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ASTRONOMY AND ASTROPHYSICS

On the formation and evolution of the globular cluster ω Centauri

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Abstract. By means of N-body/hydrodynamical simulations we model the evolution of a primordial $10^8 M_\odot$ density peak which ends up in an object closely resembling the present day globular cluster ω Centauri.

We succeed to reproduce the main features of the cluster, namely the structure, kinematics and metallicity distribution.

We suggest that ω Centauri might be a cosmological dwarf elliptical, formed at high redshift, evolved in isolation and self-enriched, and eventually fallen inside the potential well of the Milky Way, in agreement with the Searle-Zinn (1978) paradigm for galactic globular cluster formation.

We finally suggest that ω Centauri is probably surrounded by an extended Dark Matter (DM) halo, for which no observational evidence is at present available. We expect that signatures, if any, of the DM halo can be found in the kinematics of stars outside about 20 arcmin.

Key words: Galaxy: globular clusters: individual: ω Centauri – methods: N-body simulations

1. Introduction

ω Centauri is one of the most interesting globular cluster in the Milky Way, and maybe the most studied one (Majewski et al. 1999; Lee et al. 1999; Pancino 1998). A compilation of its main properties is given in Table 1.

Table 1. Basic properties of ω Centauri. Data have been taken from Harris (1996) compilation but for the ellipticity, taken from Geyer et al. (1983)

Mass $\times 10^6\ M_\odot$	Core radius arcmin	Concentration	M/L	$d_\odot$ kpc	ϵ
2.9	2.58	1.24	3.6	5.3	0.121

The most striking feature of this cluster is the measured metallicity spread, which has been interpreted as the evidence of a multiple stellar population inside it (Norris et al. 1996; Suntzeff & Kraft 1996). The precise metallicity distribution function (MDF) is nonetheless still disputed. Norris et al. (1996) suggest the presence of a secondary peak at $[Ca/H] \approx -0.9$ roughly 5 times smaller that the main peak at $[Ca/H] \approx -1.4$. This trend is not confirmed by Suntzeff & Kraft (1996), who claim for a more regular MDF.

On the base of a large photometric survey Lee et al. (1999) (but see also Ortolani et al. 1999) analyzed the color distribution of a sample of bright stars, showing that on the average it has an e-folding trend, with the presence of several significant metallicity peaks. However Majewski et al. (1999) arrive at a somewhat different conclusion, showing that the MDF has a gaussian shape with the maximum at $[Fe/H] \approx -1.7$, and with some evidences of a secondary peak. Although different, all these analyses point to the common picture of an object which experienced an irregular self-enrichment over its evolution.

Putting together the chemical and kinematical properties Majewski et al. (1999) claim that ω Centauri might be a possible dwarf galaxy relict.

In this paper we propose a N-body/gasdynamical model for the formation and evolution of ω Centauri, suggesting that this globular cluster can actually be the remnant of a dwarf elliptical galaxy, formed and evolved avoiding strong mergers, and eventually captured by the Milky Way.

To this aim, the plan of this paper is as follows. In Sect. 2 we describe our model and the initial conditions setup; Sects. 3 to 5 are dedicated to the analysis of the structure, chemistry and internal kinematics, respectively, of our model, and the comparison with ω Centauri; in Sect. 6 we investigate about the possible presence of an extended DM halo around the cluster. Finally Sect. 7 summarizes our results.

2. Technique and initial conditions

The simulation presented here has been performed using the Tree–SPH code developed by Carraro at al. (1998) and Buonomo et al. (2000). In this code, the properties of the gas component are described by means of the Smoothed Particle Hydrodynamics (SPH) technique, whereas the gravitational forces are computed by means of a hierarchical tree algorithm using a tolerance parameter $\theta = 0.8$ and expanding tree nodes to quadrupole order. We adopt a Plummer softening parameter. In SPH each particle represents a fluid element whose position, velocity, energy, density etc. are followed in time and space. The properties of the fluid are locally estimated by an interpolation

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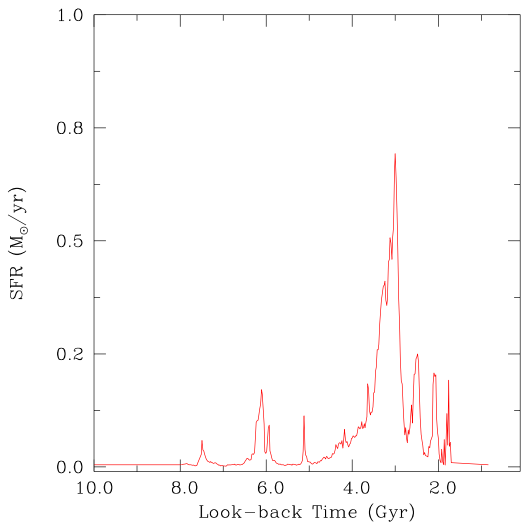

Fig. 1. Star Formation Rate as a function of the look-back time

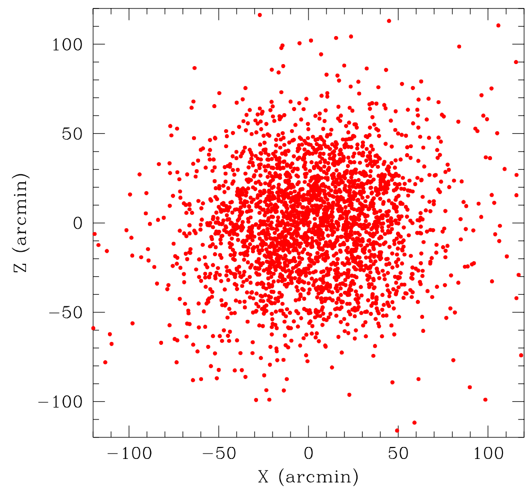

Fig. 2. The final distribution of stars in the X-Z plane. The object has been put at the distance of ω Centauri

which involves the smoothing length h_i. In our code each particle possesses its own time and space variable smoothing length h_i, and evolves with its own time-step. This renders the code highly adaptive and flexible, and suited to speed-up the numerical calculations. Radiative cooling is described by means of numerical tabulations as a function of temperature and metallicity taken from Sutherland & Dopita (1993) and Hollenbach & McKee (1979). This allows us to account for the effects of variations in the metallicity among the fluid elements and for each of these as a function of time and position. The chemical enrichment of the gas-particles caused by Star Formation (SF) and stellar ejecta is described by means of the closed-box model applied to each gas-particle (cf. Carraro et al. 1998 for more details). SF and Feed-back algorithm are described in great detail by Buonomo et al. (2000). In brief, SF is let depend on the total mass density – baryonic (gas and stars) and dark matter – of the system and on the metal–dependent cooling efficiency. Moreover we consider the effects of energy (and mass) feedback from SNe of type II and Ia, and stellar winds from massive stars.

Instead of selecting halos from large cosmological N-body simulations, we opted to set up a protogalaxy as an isolated virialized DM halo, whose density profile is:

$$\rho(r) \propto \frac{1}{r}.$$

DM particles are distributed inside the sphere according to an *acceptance–rejection* procedure. Along with positions, we assign also velocities according to:

$$v(r) \propto \sqrt{\left(r \times ln\left(\frac{1}{r}\right)\right)}.$$

which is the solution of the Jeans equation for spherical isotropic collisionless system for the adopted density profile.

The system is let evolve until virial equilibrium is reached. Gas particles are then distributed homogeneously inside the DM halo with zero velocity field, thus mimicking the cosmological gas infall inside the DM potential well (White & Rees 1978).

For the simulation presented here we consider a $9 \times 10^7 M_\odot$ DM halo, sampled by 10,000 particles, homogeneously filled with $1 \times 10^7 M_\odot$ baryonic mass in form of metal poor ($Z = 10^{-4}$) gas, sampled by 10,000 particles. This way each gas particle has a mass of $10^3 M_\odot$.

3. The structure

The evolution of our model is shown in Fig. 1, where we plot the SF as a function of time. Starting from a $10^{4\ o}$ K metal poor gas, cooling drives baryons towards the center of the DM potential well. Part of this gas (about 20%) is transformed into stars with a very irregular SF history, whereas the remaining 80% is thrown away via a galactic wind mechanism, for which SNe and stellar winds are responsible.

The final stars distribution resembles a triaxial object, with $a/b = 0.859$ and $a/c = 0.967$. Correspondingly the ellipticity ($\epsilon = 1 - b/a$) turns out to be 0.141, not far from the mean value reported by Geyer et al. (1983). The stars distribution is shown in Fig. 2 (onto the X-Z plane) and 3 (onto the X-Y plane). For the sake of an easier comparison with ω Centauri the model has been placed at the cluster actual distance (5.3 kpc).

The total mass in stars amount to about $2 \times 10^6 M_\odot$, sampled by about 2,000 star particles. The spherically averaged mass density profile derived from our simulation is shown in Fig. 4. Each filled circle represents the stars density ρ_i computed as the mass inside a spherical shell i with size the softening ϵ, divided by the shell volume. For each density estimate ρ_i we plot as error bar the uncertainty of the density estimate evaluated as the poissonian error related to the shell population.

We perform a fit with a King (1962) profile to check whether our model recovers the structural properties of ω Centauri. The cluster indeed (see Table 1) has a core and tidal radius r_c and r_t equal to 2.6 and 45 arcmin, respectively.

By using a King (1962) model (solid overimposed line), we found the best fit for r_c= 3.2 and r_t= 65 arcmin, which implies a concentration $c = log(\frac{r_t}{r_c})$ = 1.30, somewhat higher than the

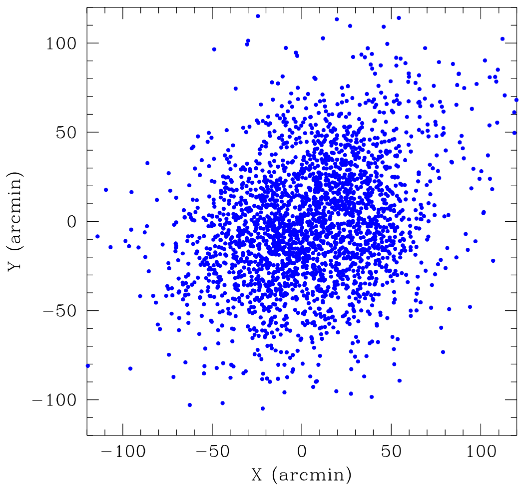

Fig. 3. The final distribution of stars in the X-Y plane. The object has been put at the distance of ω Centauri

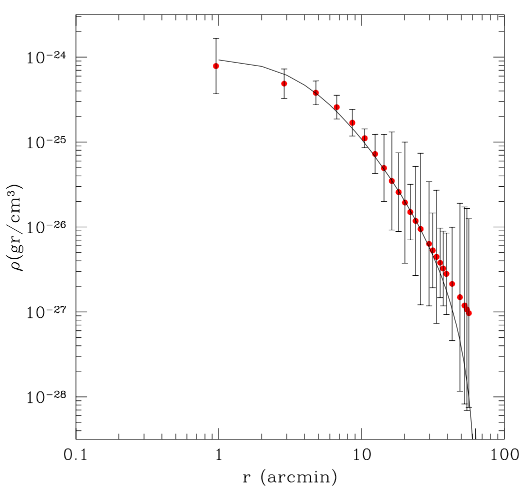

Fig. 4. Spherically averaged density profile for our ω Centauri N-body/hydrodynamical model (filled circles). Overimposed (solid line) is a King (1962) profile for $r_c = 3.2$ arcmin and $r_t = 65$ arcmin. Uncertainties in the density estimates are shown as error bars

value reported in Table 1. While the value of r_c we obtain agrees with the observed one, the value of r_t turns out to be much larger than the measured one for ω Centauri. In other words we overestimate the tidal radius. In our opinion this is due to the fact that in our simplified model we neglect the effect of the tidal stripping that the cluster probably did experience when it was accreted by the Milky Way. This way the outermost stars were probably removed reducing the tidal radius.

Finally, the central density, computed assuming the r_c derived above, is about 2660 $M_{\odot}/pc^3$.

4. Internal kinematics

The internal kinematics of ω Centauri has been analyzed in great detail by Merritt et al. (1997) using the radial velocity catalogue obtained with CORAVEL by Mayor et al. (1997). From this study it emerges that the cluster has a peak rotational speed of

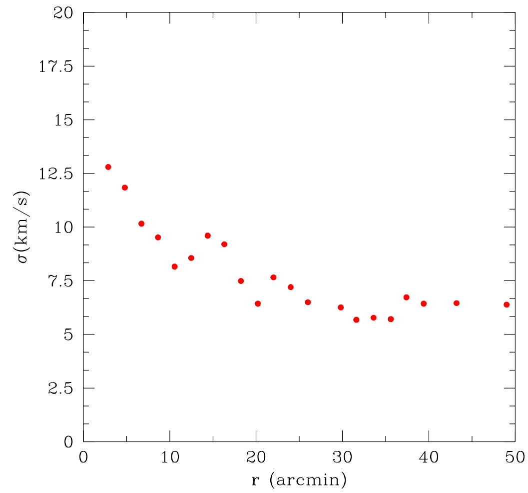

Fig. 5. Spherically averaged velocity dispersion profile

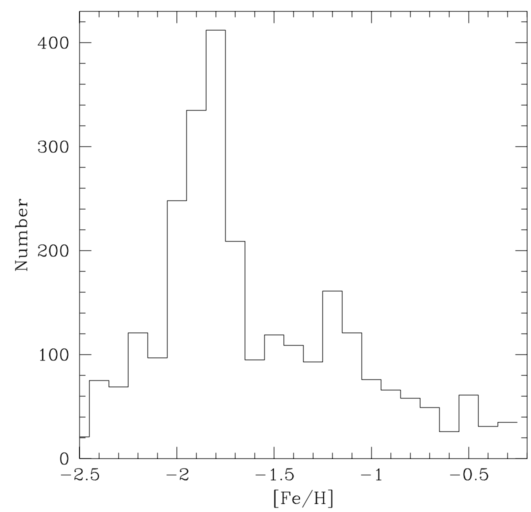

Fig. 6. Histogram of the star metallicity distribution at the end of the simulation

about 8 km s^{-1} at 11 pc from the center. Moreover the cluster has a central velocity dispersion σ = 17 km s^{-1}, the higher one among globular clusters (see Fig. 8 in Merritt et al. 1997).

From the analysis of our data we find evidences of smaller rotational speed (about 4 km s^{-1} at 15 pc), whereas the velocity dispersion profile $\sigma(r)$ (see Fig. 5) shows a central value of about 13 km s^{-1}, denoting that our model is somewhat colder than ω Centauri.

5. Metallicity distribution

The stars MDF at the end of the simulation is presented in Fig. 6. The bulk of stars has a metallicity in the range between [Fe/H] $= -1.9$ and [Fe/H] -1.6. A secondary peak is observed at [Fe/H] $= -1.2$, about 4 times smaller than the major peak.

Finally a significant number of stars has a relatively high metallicity around [Fe/H] $= -0.50$. The global shape resembles the e-folding SF history shown in Fig. 1, with secondary peaks which mark successive bursts of star formation.

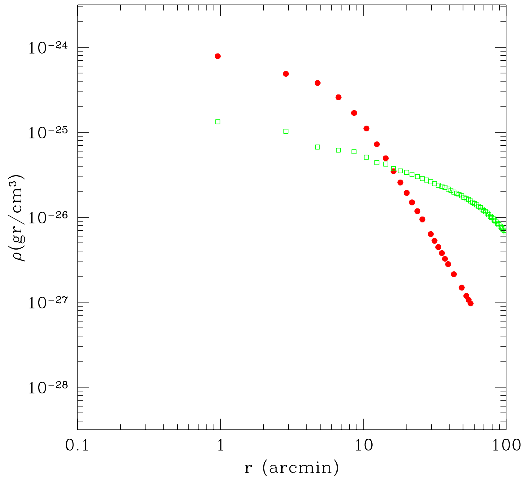

Fig. 7. DM (open squares) and stars (filled circles) density profiles at the end of the simulation

The good agreement we find with the data presented by Majewski et al. (1999) confirms their suggestion that ω Centauri experienced an irregular self-enrichment over its evolution and may actually be the core of a larger dwarf elliptical galaxy.

6. Dark Matter around ω Centauri?

Our simulation starts with a virialised DM halo, in whose center gas concentrates due to cooling instability, forming stars. The final stars and DM distribution is shown in Fig. 7, where open squares refer to DM, and filled circles represent stars. The inner region of the cluster is dominated by stars up to 20 arcmin, which we call the transition radius r_{tr}. In the outer region DM dominates over a distance 6 times larger than the transition radius.

We expect that the internal kinematics of stars in the inner region is unlikely to be influenced by DM. On the contrary, stars outside the transition radius r_{tr} (20 arcmin) should show a kinematics strongly influenced by DM. A detail spectroscopic study of the stars kinematics in the cluster envelope should be able to confirm or deny the presence of DM. There is indeed in our model a trend of the velocity dispersion to weakly increase out of the transition radius.

7. Conclusions

We have presented a N-body/gasdynamical simulation of the formation and evolution of the globular cluster ω Centauri. We are able to reproduce the bulk properties of the cluster, namely structure, kinematics and chemistry assuming that it formed and evolved in isolation, and eventually fell inside the Milky Way potential well.

According to our results and to the dwarf galaxies taxonomy proposed by Roukema (1999), ω Centauri can actually be a cosmological *dwarf by mass*, formed in a high redshift low mass halo, which escaped significant merging up to the present time. Finally we stress that in order to obtain these results, an extended DM halo should surround the present day ω Centauri.

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