observed to deteriorate grossly (as judged both by graphical display and by the values of \( \chi^2 \)). At this stage the best parameter values found were approximately \( M = 10^7 M_\odot, W_0 = 8, \alpha_2 = 1.9 \) and \( m_b = 0.6 M_\odot \).

In order to improve these preliminary values several methods were tried, and we describe here the two most successful ones. The first was simply to conduct a Monte Carlo search of the range constrained by the values in Table 1, i.e. by uniform random sampling of the corresponding hypercube in parameter space. By plotting the resulting values of \( \chi^2 \) against each parameter, it was quite easy to determine the best values with acceptable accuracy. This is a relatively slow method, however, and requires thousands of Monte Carlo runs. A faster and automatic method, requiring only of order 50 runs, treats our problem as one of stochastic optimization, the stochasticity arising from the nature of the Monte Carlo method used for the dynamical evolution. Known simply as DIRECT, for “Dividing RECT-angles” (Jones 2001), it proceeds by subdividing the search domain in a manner that balances global and local searches for a minimum.

3.3 Features of a typical model

Both methods described in the previous subsection led to fairly consistent conclusions. The first method yielded initial conditions \( M \simeq 1.0 \times 10^7 M_\odot, W_0 \simeq 7.7, \alpha_2 \simeq 1.9 \) and \( m_0 \simeq 0.6 M_\odot \), while DIRECT gave results in the ranges \( 0.94 \times 10^7 M_\odot < M < 1.23 \times 10^7 M_\odot \), \( 7.4 < W_0 < 7.9, 1.95 < \alpha_2 < 2.12 \) and \( 0.63 M_\odot < m_b < 1.14 M_\odot \). One of the best models is illustrated in Fig.1. The current mass is \( 3.6 \times 10^6 M_\odot \), which is perhaps a little too small: the resulting tidal radius is perhaps a little too small to account for the surface brightness profile at the largest radii. On the other hand the modelling of the tide as a cutoff is inaccurate near the tidal radius, and so a good fit here may not be achievable.

We have not tried to adjust the initial mass function on the lower main sequence to improve the detailed fit with the mass function. Of greater concern is the fact that the model mass functions are often slightly but systematically too low or high, at the inner and outer radii, respectively. The suggestion that the ellipticity exceeds the value we used (see Sec.2.1) would help.

In attempting to construct a multi-mass King model for \( \omega \) Cen, Meylan (1987) drew attention to the need for heavy remnants, by which we mean here both neutron stars and white dwarfs. Our models include such remnants, which arise from the evolution of stars above the turnoff mass in our mass function. Their proportion by mass at the present day, in our best models, is of order 50%, and even so it is not possible to quite reach the observed velocity dispersion at small radii. This problem worsens if all neutron stars are removed at birth (i.e. it is assumed that each receives a kick exceeding the escape speed). Though the total fraction of degenerate stars declines only to about 40%, the central velocity dispersion drops to about 12km/s.

Several other features of these models may be of interest. The models are mildly anisotropic. If the anisotropy parameter \( \beta \) is defined by \( \beta = 1 - \langle v_r^2 \rangle / \langle v_\beta^2 \rangle \), where \( v_r, v_\beta \) are the radial and transverse velocities \textit{in the plane of the sky} (i.e. as measured by proper motions), we find that \( \beta \) varies from a value of about 0 within the innermost 2pc to about \(-0.15 \) at a radius of 10 pc, and then rises towards 0 as the tidal boundary is approached. At 20 pc, close to the radius where King & Anderson (2002) found only mild anisotropy, \( \beta \simeq -0.05 \).

The models also exhibit mild mass segregation. In the model exhibited in Fig.1, the mean mass of unevolved stars is nearly \( 0.40 M_\odot \) at all (projected) radii less than about 1pc, and about 0.34 beyond 10pc; the mean mass declines steadily between 1 and 10pc. The primordial value (over the same range of stellar masses) was \( 0.35 M_\odot \). For a single power law \( f(m) dm \propto m^{-\alpha} dm \) between the minimum mass and turnoff, the variation of mean mass corresponds to a variation of \( \alpha \) of about 0.5. Relative to the centre, therefore, there is an excess of stars of lowest mass at the outside of the cluster by a factor of order 3 (0.5dex). Anderson (2002) has observed slight mass segregation by comparing the luminosity function at the centre relative to a field at about 7'. His faintest stars are underabundant at the centre by about 0.2dex, but do not extend to such low masses.
Table 1. Preliminary parameter values.

| Parameter and range | effect of increase                                      | effect of decrease                                      |
|---------------------|--------------------------------------------------------|--------------------------------------------------------|
| $6 \times 10^6 \, M_\odot < M < 1.4 \times 10^7 \, M_\odot$ | mf and $v^2$ too great                                | mf and $v^2$ too low                                   |
| $7.1 < W_0 < 8.6$   | sfb too concentrated                                   | underluminous at centre                                |
| $1.7 < \alpha_2 < 2.2$ | mf and sfb too high                                     | model underluminous; central $v^2$ too small; mf at inner radius poor |
| $0.6 \, M_\odot < m_b < 0.95 \, M_\odot$ | sfb too concentrated, centre overluminous, mf wrong | mf at smaller radius too low                           |

Notes: mf = mass function; sfb = surface brightness profile; $v^2$ = radial velocity dispersion

Figure 1. One of the best models. Here $M = 0.94 \times 10^7 \, M_\odot$, $W_0 = 7.6$, $\alpha_2 = 1.95$ and $m_b = 0.63 \, M_\odot$; the number of superstars was 16384. Left: logarithmic surface brightness profile (in units of 10.00 $V$ mag per square arc minute) against $R$ (pc); lower right: velocity dispersion profile (km/s); upper right: mass function (stars per unit mass per square arc minute; the upper and lower plots correspond to the inner and outer observed radii, respectively).

The fact that the signatures of dynamical evolution in $\omega$ Cen are not great is no surprise, but this is perhaps the first time they have been quantified theoretically.

4 DISCUSSION AND CONCLUSIONS

4.1 Discussion

Before summarising the tentative findings of this study, it is important to set out some aspects of $\omega$ Cen which we have not included.

The most important constituent we have omitted is any population of binary stars. At the expense of introducing further parameters, it would have been possible to do so by treating the population as dynamically “inert”, i.e. as simply a population of slightly more massive stellar objects. Nevertheless it would have been desirable to treat their stellar evolution in a fundamentally different way from that of the single stars, and so for this exploratory study they were neglected entirely. If included, they might have helped to deepen the potential well and increase the central velocity dispersion, without unduly disturbing the surface brightness there. They might also assist the retention of neutron stars, with the same result. Our treatment of the evolution of single stars could also be improved significantly.

Dynamically, we have taken no notice of the fact that $\omega$ Cen is rotating (see Merritt et al 1997). For purposes of dynamical evolution it seems that rotation does not play a dominant role (Spurzem 2001), but our practical reason for omitting rotation is that the code cannot cope with it. The rotation of $\omega$ Cen may be a symptom of past mergers (Norris et al 1997), and this possibility is ignored here also.

In fitting models to observational data we have ignored the kinematical evidence from internal proper motions (van Leeuwen et al 2000). This data appears to be entirely consistent with the radial velocity, which we did employ, and also covers a similar range of radius within the cluster. Another reason for neglecting this data is that we have it in mind to apply our methods to several other clusters for which such data is lacking entirely.

A significant dynamical mechanism that we have also ignored is the time taken for stars to escape. As Baumgardt (2001) has shown, the effect is that the lifetime in a tidal field is not proportional to the relaxation time, as we would find using our Monte Carlo code. On the other hand we have also simplified the treatment of the tidal boundary condition.
by supposing that the tide is steady, as for a cluster on a
circular galactic orbit. We have made no attempt to model the
tidal debris of ω Cen, whose mass is considerable (Leon et al 2000).

An issue which we would have liked to address is the
uniqueness of the model initial conditions that we have
found. While we have explored the parameter space in var-
cious ways, and have tried to place bounds on the param-
ters which give acceptable models, perhaps radically differ-
ent models are possible.

Our best model is no more than a tolerable fit to the
data with which it has been compared. On the other hand
the data itself is not without problems, such as the diffi-
culty of converting from a magnitude distribution to a mass
function.

4.2 Conclusions

We have found that the surface brightness profile, velocity
dispersion profile and mass function of ω Cen can be fitted
approximately by the dynamical evolution, over 12Gyr, of a
cluster with the following initial conditions: the initial mass
is about $1.1 \times 10^6 M_\odot$, the initial tidal radius is about 90pc,
and the initial model is a King model with a scaled central
potential $W_0 = 7.7$ approximately; the initial mass function
is a broken power law, with slopes of about 1 and 1.9 re-
spectively below and above the break-point mass of about
0.6$M_\odot$.

The resulting present mass and tidal radius are about
$3.6 \times 10^6 M_\odot$ and 61pc, respectively. The current proportion
of mass in heavy remnants in our model is about 55%.

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