BREAKING NEWS ABOUT OLD GLOBULAR CLUSTERS

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The study of globular star clusters has been an active area of research for more than half a century, but every year new science emerges from the investigation of the properties of these old stellar systems. Some recent exciting discoveries about stellar evolution, stellar dynamics, and black hole physics have tremendously enriched our understanding of these fascinating stellar systems.

1 Globular star clusters and their role in modern Astrophysics

Globular star clusters can be considered as the "building blocks" of galaxies, since they are among the first recognizable stellar structures that were born on sub-galactic scales and their age is comparable to the age of the Universe. They are compact groups of about a million stars, which are held together by their mutual gravitational attraction, and are characterized by a nearly spherical distribution and a high density in the central regions (47 Tucanae, the second brightest globular cluster in our Galaxy, is showcased in fig. 1) . For the astrophysical community this class of stellar systems has been valuable in many ways, from the first applications of the theory of stellar evolution to recent investigations in the context of what is called "near-field cosmology", *i.e.* the use of stellar populations of local galaxies to gain insight about cosmological models.

The typical range of masses (10^4 to 10^6 solar masses) places globular star clusters at the low-mass end of stellar systems, between open clusters and dwarf galaxies. At this mass regime a puzzling dichotomy is observed. On the one hand, the available observational data suggest that there is no need to invoke large amounts of dark matter to interpret the dynamics of globular star clusters, since they can generally be well described by Newtonian gravity. On the other hand, there are the more spatially extended dwarf galaxies, whose dynamics appears to be dominated by the effects of dark matter and which are usually related to cosmological substructures. This classical boundary has been blurred by the recent discovery of new classes of stellar groups, such as ultra-faint dwarf spheroidals, ultra-massive super star clusters, ultra-compact dwarf galaxies, and dark-matter-poor tidal dwarf galaxies (see fig. 2 and [1]).

Fig. 1 These images showcase the ancient globular cluster 47 Tucanae, the second most luminous in our Galaxy. The image on the left shows the entire cluster, which measures about 120 light-years across. Located in the southern constellation Tucana, the cluster is about 16700 light-years away. The image is part of the Digitized Sky Survey (DSS) and was taken by the UK Schmidt Telescope at Siding Spring Observatory in New South Wales, Australia. The image on the right captures a close-up view of thousands of cluster stars: the large, bright stars in the image are red giants. Credit: NASA, ESA, H. Richer and J. Heyl (University of British Columbia), and J. Anderson and J. Kalirai (STScI).

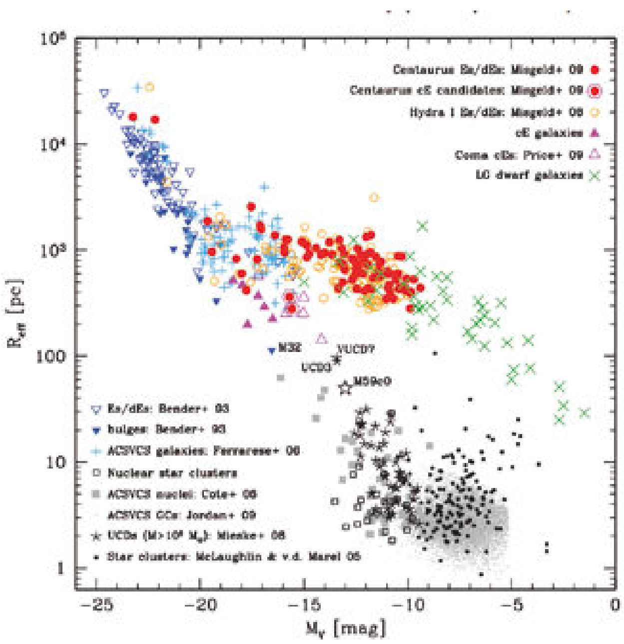

Fig. 2 Effective radius (*i.e.*, the radius enclosing half of the total luminosity emitted by the system) plotted *versus* the total absolute magnitude M_V in V band for several families of stellar systems. Credit: Figure 2, "Families of dynamically hot stellar systems over 10 orders of magnitude in mass", I. Misgeld and M. Hilker, Mon. Not. R. Astron. Soc., 414, 3699-3710, ©2011, The Royal Astronomical Society.

The study of the internal dynamics of the low-mass stellar systems in the transition region between classical star clusters and dwarf galaxies is therefore of great importance in the context of structure formation theories because only accurate dynamical models can lead to a reliable interpretation of the photometric and kinematic observables, providing an estimate of the relevant mass-to-light ratio, so as to firmly exclude or require the presence of significant amounts of dark matter in these systems. In this context, globular star clusters also play an important role as interesting targets to test fundamental gravitational paradigms, as in the recent debate between Modified Newtonian Dynamics and Newtonian Dynamics [2].

1.1 Basic properties

As individual objects, globular clusters are studied with particular reference to two main classes of observables, as determined from the photometric and spectroscopic data, which provide information about the structural and kinematical properties of the systems, respectively. In particular, most dynamical models designed for the description of this class of stellar systems can be constrained by a joint analysis of the surface brightness profile and the projected velocity dispersion profile of a cluster. Such observable quantities are usually constructed under the simplifying assumption of spherical symmetry and are often interpreted on the basis of geometrically simple, physically based dynamical models.

From the morphological point of view, globular clusters indeed present only small deviations from sphericity. Yet, there is observational evidence of flattening, as measured by the ellipticity parameter, defined as $\varepsilon = 1 - b/a$, where b and a denote the minor and major axis of the projected image of a cluster, respectively. According to the White and Shawl [3] database of ellipticities, galactic globular clusters indeed appear to be predominantly round, with the peak of the distribution at $\varepsilon \approx 0.05$, maximum value of the entire sample given by $\varepsilon \approx 0.3$, and axial ratios randomly oriented in space. However, a more recent study by Chen and Chen [4] reports a distribution of ellipticities peaked at $\varepsilon \approx 0.15$, with the majority of the values falling in the range [0.05, 0.25], and maximum value $\varepsilon \approx 0.45$. In addition, especially for the clusters in the region of the Galactic Bulge, their major axes preferentially point toward the Galactic Center. Internal rotation, external tides, and pressure anisotropy are the main physical factors that could be responsible for such observed flattening, but we still do not know which is the dominant cause of the observed deviations from spherical symmetry [5].

From the kinematical point of view, globular clusters can be considered as pressure-supported stellar systems, characterized by a high degree of isotropy in the velocity space, as expected for systems close to a thermodynamically relaxed state (see sect. 1.2). Nonetheless, indications of the presence of some degree of anisotropy in the velocity space have been found and some moderate internal rotation has been measured in a progressively increasing number of objects (see sect. 5).

Globular clusters in our own Galaxy can be collectively described as a system of approximately 150 objects, for which there is a clear evidence of the existence of two sub-systems associated to the Galactic disk and with the Galactic halo, respectively (for details, see [6]). Star clusters of the halo sub-system represent a kinematic tracer of the Galactic gravitational field at large scale, and their spatial distribution provide stringent constraints for the models of the dark matter distribution in the outer part of the Galaxy. When considered as a system, globular clusters also play a fundamental role in the validation of theories of formation and evolution of the Milky Way itself, as they can offer a record of the chemical and dynamical conditions of its formation phase.

Globular clusters are indeed present also in external galaxies: after the first observational studies of relatively small samples of objects in the nearby Magellanic Clouds, the investigation has been extended also to the globular clusters systems in some galaxies of the Local Group and the Virgo Cluster. In particular, a number of observational programs performed Hubble Space Telescope have determined high-resolution photometric profiles for large samples of globular clusters in Andromeda (M31), the giant elliptical galaxy Centaurus A (NGC 5128), the Small and Large Magellanic Clouds, the dwarf galaxies Fornax and Sagittarium, and the giant elliptical galaxy M87 (*e.g.*, see Barmby *et al.* [7]). Such photometric studies show that the globular cluster system in M31 is quite similar to the Galactic one, being composed of old, approximately round stellar systems. However, the majority of the globular clusters in the Magellanic Clouds and Fornax, as well as a significant fraction of clusters in NGC 5128, seem to be systematically younger, more spatially extended and flattened with respect to the Galactic clusters.

1.2 Unique laboratories for the study of stellar dynamics

Globular star clusters have long been considered as the ideal astrophysical systems for the study of stellar dynamics. From a theorist's perspective, they are indeed an excellent physical realization of the "gravitational *N*-body problem", which is the problem of understanding the evolution of a system of *N* point masses interacting by gravitational forces. A quantity of particular importance for the study of the internal dynamics of globular clusters is therefore the relaxation time, which may be regarded as the time scale on which a stellar system approaches thermodynamical equilibrium, as a result of deflections and kinetic-energy exchanges associated with the two-body encounters between the stars. Since globular clusters are characterized by a substantial density variation between the central regions and the outer parts, the value of the relaxation time may change significantly over the entire radial extension. Nonetheless, for such stellar systems, the two-body relaxation time is typically shorter than their age, so that it can be argued that they are close to a thermodynamically relaxed state.

A classical problem in stellar dynamics is the search for self-consistent equilibrium solutions of the Boltzmann equation,

$$\frac{\partial f}{\partial t} + v\frac{\partial f}{\partial x} - \frac{\partial f}{\partial v}\frac{\partial \phi_c}{\partial x} = \left(\frac{\partial f}{\partial t}\right)_{coll} ,$$

where, on the right-hand side, the collision integral is often treated in terms of the Fokker-Planck approximation. On the left-hand side ϕ_c denotes the mean-field potential generated by the entire system, which is associated with the zeroth-order moment of the distribution function (*i.e.*, the density) by means of the Poisson equation (*e.g.*, see Bertin [8]). In this approach, the starting point is the identification of an appropriate form for the one-particle distribution function in phase space. Indeed, as a zeroth-order dynamical description, the class of equilibrium models defined as a "lowered" Maxwellian distribution function,

$$f_k(E) = A\left[\exp(-aE) - \exp(-aE_0)\right] ,$$

if $E \le E_0$ (and vanishing otherwise; E denotes the single star energy) supplemented by the assumption of spherical symmetry (the King models [9]), has had remarkable success in the application to observed globular clusters. In recent years, thanks to high-resolution space and ground-based observations, great progress has been made in the acquisition of detailed information of the structure of these stellar systems (*e.g.*, see Anderson and van der

Box:
Globular star clusters and the "gravitational *N*-body problem"

The most accurate technique to solve the gravitational *N*-body problem is that of direct summation. In this approach, the force exerted on each particle is computed by evaluating explicitly the contributions from all other particles and all trajectories are determined by means of a numerical solver.

Alternative particle-based methods adopt the strategy of grouping particles together according to their spatial distribution and compute the force exerted by the whole group instead of considering the contribution of the individual particles. The most popular example in this class is probably given by the "tree code", which arranges particles in cells and computes the force contributions from these cells by means of truncated multipole expansions.

A different class of approximated methods includes Monte Carlo methods, Fokker-Planck methods and Gaseous methods. In this approach, the dynamics of a system of particles interacting gravitationally can be followed by solving the time-dependent Boltzmann equation, often treated in terms of the Fokker -Planck approximation, coupled with the self-consistent Poisson equation. In particular, Monte Carlo methods can be regarded as a statistical way of solving the Fokker-Planck equation, while Fokker-Planck methods are based on the numerical solution of such equation, as expressed in the energy and momentum space, under some assumptions for derivation of the relevant diffusion coefficients. Gaseous methods solve several equations for higher-order moments of the Boltzmann equation.

Direct *N*-body simulations are indeed computationally demanding: direct summation methods present an $O(N^2)$ scaling with the number of particles. In fact, the development of approximated methods was motivated originally by the intention to reduce the computational complexity of direct methods. From a hardware point of view, special-purpose computers have being built to accelerate the computation of gravitational forces. The GRavity PipE (GRAPE) family of computers, has proven very efficient for this purpose. In the very last years, Graphic Processing Units (GPUs) have emerged in the scene of high-performance scientific computing, gaining immediate attention from the theoretical astrophysics community and, in many cases, becoming the hardware of choice for performing direct *N*-body simulations. References and additional information about the use of *N*-body simulations in the context of the study of the dynamics of dense stellar systems may be found in Heggie and Hut (2003) [44].

Marel [10]). In addition, recent improvements in computational speed of the codes for performing *N*-body simulations and the availability of accelerator hardware (GRAvity PipEs, Graphic Processing Units; see Box) allow us to begin the study of the entire dynamical evolution of selected globular star clusters on a star-by-star basis (see the *N*-body models of Palomar 14 and M4, by Zonoozi *et al.* [11] and D. C. Heggie, in preparation, respectively).

Such progress calls for a renewed effort on the side of dynamical modeling. In fact, more general analytical models have indeed a twofold role. On the observational side, they serve as a useful guide for the interpretation of the relevant photometric and kinematic observables and they provide a first insight into some observational issues only partly understood, such as the detailed distribution of angular momentum or the physical origin of some morphological features. On the the theoretical side, realistic analytical models provide more appropriate initial conditions for numerical simulations (*e.g.*, in which internal rotation and external tidal field are properly taken into account), allowing us to address a number of long-standing issues, such as the interplay between two-body relaxation processes and angular-momentum transport or the effects induced by different tidal environments on the dynamical evolution of star clusters. Some recent results about the effects of internal rotation and external tidal field on the dynamics of globular clusters are reported in the final Sections of this article, but first we will review some exciting discoveries about stellar evolution and black hole physics that, in the last few years, have tremendously enriched our understanding of these fascinating stellar systems.

2 A radical change in perspective: multiple stellar populations

For many decades globular clusters have been considered as a collection of coeval stars characterized by the same initial chemical composition, with masses distributed according to an initial mass function. Such systems have been indeed treated as a prototype of a "simple stellar population", characterized by a single isochrone in the color-magnitude diagram. Several photometric and spectroscopic observations have now showed that there is evidence of the presence of multiple stellar populations in all the clusters that have been examined in detail. The most convincing evidence of the presence of multiple stellar populations in globular clusters is the fact that different stars in the same cluster may be characterized by different chemical composition and by the presence of a splitting of the evolutionary sequences in the color-magnitude diagram (for a recent review, see Gratton *et al.* [12]).

The suggested interpretative picture is therefore that multiple generations of stars must have formed at different times in globular clusters. It is also argued that second-generation stars formed in the central regions of the system, from material polluted by the ejecta from some first-generation Asymptotic Giant Branch stars [13] or from interacting massive binary and rapidly rotating stars on to their circumstellar discs, and ultimately on to the young second-generation stars [14]. Second-generation stars indeed appear to be more centrally concentrated with respect to the first-generation stars and they might also be characterized by different kinematical properties, both regarding internal rotation and anisotropy in velocity space. In this respect, a recent dynamical study suggests that the cluster 47 Tucanae is likely to be the first example of the possible existence of a dynamical signature of multiple populations, with the second-generation stars being more radially anisotropic than the first-generation ones [15].

The first photometric evidence of the presence of multiple stellar populations in a globular cluster was the discovery of a splitting of the main sequence of ω Cen into two branches [16]. A spectroscopic follow-up analysis showed that stars in the blue main sequence have metal abundances twice as large as the ones of stars in the dominant red main sequence [17]. The results obtained from the observations of ω Cen stimulated a number of similar photometric studies devoted to investigate the phenomenon in many other globular clusters. The multiple sequences in the color-magnitude diagram of globular cluster NGC 2808 are illustrated in fig. 3.

From the spectroscopic point of view, the most convincing evidence of the presence of multiple populations is indeed the discovery of the existence of anticorrelations between several elements in the chemical composition of the main

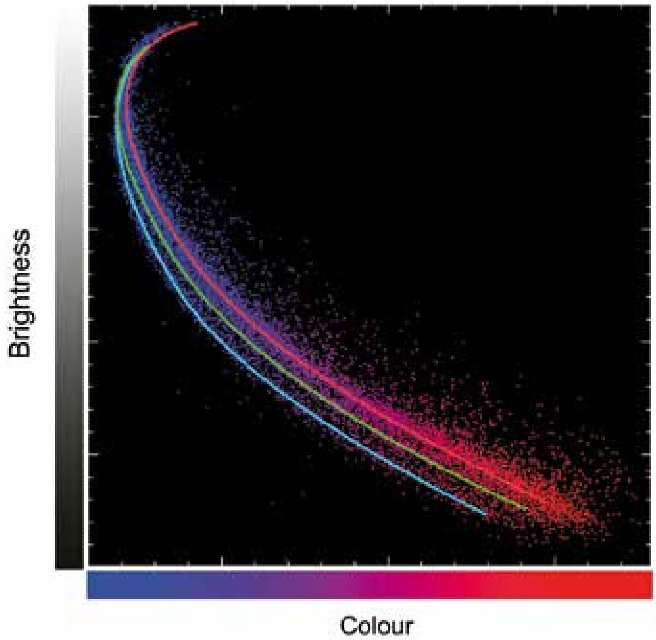

Fig. 3 Each point in this graph represents one star in NGC 2808. The vertical axis represents the brightness (as measured through Hubble's near-infrared F814W filter) of the stars (the brightest stars near the top). The horizontal axis represents the colors of the stars, with bluer stars to the left and redder to the right (blue magnitude minus near-infrared magnitude). The three colored curved lines, red, green and blue, represent the three different stellar generations that are present in the globular cluster. Credit: European Space Agency, NASA, G. Piotto (University of Padua, Italy), A. Sarajedini (University of Florida, USA) and Martin Kornmesser (ESA/Hubble).

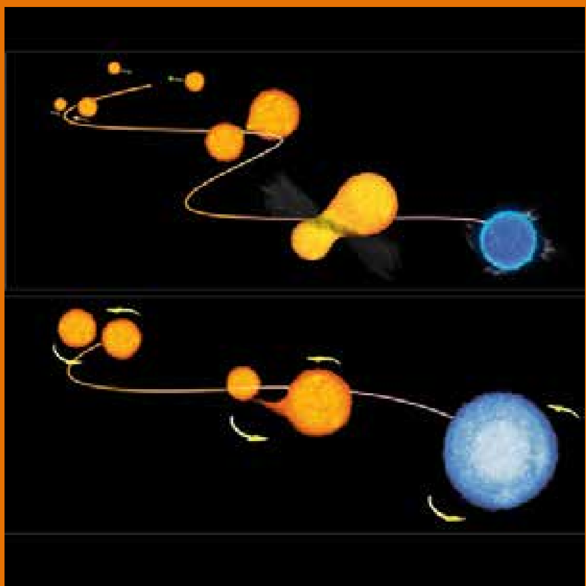

Fig. 4 This illustration shows the two ways in which blue stragglers – or "rejuvenated stars" – in globular clusters form. The upper illustration shows the collision model, where two low-mass stars in an overcrowded environment experience a head-on collision, combining their fuel and mass to form a new, single, hot (hence blue) and seemingly young star. The lower illustration depicts the "vampire" model, consisting of a pair of stars where the lower-mass object drains its heavier companion of hydrogen, that fuels its rebirth. Credits: Cosmic-Lab project, funded by the European Research Council.

sequence stars of globular clusters, in particular sodium and oxygen, as showed in a recent and extensive survey of 19 Galactic globular clusters [18].

This radical change in the stellar evolution perspective obviously opens up a number of interesting questions regarding the traditional paradigm for the interpretation of the dynamical evolution of globular clusters, especially concerning the evaluation of the time scale for the spatial and kinematical mixing of the two populations [19]. In addition, hydrodynamical simulations suggest that globular clusters composed of two generations of stars might have had a significant amount of rotation when they were formed [20], leading to appreciable differences in the distribution of angular momentum between the two populations.

3 An exotic product of stellar evolution: blue stragglers stars

Blue straggler stars are main-sequence stars that are brighter and bluer than the main-sequence turnoff point: they are therefore younger and more massive than the other stars in the cluster. This class of star represents indeed an exotic product of stellar evolution, and several explanations for their existence have been suggested over the years (see fig. 4). One formation channel is given by collisions or mergers between two single main-sequence stars (*e.g.*, see Sills *et al.* [21]). The other main scenario suggests that blue stragglers are produced via mass transfer within primordial binaries (*e.g.*, see Knigge *et al.* 2009 [22]).

Blue stragglers formed via stellar collisions are expected to be preferentially located near the center of the cluster, where the density, and therefore the collision rate, is higher; on the other hand, the distribution of blue stragglers outside the cluster core seems to be due to objects generated by mass transfer in primordial binary system. Numerous observational studies have been recently devoted to the study of the radial distribution of blue stragglers in different Galactic globular clusters, and, as a result, some fundamental properties of this observable quantity have emerged.

In particular, it has been suggested [23] that the evolution of the shape of the radial profile of the distribution of blue straggler stars might reflect the dynamical status of the cluster itself, as a "dynamical clock", that is, a tracer of its dynamical age. The observed distribution, in fact, presents a minimum at intermediate radii which seems to progressively move outward as cluster becomes dynamically older. This behavior may be interpreted in terms of the long-term effects of dynamical friction, a process that acts on the most massive components of a cluster, including the population of binaries, since the early stages of its evolution. This topic is currently of great interest for the star cluster community and additional simulations, performed with a Monte Carlo method, will soon provide an independent assessment of the uniqueness and appropriateness of this intriguing empirical method to evaluate the dynamical state of a globular cluster (Hypki *et al.*, in preparation).

4 Hunting for black holes

4.1 Stellar mass black holes

A theoretical scenario proposed almost twenty years ago (see Kulkarni *et al.* [24]) suggests that globular clusters may contain up to several hundreds stellar mass black holes, resulting primarily from the evolution of a – typically abundant – population of millisecond pulsars. The high density of the central regions of a globular clusters nonetheless is expected to determine a rapid dynamical evolution of the population of stellar mass black holes, which should abandon the host system by "dynamical ejection" on a relatively rapid time scale. The likelihood of finding a stellar mass black hole inside a globular cluster was therefore expected to be very low, due to the low retention rate of these objects in a highly collisional environment.

This view has been seriously challenged by the very recent observational evidence of the possible presence of two stellar mass black holes in M22 (see fig. 5 and Strader *et al.* [25]) and one in M62 [26]. These discoveries represent the first evidence of the possible presence of a stellar mass black holes in globular clusters within our own Galaxy. It should be recalled that the very first direct observational indication of the existence of a stellar mass black hole dates back to 2007, with the discovery of an X-ray emission consistent with being originated from an accretion event on a stellar mass black hole in a globular cluster in the giant elliptical galaxy NGC 4472 [27].

Interestingly, in the past decade numerical simulations have also indicated that stellar mass black holes may persist in globular clusters longer than originally thought. Such numerical experiments are consistent with a recently proposed theoretical treatment (see Breen and Heggie [28]), which predicts the time scales for the depletion of BH from a cluster to be significantly longer with respect to the traditional view.

If confirmed, the survival of a population of stellar mass black holes in globular clusters will have significant implications both in terms of the effects on the structure and dynamics of the host clusters and from the point of view of the dynamical evolution of the black hole "sub-system" itself (*e.g.*, formation and merging of binaries of stellar mass black holes and consequently possible emission of gravitational wave associated to such an event).

4.2 Intermediate mass black holes

Super-massive black holes (SMBHs), *i.e.*, black holes characterized by masses larger than 10^6 solar masses, have been found in the bulges of several galaxies in the Local Group (*e.g.*, see van den Bosch *et al.* [29]), including the Milky Way [30]. Evidences of the existence of SMBH at high-redshift indicates that these objects formed at a very early stage of galaxy formation. IMBHs would therefore naturally bridge a gap between two observational regimes, stellar mass black holes and super-massive black holes, where relatively firm detections exist and they would also represent the ideal candidate to be considered as seeds of SMBH. In addition, the extrapolation of the empirical scaling relation between super-massive black holes masses and the velocity dispersion of their host spheroid (see Ferrarese and Merritt [31], and fig. 6) to a lower mass range also encourages to strongly consider the existence of IMBHs and to expect them to be in globular clusters. These reasons indeed motivate the great effort that has recently been made to find signatures of the presence of these objects in several Galactic globular clusters.

Numerous scenarios for the formation of intermediate-mass black holes have been proposed, including that they could be the end product of Population III stars or that they could be the result of runaway stellar collisions in dense young globular clusters.

To the present day, direct detection of an intermediate-mass black hole in globular clusters is still missing. In fact, the most promising route into this controversial issue comes from stellar dynamics, as appreciable central gradients in the velocity dispersion profiles are often ascribed to the presence of an IMBH, because a massive BH can influence stellar kinematics out to the half-mass radius of the cluster [32].

Indeed, recent claims of IMBHs

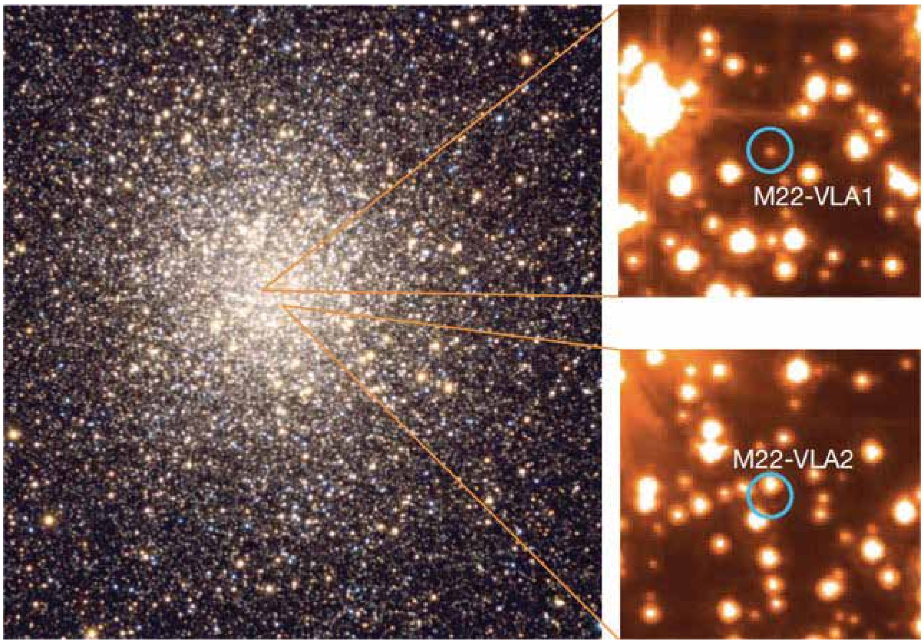

Fig. 5 Optical images of M22 and the candidate companion stars to the radio sources (stellar mass black hole candidates) M22-VLA1 and M22-VLA2: the globular cluster M22, on the left, and the location of the radio sources on archival Hubble images, on the right. Credits: Doug Matthews / Adam Block / NOAO / AURA / NSF / Hubble team / NASA / ESA.

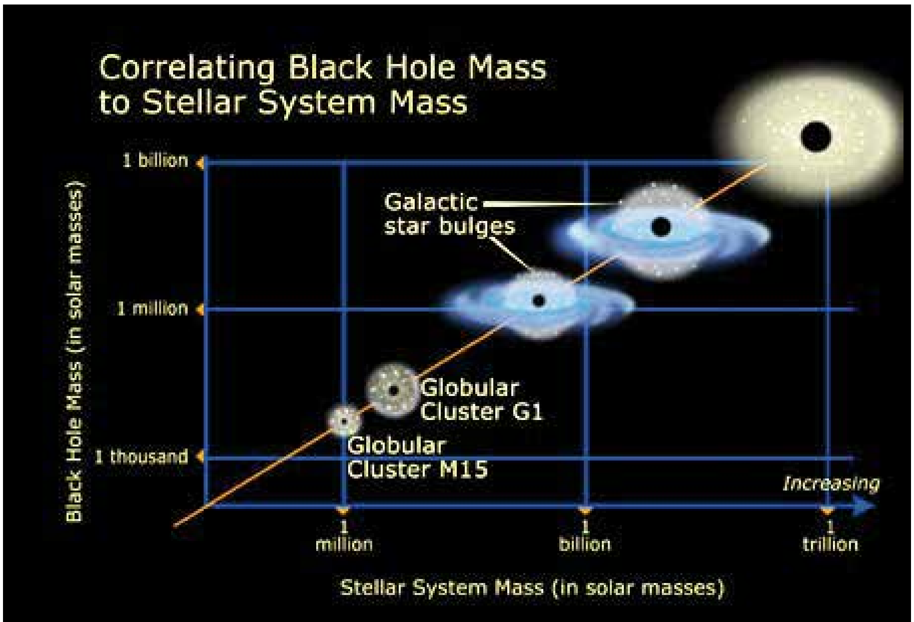

Fig. 6 Astronomers have known that the mass of the black hole at a galaxy's core depends on the mass of the galaxy's central bulge of stars. Now it seems that this relation extends all the way down to the black holes candidates newly identified at the cores of two globular clusters M15 and G1. Credit: A. Feild / STScI / NASA.

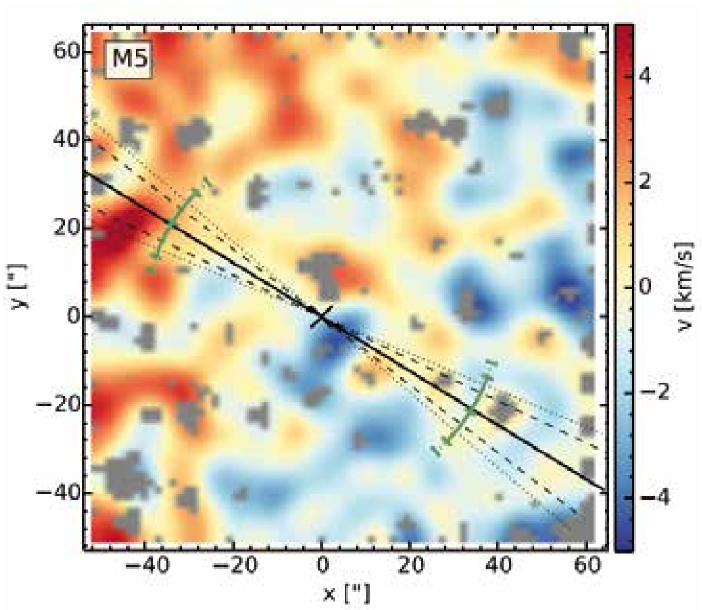

Fig. 7 Velocity field of the Galactic globular cluster M5. The cross indicates the cluster center, while the straight solid line shows the kinematic position angle. The dashed line shows the systematic uncertainty and the dotted line shows the systematic plus the statistical uncertainty. The green arcs indicate photometric position angle. Credit: Figure 1, "The central rotations of Milky Way clusters", M. H. Fabricius, E. Noyola, S. Rukdee *et al.*, Astrophys. J. Lett., 787, L26, © 2114, The American Astronomical Society.

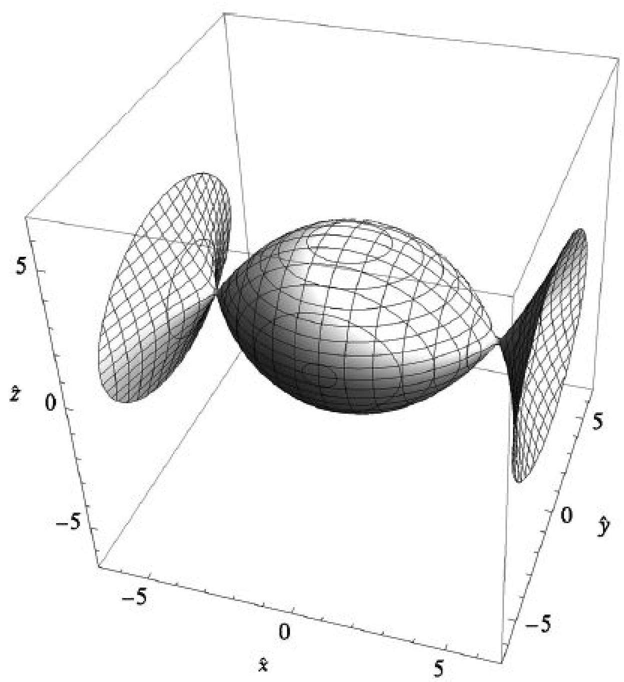

Fig. 8 Critical equipotential surface for a triaxial model in which the effects of the external tidal field are fully taken into account. The stars can escape only through the Lagrangian points, to form the tidal tails (see fig. 9). Credits: Figure 1, "The construction of nonspherical model for quasi-relaxed stellar systems", G. Bertin and A. L. Varri, Astrophys. J. , 689, 1005, © 2008, The American Astronomical Society.

detections in globular clusters are mostly based on the dynamical interpretation of shallow cusps in the surface brightness profile and slopes in the velocity dispersion profile towards the center. However, these signatures are non-unique, as similar features can also be produced by different dynamical processes. In particular it has been showed with *N*-body simulations [33] that mass segregation, core collapse, or the presence of binary stars in the center can also generate a similar shallow cusp in the surface brightness profile.

Some kinematical properties can also be explained in terms of simple effects of the anisotropy in the velocity space, specifically with respect to the proportion of radial orbits in the system (*e.g.*, Zocchi *et al.* [34]). Internal rotation may also play an indirect role in this controversial issue. A critical discussion of the observed gradients is often reduced to the application of the Jeans equations in which variations of the slope of the velocity dispersion profile are obtained often by varying only the mass of the IMBH or the amount of pressure anisotropy (*e.g.*, see Luetzgendorf *et al.* [35]). However, differential rotation and pressure anisotropy may cooperate to produce nontrivial gradients in the velocity dispersion profiles and might thus be an important element to be considered in the interpretation of the data.

5 Do globular clusters rotate at heart?

Traditionally, in the context of globular clusters, relatively little attention has been paid to the role played by internal rotation in the dynamics of these objects. Since these stellar systems exhibit only modest amounts of flattening and given the success of the spherical dynamical models, often dynamical investigations have been carried out under the simplifying assumption that , in the velocity space of these systems, ordered (rotational) motions are negligible with respect to the random ones.

The detection of internal rotation in star clusters is indeed a challenging task, because the typical value of the ratio of mean velocity to velocity dispersion is only of a few tenths, for example $V/\sigma_0 \approx 0.46, 0.32$ for 47 Tucanae and ω Centauri, respectively. However, the great progress made in the acquisition of photometric and kinematical information, and in particular of the proper motion of thousands of stars, now makes this goal within reach.

Ground-based observations of nearby Galactic globular clusters have already demonstrated the power of three-dimensional kinematics [36]. The Hubble Space Telescope and the astrometric mission GAIA, with the planned acquisition of the proper motion of thousands of stars in globular clusters, will allow to measure the component of rotation in the plane of the sky, supplemented by the kinematical information derived from radial velocity measurements.

In addition, the recently announced results of a survey of the kinematics of the central regions of several Galactic globular clusters conducted with the new Integral Field Unit instrument VIRUS-W showed the presence of statistically significant signatures of internal rotation in the velocity fields of all the clusters considered in the sample (see fig. 7 and Fabricius *et al.* [37]). This result indeed calls for renewed effort on the side of a more realistic theoretical modeling, in which the effects of internal rotation are fully taken into account. In this respect, a new family of self-consistent axisymmetric dynamical models characterized by differential rotation and explicitly designed to describe, at least in the moderate rotation regime, the properties of globular clusters has been recently proposed by Varri and Bertin [38]. A first application of such family of models offered a successful global dynamical description of selected rotating Galactic globular clusters [39].

Two general questions provide further motivation to study globular clusters as quasi-relaxed rotating stellar systems. On the one hand, some investigations in the past have indeed studied the role of angular momentum in the general context of the dynamical evolution of globular clusters, but a clear interpretation is still missing. Early studies suggested that initially rotating systems should experience a loss of angular momentum induced by evaporation, that is, angular momentum would be removed by stars escaping from the cluster. Because of the small number of particles, *N*-body simulations were initially unable to clearly describe the complex interplay between relaxation and rotation. Later investigations, primarily based on a Fokker-Planck approach (*e.g.*, see Einsel and Spurzem [40]) have clarified this point, not only by testing the proposed mechanism of angular-momentum removal by escaping stars, but also by showing that rotation accelerates the entire dynamical evolution of the system. More recent *N*-body simulations confirm these conclusions and show that, when a three-dimensional tidal field is included, such acceleration is enhanced even further. The mechanism of angular momentum removal is generally considered to be the reason why Galactic globular clusters are much rounder than the (younger) clusters in the Magellanic Clouds, for which an age-ellipticity relaltion has been noted [41], but other mechanisms might operate to produce the observed correlations.

On the other hand, the role of angular momentum during the initial stages of cluster formation should be better clarified. In the context of dissipationless collapse, relatively few investigations have considered the role of angular momentum in numerical experiments of violent relaxation (*e.g.*, the pioneering studies by Gott [42]; see also Varri *et al.*, in preparation). Interestingly, the final equilibrium configurations resulting from such collisionless collapse show a central region with solid body rotation, while the external parts are characterized by differential rotation.

6 Exploring tails of stars with astrometric precision

It is commonly thought that globular clusters can be described as stellar systems of finite size, with a truncation in their density distribution determined by the tidal field of the hosting galaxy. Most of the interesting physical mechanisms that underlie the dynamical evolution of these stellar systems (such as evaporation and core collapse, see Heggie and Hut [43]) depend on such truncation and are frequently studied in the context of spherical models for which the action of tides is implemented by means of the existence of a suitable truncation radius, supplemented by a recipe for the escape of stars. Therefore, evolutionary models that rely on the assumption of spherical symmetry, such as Monte Carlo models and Fokker-Planck models are necessarily based on an approximate treatment of the tidal field.

Yet, if tides are indeed responsible for the truncation, they should also induce some deviations from spherical symmetry: in the simplest case of a cluster in circular orbit about the center of the host galaxy, the associated (stationary) tidal field is non-spherical and determines an elongation of the mass distribution in the direction of the center of mass of the host galaxy accompanied by a compression in the direction perpendicular to the orbit plane (for details, see Heggie and Hut [43]). This relatively simple physical model can be analyzed in detail, to construct a family of tidal triaxial models in which the external tidal field is taken into account self-consistently and the induced geometrical distortions are properly calculated (see fig. 8 and Heggie and Ramamani [44], Bertin and Varri [45]). Such analytic equilibria are, of course, limited to the treatment of a very idealized configuration of the cluster-galaxy system. In fact, only direct *N*-body simulations, in which an external tidal field can be taken into account explicitly, provide a tool for the study

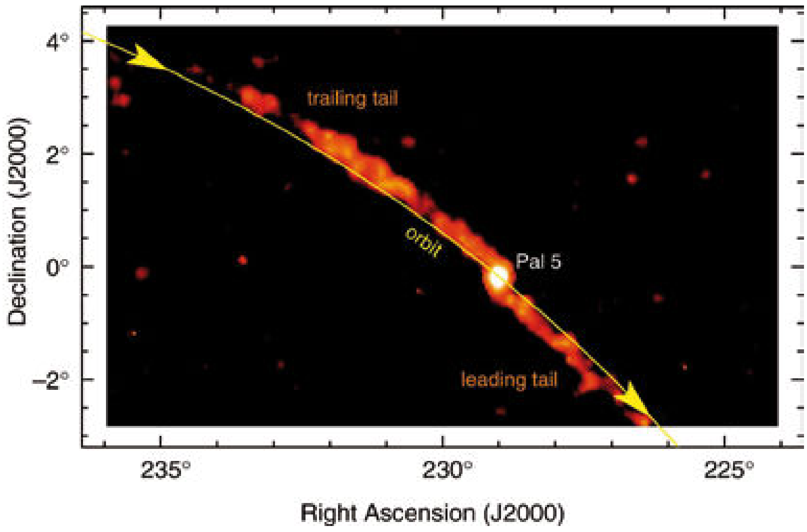

Fig. 9 Color-coded map of the distribution of stars emerging from the star cluster Palomar 5 (white blob). The two long tidal tails (orange) contain 1.3 times the mass of the cluster and delineate its orbit around the Milky Way (yellow line). Credits: Michael Odenkirchen and Eva Grebel from the Max Planck Institute for Astronomy (MPIA) in Heidelberg, Germany.

of the evolution of a tidally perturbed cluster, especially when elliptic orbits are considered, so that tidal effects are time-dependent [46]. In particular, this approach has recently led to detailed investigations of the rich morphology and kinematics of the tidal tails, *i.e.* the streams of stars escaped from the cluster (*e.g.*, see Kuepper *et al.* [47]), leading to a significant improvement of our current understanding of this unique morphological and dynamical feature. The tails of globular clusters Palomar 5 are illustrated in fig. 9.

The astrometric mission GAIA, combined with ground-based wide-field imaging and detailed spectroscopic information, will allow to select stars in tidal tails on the basis of photometric, proper motions, and parallax information, leading to a proper separation of members and "interlopers"; such selection is also critical to determine the true extension of the outskirts of a globular cluster. In addition, the next generation of astrometric data will allow to characterize the deformations induced by the external tidal fields over a significant portion of the radial extent of the stellar system (with the exclusion of the central regions, due to crowding) and to detect the possible presence of tidal tails and other nontrivial tidal structures around many Galactic globular clusters.

7 Final remarks

The study of globular star clusters has been an active area of research for more than half a century, but every year new science emerges from the investigation of the properties of these old stellar systems. Since they play the role of building blocks of the structures of the Universe, it is crucially important to understand the details of their formation and dynamical evolution. This class of objects indeed poses a number of challenges from both the point of view of stellar evolution and stellar dynamics. Our traditional notion of globular cluster as prototypes of simple stellar populations is deeply shaken, and an increasing number of exotic objects populates their color-magnitude diagram.

The hunt for stellar and intermediate-mass black holes will certainly reserve us more surprises in the near future. Proper motions of thousands of stars measured by the Hubble Space Telescope and the new-generation astrometric satellite GAIA will unlock the properties of the entire phase space of these systems, allowing us to perform detailed comparison with more realistic dynamical models and sophisticated star-by star *N*-body simulations. Stay tuned!

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References

[1] I. Misgeld and M. Hilker, *Mon. Not. R. Astron. Soc.*, 414 (2011) 3699.
[2] H. Baumga rdt, E. K. Grebel and P. Kroupa, *Mon. Not. R. Astron. Soc.*, 359 (2005) L1.
[3] R. E. White and S. J. Shawl, *Astrophys. J.*, 317 (1987) 246.
[4] C. W. Chen and W. P. Chen, *Astrophys. J.*, 721 (2010) 1790.
[5] S. van den Bergh, *Astron. J.*, 135 (2008) 1731.
[6] K. Ashman and S. Zepf, "*Globular Cluster Systems*" (Cambridge University Press) 2008.
[7] P. Barmby, D. E. McLaughlin, W. E. Harris *et al.*, *Astron. J.*, 133 (2007) 2764.
[8] G. Bertin, "*Dynamics of Galaxies*" (Cambridge University Press) 2000.
[9] I. R. King, *Astron. J.*, 71 (1966) 64.
[10] J. Anderson and R. P. van der Marel, *Astrophys. J.*, 710 (2010) 1032.
[11] A. H. Zonoozi, A. H. W. Kuepper, H. Baumgardt *et al.*, *Mon. Not. R. Astron. Soc.*, 411 (2011)1989.
[12] R. G. Gratton, E. Carretta and A. Bragaglia, *Astron. Astrophys. Rev.*, 20 (2012) 50.
[13] A. D'Ercole, E. Vesperini, F. D'Antona *et al.*, *Mon. Not. R. Astron. Soc.*, 391 (2008) 825.
[14] N. Bastian, H. J. G. L. M. Lamers, S. E. de Mink *et al.*, *Mon. Not. R. Astron. Soc.*, 436 (2013) 2398.
[15] H. B. Richer, J. Heyl, J. Anderson, *et al.*, *Astrophys. J. Lett.*, 771 (2013) L15.
[16] L. R. Bedin, G. Piotto, J. Anderson, *et al.*, *Astrophys. J. Lett.*, 605 (2004) L125.
[17] G. Piotto, S. Villanova, L. R. Bedin *et al.*, *Astrophys. J.*, 621 (2005) 777.
[18] E. Carretta, A. Bragaglia, R. G. Gratton *et al.*, *Astron. Astrophys.*, 505 (2009) 117.
[19] E. Vesperini, S. L. W. McMillan, F. D'Antona *et al.*, *Mon. Not. R. Astron. Soc.*, 429 (2013) 1913.
[20] K. Bekki, *Astrophys. J. Lett.*, 724 (2010) L99.
[21] A. Sills, J. C. Lombardi Jr., C. D. Bailyn *et al.* 1997, *Astrophys. J.*, 487, 290.
[22] C. Knigge, N. Leigh and A. Sills, *Nature*, 457 (2009) 288.
[23] F. R. Ferraro, B. Lanzoni, E. Dalessandro, *et al.*, *Nature*, 492 (2012) 393.
[24] S. R. Kulkarni, P. Hut and S. McMillan, *Nature*, 364 (1993) 421.
[25] J. Strader, L. Chomiuk, T. J. Maccarone, J. C. A. Miller-Jones and A. C. Seth, *Nature*, 490 (2012) 71 .
[26] L. Chomiuk, J. Strader, T.~J. Maccarone *et al.*, *Astrophys. J.*, 777 (2013) 69.
[27] T. J. Maccarone, A. Kundu, S. E. Zepf and K. L. Rhode, *Nature*, 445 (2007) 183.
[28] P. G. Breen and D. C. Heggie, *Mon. Not. R. Astron. Soc.*, 432 (2013) 2779.
[29] R. C. E. van den Bosch, K. Gebhardt, K. Gultekin *et al.*, *Nature*, 491 (2012) 729.
[30] R. Schoedel, T. Ott, R. Genzel *et al.*, *Nature*, 419 (2002) 694.
[31] L. Ferrarese and D. Merritt, *Astrophys. J. Lett.*, 539 (2000) L9.
[32] H. Baumgardt, J. Makino and P. Hut, *Astrophys. J.*, 620 (2005) 238.
[33] E. Vesperini, and M. Trenti, *Astrophys. J. Lett.*, 720 (2010) L179.
[34] A. Zocchi, G. Bertin and A. L. Varri, *Astron. Astrophys.*, 539 (2012) A65.
[35] N. Luetzgendorf, M. Kissler-Patig, E. Noyola *et al.*, *Astron. Astrophys.*, 533 (2011) A36.
[36] F. van Leeuwen, R. S. Le Poole, R. A. Reijns *et al.*, *Astron. Astrophys.*, 360 (2000) 472.
[37] M. H. Fabricius, E. Noyola, S. Rukdee *et al.*, *Astrophys. J. Lett.*, 787 (2014) L26.
[38] A. L. Varri, and G. Bertin, *Astron. Astrophys.*, 540 (2012) A94.
[39] P. Bianchini, A. L. Varri, G. Bertin and A. Zocchi, *Astrophys. J.*, 772 (2013) 67.
[40] C. Einsel and R. Spurzem, *Mon. Not. R. Astron. Soc.*, 302 (1999) 81.
[41] C. S. Frenk and S. M. Fall, *Mon. Not. R. Astron. Soc.*, 199 (1982) 565.
[42] R. J. Gott III, *Astrophys. J.*, 186 (1973) 481.
[43] D. Heggie, and P. Hut, "*The Gravitational Million-Body Problem*" (Cambridge University Press) 2003.
[44] D. C. Heggie and N. Ramamani, *Mon. Not. R. Astron. Soc.*, 272 (1995) 317.
[45] G. Bertin, and A. L. Varri, Astrophys. J., 689 (2008) 1005.
[46] H. Baumgardt and J. Makino, *Mon. Not. R. Astron. Soc.*, 340 (2003) 227.
[47] A.H.W. Kuepper, P. Kroupa, H. Baumgardt *et al.* , *Mon. Not. R. Astron. Soc.*, 401 (2010) 105.

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