H. Rickman (ed.), Reports on Astronomy, Vol. XXVA, 289–300.

COMMISSION 37: STAR CLUSTERS AND ASSOCIATIONS

(AMAS STELLAIRES ET ASSOCIATIONS)

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1. Introduction

At the General Assembly in Manchester (UK) in August 2000, 11 new members were added to Commission 37, increasing the total membership to approximately 240.

Each year, Commission 37 has been asked to support numerous symposia and colloquia. It is also one of the supporting commissions of three Symposia and numerous Joint Discussions to be held in the framework of the forthcoming General Assembly in July 2003 in Sydney, Australia.

Apart from these organisational activities, the Commission has been active with the regular update of its web page, containing information related to all IAU activities linked to the Commission. The same web page, reachable through the general IAU web page http://www.iau.org/, contains direct links to the following three web sites:

- The Open Clusters Database, maintained by J.-C. Mermilliod at the Institute of Astronomy of the University of Lausanne, Switzerland. The web address is http://obswww.unige.ch/webda/.
- The Catalogue of Milky Way Globular Cluster Parameters, maintained by W. E. Harris at the Astronomy Department of McMaster University, Hamilton, Ontario, Canada. The web address is http://physun.physics.mcmaster.ca/ harris/mwgc.dat.
- SCYON - The Star Clusters Young & Old Newsletter, edited by C.M. Boily at Strasbourg, P. Kroupa at Kiel, and J.-C. Mermilliod at Lausanne. This is a bi-monthly electronic newsletter devoted to star cluster research and directly linked to the WEBDA database in Lausanne. The web address is http://www.rzuser.uni-heidelberg.de/~s17/scyon/.

The remainder of this report is split into two parts. First, we give a list of some of the meetings (IAU Symposia and Colloquia, as well non-IAU conferences and workshops) held during the period between July 1, 1999 and June 30, 2002, and supported by the Commission and with direct links to star clusters and associations. Quite a few important meetings are also held outside the framework of the IAU. Second, we give a brief overview of some of the scientific highlights of star cluster research published during the report period. This compilation is based on the input of some of the members of the Commission Organising Committee which were kind enough to send their list of highlight papers. Such a compilation remains inevitably biased by the interest of the final compiler. I apologize in advance to anyone whose work is worthy of mention here but which I have neglected to include. Fortunately, the web, with its various databases (ADS, etc,...), is an efficient remedy to the limitations of the present report.

https://doi.org/10.1017/S0251107X00001607 Published online by Cambridge University Press

2. List of IAU Symposia and Colloquia

Hereafter is the list of conferences (Symposia and Colloquia), directly or indirectly related to Commission # 37, officially sponsored by the IAU during the period July 1, 1999 through June 30, 2002:

- IAU Symposium # 200: The formation of Binary Stars (April 2000, Potsdam, Germany)
- IAU Symposium # 207: Extragalactic Star Clusters (March 2001, Pucon, Chile)
- IAU Symposium # 208: Astrophysical Supercomputing Using Particle Simulations (July 2001, Tokyo, Japan)
- IAU Symposium # 212: A Massive Star Odyssey, from Main Sequence to Supernova (June 2002, Lanzarote, Spain)

3. List of Other (Non-IAU) Conferences and Workshops

- The 35th Liège International Astrophysics Colloquium: The Galactic Halo: from Globular Clusters to Field Stars (July 1999, Liège, Belgium)
- Galactic Disks 99 (October 1999, Heidelberg, Germany)
- The 11th Cambridge Workshop: Cool Stars, Stellar Systems, and the Sun (October 1999, Puerto de la Cruz, Tenerife, Spain)
- The 33rd ESLAB Symposium: Star Formation from the Small to the Large Scale (November 1999, Noordwijk, The Netherlands)
- Massive Stellar Clusters, (November 1999, Strasbourg, France)
- STAR2000: Dynamics of Star Clusters and the Milky Way (March 2000, Heidelberg, Germany)
- The 3rd Three-Island Euroconference on Stellar Clusters and Associations: From Darkness to Light-Origin and Evolution of Young Stellar Clusters (April 2000, Cargese, France)
- The 4th Teton Summer Conference: Galactic Structure, Stars and the ISM (May 2000, Grand Teton National Park, USA)
- Stellar Collisions, Mergers, and Their Consequences (May 2000, The American Museum of Natural History, New York City, USA)
- Evolution of Binary and Multiple Star Systems (June 2000, Bormio, Italy)
- The Influence of Binaries on Stellar Population Studies (August 2000, Vrije Universiteit, Brussels, Belgium)
- Modes of Star Formation (October 2000, Heidelberg, Germany)
- Dwarf Galaxies and their Environment (January 2001, Bad Honnef near Bonn, Germany)
- Compact Objects in Dense Star Clusters (June 2001, Aspen, USA)
- Observed HR Diagrams and Stellar Evolution (June 2001, Coimbra, Portugal)
- The Center for Star Formation Studies Workshop: Star Formation in the Galactic Plane (July 2001, Santa Cruz, California)
- The 12th Cambridge Workshop on Cool Stars, Stellar Systems, and the Sun (July 2001, Boulder, USA)
- ω Centauri: A Unique Window into Astrophysics (August 2001, Cambridge, UK)
- Galactic Star Formation Across the Stellar Mass Spectrum (March 2002, La Serena, Chile)
- Numerical Modeling of Young Stellar Clusters (April 2002, Cardiff, Wales, UK)
- New Horizons in Globular Cluster Astronomy (June 2002, Padova, Italy)

All IAU Symposia have proceedings published by the ASP. This is also true for quite a few of the non-IAU conferences and workshops, which have proceedings published in the ASP Conference Series.

4. Globular Clusters

4.1. Large Sets of Photometric Measurements

These last three years have seen the publications of a few major photometric studies based on large homogeneous set of observations made available through the web.

Rosenberg et al. (2000a, 2000b) present the first large and homogeneous CCD color-magnitude diagram data base, comprising 52 nearby Galactic globular clusters imaged in the V and I bands using only two ground-based telescopes (one for each hemisphere). The observed clusters represent 75 % of the known Galactic globulars with $(m - M)_V < 16.15$ mag, cover most of the globular cluster metallicity range ($-2.2 <$ [Fe/H] < -0.4), and span Galactocentric distances from about 1.2 to about 18.5 kpc.

It is worth emphasizing the ever increasing importance of the Hubble Space Telescope (HST) in most of the advanced studies related to star clusters and associations. One of the major recent outputs from HST is the very large photometric database with the color-magnitude diagrams for 74 Galactic globular clusters observed with the HST/WFPC2 camera in the F439W and F555W bands (Piotto et al. 2002).

Both ground-based and HST-based catalogs, because of their homogeneity, are expected to represent a useful data base for the measurement of the main absolute and relative parameters characterizing the color-magnitude diagrams of Galactic globular clusters. Both are available on the web through the ADS.

These data set have already been extremely valuable in attacking a number of still-open topics on evolved stars in Galactic globular clusters. In particular, these data have been used by Piotto et al. (1999a) to investigate the problem of the extended horizontal branches and by Raimondo et al. (2002) to study the properties of the red horizontal branch (HB) in metal-rich clusters; Zoccali et al. (1999) and Bono et al. (2001) have discussed the red giant branch (RGB) bump, and compared the predicted position and dimension of this feature with the observed ones; Zoccali et al. (2000) have used the star counts on the HB and on the RGB to gather information on the helium content and on the dependence of the helium content on the cluster metallicity; Zoccali & Piotto (2000) have made the most extensive comparison so far available between the model evolutionary times away from the main sequence and the actual star counts on the subgiant branch (SGB) and RGB; Cassisi et al. (2001) have compared the observed and theoretical properties of the asymptotic giant branches; Piotto et al. (2000) have used the color-magnitude diagrams in this database to study the Galactic globular cluster relative ages, and Piotto et al. (1999b) have started to investigate the Galactic globular cluster blue straggler (BS) population, and have shown how the BS color-magnitude diagram and luminosity function can differ in clusters with rather different morphologies.

4.2. Tidal Tails around Galactic Globular Clusters

In addition to the effects of their internal dynamical evolution, globular clusters suffer strong dynamical evolution from the potential well of their host galaxy. These external forces speed up the internal dynamical evolution of these stellar systems, accelerating their destruction. Shocks are caused by the tidal field of the Galaxy: interactions with the disk, the bulge and with the giant molecular clouds, heat up the outer regions of each star cluster. The stars in the halo are stripped by the tidal field. All globular clusters are expected (Combes et al. 1999) to have already lost an important fraction of their mass, deposited in the form of individual stars in the halo of the Galaxy.

This is especially true for ω Centauri which has an orbit bringing it always in the inner part of the Galaxy. The current Galacto-centric velocity is relatively low, with $V_R = -31 \pm 10$ km s^{-1}, $V_\theta = -65 \pm 10$ km s^{-1}, and $V_z = +4 \pm 10$ km s^{-1} (Gnedin et al. 2002). The spatial speed of only $V = 72$ km s^{-1} makes ω Centauri strongly bound to the Galaxy, and thus its present position at about 6.3 kpc from the Galactic center is likely to be close to the orbital apocenter. Dinescu et al. (1999) and Gnedin et al. (2002) conclude that ω Centauri remains close enough to the Galactic bulge to pass through the disk twice each orbital period. This cluster should suffer regular disk shocking and should display some scars from this phenomenon, like, e.g., tidal tails.

Leon et al. (2000) studied the 2-D structures of the distribution of stars around ω Cen and 19 Galactic globular clusters, using wide field imaging observations with field of view $5.5° \times 5.5°$. For each field, a (B vs. $B - V$) color-magnitude diagram was constructed, on which a field/cluster star selection was performed, following the pioneering method of Grillmair et al. (1995). Among the 20 globular clusters studied, ω Centauri presents one of the clearest cases of a pair of tidal tails. Its relative proximity (about 5.2 kpc from the sun) allows, for the star count selection, to reach the main sequence significantly below the turn-off, sampling a potentially large number of stars. Estimates show that about 0.6 to 1 % of its mass has been lost during the current disk shocking event. Although ω Centauri has, in this study, one of the best tail/background S/N ratios, it is by far not the only globular cluster exhibiting tidal tails. All clusters observed which do not suffer from strong observational biases present tidal tails. These tidal tails exhibit projected directions preferentially towards the Galactic center, tracing their dynamical evolution through evaporation, disk and bulge shocking (Leon et al. 2000).

Extensive numerical N-body simulations of globular clusters in orbit around the Galaxy were performed by Combes et al. (1999) in order to study quantitatively and geometrically the tidal effects. The main conclusions of their simulations can be summarized as follows: (i) All runs show that all clusters are always surrounded by two giant tidal tails and debris, in permanence along their orbits; (ii) The length of these tidal tails is of the order 5 tidal radii or more; (iii) The orientation of these tidal tails is the signature of the last disk crossing and can constrain strongly the cluster orbit and the Galactic model. Their observations of tidal tails around ω Centauri were perfectly reproduced by their simulations.

The most beautiful case, so far, of tidal tails around a globular cluster is observed by Odenkirchen et al. (2001). They discovered two well-defined tidal tails emerging from the sparse remote globular cluster Palomar 5. These tails stretch out symmetrically to both sides of the cluster in the direction of constant Galactic latitude and subtend an angle of 2.6 degrees on the sky. The tails were detected in commissioning data of the Sloan Digital Sky Survey, providing deep five-color photometry in a 2.5 degree-wide band along the equator. The stars in the tails make up a substantial part ($\sim$1/3) of the current total population of Palomar 5 cluster stars in the magnitude interval $19.5 < \mathrm{i} < 22.0$. This reveals that the cluster is subject to heavy mass loss. The orientation of the tails provides an important key for the determination of the cluster Galactic orbit.

Odenkirchen et al. (2002) further investigate the kinematics of Palomar 5 by using high-resolution spectra from the Very Large Telescope (VLT). Twenty candidate cluster giants located within 6 arcmin of the cluster center have been observed with UVES on VLT-UT2. The spectra provide radial velocities with a typical accuracy of 0.15 $\mathrm{km\,s^{-1}}$. From the 17 confirmed members they determine that the total line-of-sight velocity dispersion of the cluster stars is 1.1 ± 0.2 $\mathrm{km\,s^{-1}}$ (all members) or 0.9 ± 0.2 $\mathrm{km\,s^{-1}}$ (stars on the red giant branch only). The shape of the velocity distribution suggests that there is a significant contribution from orbital motions of binaries and that the dynamical part of the velocity dispersion is therefore still substantially smaller than the total dispersion. Comparing the observations with the results of Monte Carlo simulations of binaries they find that the frequency of binaries in Palomar 5 is most likely between 24 % and 63 % and that the dynamical line-of-sight velocity dispersion of the cluster must be smaller than 0.7 $\mathrm{km\,s^{-1}}$ (90 % confidence upper limit). The most probable values of the dynamical dispersion lie in the range $0.12 < \sigma/\mathrm{km\,s^{-1}} < 0.41$ (68 % confidence). Palomar 5 thus turns out to be a dynamically very cold system. These results are compatible with an equilibrium system. They find that the luminosity of the cluster implies a total mass of only 4.5 to 6.0 10^3 $\mathcal{M}_\odot$. A dynamical line-of-sight velocity dispersion of 0.32 to 0.37 $\mathrm{km\,s^{-1}}$ admits a King model that fits the observed surface density profile of Palomar 5 and its mass.

4.3. Palomar 13: Last Stand or Unusual System?

Siegel et al. (2001) present a proper-motion CCD photometric study of stars in the distant halo globular cluster Palomar 13. The absolute proper motion of this cluster, with a resultant total space velocity of 315 $\mathrm{km\,s^{-1}}$, implies that Palomar 13 is in the inner part of its orbit near perigalacticon. Orbital integration reveals that the cluster possesses an inclined, very eccentric, retrograde orbit. The small size of this cluster, combined with the shape of its light profile, which shows a clear departure from a classical King function beyond the tidal radius, suggests that Palomar 13 is in the final throes of destruction. This could explain the large blue straggler specific frequency, as destructive processes would preferentially strip less massive stars.

Côté et al. (2002) report precise radial velocities for 30 candidate red giants in the direction of Palomar 13. They combined these radial velocities with Siegel et al. (2001) proper motion membership probabilities and new CCD photometry from the Keck and Canada-France-Hawaii telescopes to isolate a sample of 21 probable members. They measure a systemic velocity of $V_s = 24.1 \pm 0.5\ \mathrm{km\,s^{-1}}$ and a projected, intrinsic velocity dispersion of $\sigma = 2.2 \pm 0.4\ \mathrm{km\,s^{-1}}$. Although modest, this dispersion is nevertheless several times larger than that expected for a globular cluster of this luminosity and central concentration. Taken at face value, it implies a mass-to-light ratio of $\mathcal{M}/L = 40\ ^{+24}_{-17}$ based on the best-fit King-Michie model. The surface density profile of Palomar 13 also appears unusual compared to most Galactic globular clusters; depending upon the details of background subtraction and model-fitting, Palomar 13 either contains a substantial population of "extratidal" stars, or is considerably more spatially extended than previously suspected. The full surface density profile is equally well fitted by a King-Michie model having a high concentration and large tidal radius, or by a Navarro-Frenk-White model. They examine – and tentatively reject – a number of possible origins for the observed characteristics of Palomar 13 (e.g., velocity "jitter" among the red giant branch stars, spectroscopic binary stars, nonstandard mass functions, modified Newtonian dynamics) and conclude that the two leading explanations are either catastrophic heating during a recent perigalacticon passage or the presence of a dark matter halo. The available evidence therefore suggests that Palomar 13 is either a globular cluster that is now in the process of dissolving into the Galactic halo or a faint, dark matter-dominated stellar system.

4.4. High-Quality Stellar Proper Motions from HST Data

Large samples of stars with not only photometric but also kinematic data (thousands of radial velocities and proper motions) now become available. Anderson & King (2000) have developed a new method and new software which provide the most precise proper motions obtained so far with HST. A new generation of studies interpreting large samples of radial velocities and proper motions will soon allow a much more reliable insight into the internal kinematics and dynamics of ω Centauri and 47 Tucanae, among other globular clusters.

The first study based on such a large sample has been published by van Leeuwen et al. (2000), who measured the ground-based proper motions of 7853 individual stars in ω Centauri, based on 100 photographic plates obtained with the Yale-Columbia 66-cm refractor during the first epoch, from 1931 - 1935, in South Africa and during the second epoch, from 1978 - 1983, in Australia. For the first time, a velocity dispersion profile has been obtained in a globular cluster, from individual stellar proper motions: in the core $\sigma_{obs} = 1.0$ to 1.2 mas $\mathrm{yr^{-1}}$, corresponding to 25 to 29 $\mathrm{km\,s^{-1}}$, while in the outer regions $\sigma_{obs} = 0.3$ mas $\mathrm{yr^{-1}}$, corresponding to 7.5 $\mathrm{km\,s^{-1}}$.

Another application of the high-quality proper motions is linked to the study of the mass function down the Main Sequence. In a continuation of the pioneering work by King et al. (1998), Bedin et al. (2001) made a proper-motion separation of M4 members from field stars, using deep HST observations separated by a time baseline of 5 years, allowing the study of a pure sample of cluster main-sequence stars almost to the minimum mass for hydrogen burning. High-precision photometry shows how badly current theoretical models fail to reproduce the color-magnitude diagram of low-mass stars of moderate metallicity ([M/H] $\simeq -1$). This inability of theory to reproduce the luminosity-color relation casts doubt on the theoretical mass-luminosity relation, which is needed to convert the observed luminosity function into a mass function as well as to convert our locally determined luminosity function into a global mass function.

4.5. Stellar Abundances and Rotation

Numerous studies address the problem of stellar abundances in the framework of the chemical evolution of the globular cluster (see, e.g., Smith et al. 2000).

Ramírez & Cohen (2002) obtained abundance ratios for 23 elements with respect to Fe in a sample of stars with a wide range in luminosity, from luminous giants to stars near the turnoff in a globular cluster. Their sample of 25 stars in M71 includes 10 giant stars more luminous than the red horizontal branch (RHB), three HB stars, nine giant stars less luminous than the RHB, and three stars near the turnoff. The analyzed spectra, obtained with HIRES at the Keck Observatory, are of high dispersion (R=35,000).

They find that the neutron capture, the iron peak, and the α-element abundance ratios show no trend with $T_{\rm eff}$ and low scatter around the mean between the top of the RGB and near the main-sequence turnoff. The α-elements Mg, Ca, Si, and Ti are over abundant relative to Fe. The anti-correlation between O and Na abundances observed in other metal-poor globular clusters is confirmed and extends to the main sequence. A statistically significant correlation between Al and Na abundances is observed among the M71 stars in their sample, extending to $M_V = +\,1.8$, fainter than the luminosity of the RGB bump in M5. Lithium is varying, as expected, and Zr may be varying from star to star as well. M71 appears to have abundance ratios very similar to M5, but seems to have a smaller amplitude of star-to-star variations at a given luminosity, as might be expected from its higher metallicity. Neither extremely O-poor, Na-rich stars nor extremely O-rich, Na-poor, stars such as are observed in M5 and in M13, are present in their sample of M71 stars.

The results of Ramírez & Cohen (2002) abundance analysis of 25 stars in M71 provide sufficient evidence of abundance variations at unexpectedly low luminosities to rule out the mixing scenario. Either alone or, even more powerfully, combined with other recent studies of C and N abundances in M71 stars, the existence of such abundance variations cannot be reproduced within the context of our current understanding of stellar evolution.

Behr et al. (2000a), from high-resolution optical spectra of 18 blue horizontal-branch stars in the globular cluster M15, find stellar rotation rates and photospheric compositions that vary strongly as a function of effective temperature. These results are qualitatively very similar to those previously reported for M13 and NGC 6752. E.g., in M13, the sample of Behr et al. (2000b) spans the photometric gap observed in the horizontal-branch distribution at $T_{\rm eff}$ 11,000 K and reveals a pronounced difference in stellar rotation on either side of this feature: blueward of the gap, all the stars show modest rotation, $V \sin i < 10\ {\rm km\,s^{-1}}$, while to the red side of the gap, the population rotates more rapidly. However, Recio-Blanco et al. (2002), from observations of 56 stars in the extended horizontal-branch of the Galactic globular clusters NGC 1904, NGC 2808, NGC 6093, and NGC 7078, find that the connection between photometric gaps in the HB and the change in the projected rotational velocities is not confirmed.

4.6. Binaries in Globular Clusters

One of the by-products of a search for, and conclusion of a lack of, planets in 47 Tucanae, from a major HST search (Gilliland et al. 2000), has been one of the most precise and significant determinations of the frequency of binary stars in the core of 47 Tucanae (Albrow et al. 2001).

Differential time series photometry were derived for 46,422 main-sequence stars in the core of 47 Tucanae. The observations consisted of near-continuous 160-sec exposures alternating between the F555W and F814W filters for 8.3 days in 1999 July with HST/WFPC2. Using Fourier and other search methods, 11 detached eclipsing binaries and 15 W Ursa Majoris stars were discovered plus an additional 10 contact or near-contact non-eclipsing systems.

After correction for nonuniform area coverage of the survey, the observed frequencies of detached eclipsing binaries and W UMa stars within 90 arcsec of the cluster center are 0.022 % and 0.031 %, respectively. The observed detached eclipsing binary frequency, the assumptions of a flat binary distribution with log period, and assuming that the eclipsing binaries with periods longer than about 4 days have essentially their primordial periods imply an overall binary frequency of 13 % ± 6 %. The observed W UMa frequency and the additional assumptions that W UMa stars have evolved to contact according to tidal circularization and angular momentum loss theory and that the contact binary lifetime is 109 yr imply an overall binary frequency of 14 % ± 4 %.

4.7. Are some Globulars the Remnant Cores of Dwarf Ellipticals?

The earliest photometric study of ω Centauri noticed the unusually broad red-giant branch in the color-magnitude diagram of this cluster. Cannon & Stobie (1973) suggested, for the first time, that the red-giant branch scatter could be intrinsic, possibly due to some metallicity inhomogeneity between cluster stars. This was the first of a series of surprises which have accumulated during the last few years: in spite of (or maybe because of) the fact that ω Centauri is one of the best studied globular clusters, there are a few conundrums, i.e., puzzling published results which have no clear solid explanations. Here they are!

The dependence of kinematics on abundance. For a sample of about 400 red giants, Norris et al. (1997) find that the 20 % metal-rich tail of the [Ca/H] distribution, as well as being more centrally concentrated, is kinematically cooler than the 80 % metal-poorer component. At first glance one might interpret this as evidence consistent with a dissipative enrichment scenario of cluster formation. However, while the metal-poorer stars exhibit a well-defined systemic rotation, the metal-richer stars show no evidence of rotation, in contradistinction to the simple dissipative picture.

The multiple stellar populations in color-magnitude diagram. Wide-field images have changed dramatically the amount of information available in photometric studies. From the color-magnitude diagram of more than 50,000 stars, Lee et al. (1999) observed a clear evidence of multiple stellar populations in ω Centauri. These results were confirmed by Pancino et al. (2000) in a photometric study involving 230,000 stars in this cluster.

The bi-modal main sequence. In a study with exquisitely good HST photometry, Anderson (2002) discovered what may be the most unexpected result: the main sequence of ω Centauri becomes bi-modal over a range a 2-3 magnitudes centered around F606W $\sim$ 21 mag.

Early on-going star formation. In a photometric study using *vby* filters, Hughes & Wallerstein (2000) found that the comparatively metal-rich stars are younger than the metal-poor stars by at least 3 Gyr. This correlation of metallicity with age suggests that ω Centauri has enriched itself over a timescale of about 3 Gyr, and possibly longer. They interpret these results as possible evidence that ω Centauri could have been part of a dwarf galaxy in which all the activity occurred before being captured by our Galaxy. These results are confirmed by Hilker & Richtler (2000).

4.8. Mayall II ≡ G1: the M31 Twin of ω Centauri?

Mayall II ≡ G1 is one of the brightest globular clusters belonging to M31. It is located at a projected distance of about 3°, i.e. 40 kpc, from the center of this galaxy. In their photometric study, Meylan et al. (2001) present a color-magnitude diagram implying a rather high mean metallicity of [Fe/H] = − 0.95 ± 0.09, somewhat similar to 47 Tucanae. They observe a larger spread in $V-I$ color than can be attributed to only an intrinsic metallicity dispersion amongst the stars of G1. This makes G1 the second globular cluster, after ω Centauri, to exhibit such a metallicity spread, which may be the consequence of self-enrichment during the early stellar/dynamical evolutionary phases of these clusters, a phenomenon certainly related to the deep potential well of each of these two stellar systems.

The masses of both ω Centauri and G1 are uncertain to about a factor of two. Although not very precise, all the mass estimates ($\mathcal{M}_{tot}$ = 7- 14 $10^6 \mathcal{M}_\odot$) make G1 more than twice as massive as ω Centauri, the most massive Galactic globular cluster. G1 is the heaviest of the weighed globular clusters. See Ferguson et al.2002, astro-ph/0205530.

The positions of both ω Centauri and G1 in the different diagrams defined by Kormendy (1985), using the following four parameters (the central velocity dispersion $\sigma_p(0)$, the integrated absolute visual magnitude M_V, the core radius r_c, and the central surface brightness $\mu(0,V)$), always put these two clusters on the sequence defined by globular clusters, and definitely away from the other sequences defined by elliptical galaxies, bulges, and dwarf spheroidal galaxies.

Little is known about the positions, in these diagrams, of the nuclei of nucleated dwarf elliptical galaxies, which could be the progenitors of the most massive, but not necessarily all, globular clusters. The above four parameters are known only for the nucleus of one dwarf elliptical, viz., NGC 205, and their values put this object, in Kormendy's diagram, close to G1, right on the sequence of globular clusters. This result does not prove by itself that all massive globular clusters are the remnant cores of nucleated dwarf galaxies! In any case, by the mere fact that their large masses imply complicated stellar and dynamical evolutions, the very massive globular clusters may blur the former clear (or simplistic) difference between globular clusters and dwarf galaxies.

The structure of a very bright ($M_V = -10.9$) globular cluster in NGC 1023 was analyzed on two sets of images taken with the HST by Larsen (2001). From careful modeling of King profile fits to the cluster image, a core radius of $r_c = 0.55 \pm 0.1$ pc, an effective radius $R_e = 3.7 \pm 0.3$ pc, and a central surface brightness of $\mu(0,V) = 12.9 \pm 0.5$ mag arcsec^{-2} were derived. This makes this cluster in NGC 1023 much more compact than ω Centauri, but very similar to G1, the brightest globular cluster in M31.

4.9. Are Black Holes Back into Globulars?

The presence of black holes in the core of some globular clusters has been proved and disproved a few times over the past three decades, partly in relation to X-ray sources and to core collapse. Gebhardt et al. (2000) have used an Imaging Fabry-Perot Spectrophotometer with the Adaptive Optics Bonnette on the Canada-France-Hawaii Telescope to measure stellar radial velocities in the globular cluster M15. Their estimate of the velocity dispersion inside a radius of 2 arcsec is 11.5 km s^{-1}, with a projected net rotation that increases dramatically at small radii. Current theoretical models do not predict either this large an increase in the rotation amplitude or such a change in the position angle. However, a central mass concentration, such as a black hole, could possibly sustain such a configuration. The rotation increase is consistent with the existence of a central dark mass concentration equal to 2500 $\mathcal{M}_\odot$.

5. Open Clusters and Associations

5.1. Circumstellar Disks and Candidate Protostars

Lada et al. (2000) report the results of a sensitive near-infrared JHKL imaging survey of the Trapezium cluster in Orion. They use the JHKL colors to obtain a census of infrared excess stars in the cluster. Of 391 stars brighter than 12th magnitude in the K and L bands, 80 % $\pm$ 7 % are found to exhibit detectable infrared excess on the J-H, K-L color-color diagram. Examination of a subsample of 285 of these stars with published spectral types yields a slightly higher infrared excess fraction of 85 %. They find that 97 % of the optical proplyds in the cluster exhibit excess in the JHKL color-color diagram indicating

https://doi.org/10.1017/S0251107X00001607 Published online by Cambridge University Press

that the most likely origin of the observed infrared excesses is from circumstellar disks. They interpret these results to indicate that the fraction of stars in the cluster with circumstellar disks is between 80 %-85 %, confirming earlier published suggestions of a high disk fraction for this young cluster. Moreover, the probability of finding an infrared excess around a star seems independent of stellar mass over essentially the entire range of the stellar mass function down to the hydrogen burning limit. Consequently, the vast majority of stars in the Trapezium cluster appear to have been born with circumstellar disks and the potential to subsequently form planetary systems, despite formation within the environment of a rich and dense stellar cluster.

See Haisch et al. (2001) for similar studies in the intermediate-age (2.5-30 Myr) clusters NGC 2264, NGC 2362, and NGC 1960. They find disk fractions of 52 % $\pm$ 10 %, 12 % $\pm$ 4 %, and 3 % $\pm$ 3 % for the three clusters, respectively. Together with previously published JHKL investigations of the younger NGC 2024, Trapezium, and IC 348 clusters, this makes the first systematic and homogeneous survey for circumstellar disks in a sample of young clusters that both span a significant range in age (0.3-30 Myr) and contain statistically significant numbers of stars whose masses span nearly the entire stellar mass spectrum. Analysis of the combined survey indicates that the cluster disk fraction is initially very high ($>$ 80 %) and rapidly decreases with increasing cluster age, such that one-half the stars within the clusters lose their disks in $<$3 Myr. Moreover, these observations yield an overall disk lifetime of $\sim$6 Myr in the surveyed cluster sample. This is the timescale for essentially all the stars in a cluster to lose their disks. This should set a meaningful constraint for the planet-building timescale in stellar clusters. See also Muench et al. (2001).

5.2. Observed Luminosity and Mass Functions

Luminosity and mass functions are essential observations to constrain models. One of the best targets is the Inner Orion Nebula Cluster. From H,K observations, Hillenbrand & Carpenter (2000) find that their data are inconsistent with a mass function that rises across the stellar/substellar boundary. Instead, they find that the most likely form of the mass function is one that rises to a peak around 0.15 $\mathcal{M}_\odot$, and then declines across the hydrogen-burning limit.

Carpenter (2000) uses the 2MASS Catalog to investigate the spatial distribution of young stars in the Perseus, Orion A, Orion B, and MonR2 molecular clouds. From the first extensive mid-infrared imaging survey of the rho Ophiuchi embedded cluster, performed with the ISOCAM camera on board the ISO satellite, Bontemps et al. (2001) find its luminosity and mass functions. Preibisch & Zinnecker (2002) explore the X-ray properties of the young stellar and substellar objects in the open cluster IC 348 from deep Chandra X-Ray image, supplemented with optical and infrared data.

Moitinho et al. (2001) present UBVRI photometry for the young open cluster NGC 2362. They derive an age = 5 Myr, a distance = 1480 pc, and E(B-V) = 0.10 mag. Analysis of color-magnitude diagram reveals a well-defined pre-main sequence (covering ΔV $\sim$ 9 mag in V and extending from early A stars to near the hydrogen-burning limit), which makes this cluster an ideal laboratory for pre-main-sequence evolution studies.

Muench et al. (2000) present the results of numerical experiments designed to evaluate the usefulness of near-infrared (NIR) luminosity functions for constraining the initial mass function of young stellar populations. They test the sensitivity of the NIR K-band luminosity function of a young stellar cluster to variations in the underlying IMF, star-forming history, and pre-main-sequence mass-to-luminosity relations. Using Monte Carlo techniques, they create a suite of model luminosity functions systematically varying each of these basic underlying relations. From this numerical modeling, they find that the luminosity function of a young stellar population is considerably more sensitive to variations in the underlying initial mass function than to either variations in the star-forming history or assumed pre-main-sequence mass-to-luminosity relation.

5.3. Theoretical Luminosity and Mass Functions, Cluster Formation

Open clusters, because of their relatively low numbers of stars, are the ideal targets for N-body simulations running Aarseth's codes on special-purpose computers. See, e.g., Portegies Zwart, Makino, McMillan & Hut (2002) and all their other studies.

Kroupa et al. (2001) present direct N-body calculations of the formation of Galactic clusters using GasEx, which is a variant of the code Nbody6. The calculations focus on the possible evolution of the Orion nebula cluster (ONC) by assuming that the embedded OB stars explosively drove out 2/3 of its mass in the form of gas about 0.4 Myr ago. A bound cluster forms readily and survives for 150 Myr despite additional mass loss from the large number of massive stars, and the Galactic tidal field. This is the very first time that cluster formation is obtained under such realistic conditions. The cluster contains about 1/3 of the initial 104 stars, and resembles the Pleiades cluster to a remarkable degree, implying that an ONC-like cluster may have been a precursor of the Pleiades. This scenario predicts the present expansion velocity of the ONC, which will be measurable by upcoming astrometric space missions. These missions should also detect the original Pleiades members as an associated expanding young Galactic-field subpopulation. The results arrived at here suggest that Galactic clusters form as the nuclei of expanding OB associations. The results have wide implications, also for the formation of globular clusters and the Galactic-field and halo stellar populations. In view of this, the distribution of binary orbital periods and the mass function within and outside the model ONC and Pleiades is quantified, finding consistency with observational constraints. Advanced mass segregation is evident in one of the ONC models. The calculations show that the primordial binary population of both clusters could have been much the same as is observed in the Taurus-Auriga star-forming region. The computations also demonstrate that the binary proportion of brown dwarfs is depleted significantly for all periods, whereas massive stars attain a high binary fraction.

Adams & Myers (2001) argue that star-forming environments should be classified into finer divisions than the traditional isolated and clustered modes. Using the observed set of Galactic open clusters and theoretical considerations regarding cluster formation, they estimate the fraction of star formation that takes place within clusters. They find that less than $\sim$ 10% of the stellar population originates from star-forming regions destined to become open clusters, confirming earlier estimates. The smallest clusters included in the observational surveys (having at least N$\sim$100 members) roughly coincide with the smallest stellar systems that are expected to evolve as clusters in a dynamical sense. They show that stellar systems with too few members N<100 have dynamical relaxation times that are shorter than their formation times ($\sim$1-2 Myr).

6. Extragalactic Star Clusters

The availability of 10-m class telescopes and of the HST allows the study of individual extragalactic star clusters, of various ages and absolute luminosities. This will make, in the near future, the link of this Commission to Division VII and the Galaxy more and more outdated.

After Barmby et al. (2002) for M31, Harris et al. (2002) present new imaging measurements of 43 individual globular clusters in the halo of the nearby elliptical galaxy NGC 5128, obtained with HST/WFPC2. They use the cluster light profiles to determine their structural parameters (core and half-light radii, central concentration, and ellipticity). They find that classic King model profiles match the clusters extremely well and that their various structural parameters (core and half-light radius, central surface brightness, and central concentration) fall in very much the same range as do the clusters in the Milky Way and M31. They find half a dozen bright clusters that show tentative evidence for "extratidal light" that extends beyond the nominal tidal radius, similar in nature to several such objects previously found in the Milky Way and M31. They also confirm previous indications that NGC 5128 contains relatively more clusters with large ($\epsilon > 0.2$) ellipticity than does the Milky Way. Instead, the ellipticity distribution of the NGC 5128 clusters strongly resembles that of the old clusters in the Large Magellanic Cloud and also in M31. Finally, calculations of the cluster binding energies E_b as defined by McLaughlin (2000) show that the NGC 5128 clusters occupy the same extremely narrow region of the parametric "fundamental plane" as do their Milky Way counterparts. These data are thus strongly consistent with the claim that the globular clusters in both NGC 5128 and the Milky Way are the same type of object: old star clusters with similar mass-to-light ratios and King model structures.

Not only individual clusters, but also systems of star clusters are used as tracers of the connection between globular cluster systems and their host galaxies. A large number of early-type galaxies are now known to possess blue and red subpopulations of globular clusters. Forbes & Forte (2001) have compiled a data base of 28 such galaxies exhibiting bimodal globular cluster color distributions. After converting to a common V-I color system, they investigate correlations between the mean color of the blue and red subpopulations with galaxy velocity dispersion. They support previous claims that the mean colors of the blue globular clusters are unrelated to their host galaxy. They must have formed rather independently of the galaxy potential they now inhabit. The mean blue color is similar to that for halo globular clusters in our Galaxy and M31. The red globular clusters, on the other hand, reveal a strong correlation with galaxy velocity dispersion. Furthermore, in well-studied galaxies the red subpopulation has similar, and possibly identical, colors to the galaxy halo stars. These results indicate an intimate link between the red globular clusters and the host galaxy; they share a common formation history. A natural explanation for these trends would be the formation of the red globular clusters during galaxy collapse.

Chandar et al. (2002) find evidence for apparently distinct populations through the kinematics of star clusters in M33. When clusters are divided into age groups, the old clusters clearly have very different kinematics from the young population and from the gas disk. Monte Carlo simulations comparing synthetic disk plus halo systems with the observed velocity distribution for their old M33 clusters suggest that old clusters are likely to be composed of two distinct subpopulations, an 85 % ± 5 % halo component plus a 15 % ± 5 % disk component. This is the first evidence for distinct kinematic subpopulations among the old M33 clusters, and this galaxy appears to have a higher halo/bulge fraction of old stellar objects than found in the Galaxy.

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References

Adams, F.C., Myers, P.C., 2001, ApJ, 553, 744
Albrow, M.D., Gilliland, R.L., Brown, T.M., et al., 2001, ApJ, 559, 1060
Anderson, J., 2002, ASP Conf. Series. # 265, p. 87
Anderson, J., King, I.R., 2000, PASP, 112, 1360
Barmby, P., Holland, S., Huchra, J.P., 2002, AJ, 123, 1937
Bedin, L.R., Anderson, J., King, I.R., Piotto, G., 2001a, ApJ, 560, L75
Behr, B.B., Cohen, J.G., McCarthy, J.K., 2000b, ApJ, 531, L37
Behr, B.B., Djorgovski, S.G., Cohen, J.G., et al., 2000, ApJ, 528, 849
Bontemps, S., André, P., Kaas, A.A., et al., 2001, A&A, 372, 173
Bono, G., Cassisi, S., Zoccali, M., Piotto, G. 2001, ApJ, 546, L109
Cannon, R.D., Stobie, R.S., 1973, MNRAS, 162, 207
Carpenter, J.M., 2000, AJ, 120, 3139
Cassisi, S., Castellani, V., Degl'Innocenti, S., et al., 2001, A&A, 366, 578
Chandar, R., Bianchi, L., Ford, H.C., Sarajedini, A., 2002, ApJ, 564, 712
Combes, F., Leon, S., Meylan, G., 1999, A&A, 352, 149
Côté, P., Djorgovski, S.G.., Meylan, G.., et al. 2002, ApJ, 574, 783

Dinescu D.I., Girard T.M., van Altena W.F., 1999, AJ, 117, 1792
Forbes, D.A., Forte, J.C., 2001, MNRAS, 322, 257
Gebhardt, K., Pryor, C., O'Connell, et al., 2000, AJ, 119, 1268
Gilliland, R.L., Brown, T.M., Guhathakurta, P., et al., 2000, ApJ, 545, L47
Gnedin, O.Y., Fall, S.M., Livio, M., et al., 2002, ApJ, 568, L23
Grillmair C.J., Freeman K.C., Irwin M., Quinn P.J., 1995, AJ, 109, 2553
Haisch, K.E., Lada, E.A., Lada, C.J., 2001, ApJ, 553, 153
Harris, W.E., Harris, G.L.H., Holland, S.T., McLaughlin, D.E., 2002, AJ, 124, 1435
Hilker, M., Richtler, T., 2000, A&A, 362, 895
Hillenbrand, L.A., Carpenter, J.M., 2000, ApJ, 540, 236
Hughes, J., Wallerstein, G., 2000, AJ, 119, 1225
King, I.R., Anderson, J., Cool, A.M., Piotto, G., 1998, ApJ, 492, L37
Kormendy, J., 1985, ApJ, 295, 73
Kroupa, P., Aarseth, S., Hurley, J., 2001, MNRAS, 321, 699
Lada, C.J., Muench, A.A., Haisch, K.E., 2000, AJ, 120, 3162
Larsen, S.S., 2001, AJ, 122, 1782
Lee, Y.-W., Joo, J.-M., Sohn, Y.-J., et al., 1999, Nature, 402, 55
Leon, S., Meylan, G., Combes, F., 2000, A&A, 359, 907
McLaughlin, D.E. 2000, ApJ, 539, 618
Meylan, G., Sarajedini A., Jablonka P., Djorgovski, S.G., Bridges, T., Rich R.M., 2001, AJ, 122, 830
Moitinho, A., Alves, J., Huélamo, N., Lada, C.J., 2001, ApJ, 563, 73
Muench, A.A., Alves, J, Lada, C.J., Lada, E.A., 2001, ApJ, 558, 51
Muench, A.A., Lada, E.A., Lada, C.J., 2000, ApJ, 533, 358
Norris, J.E., Freeman, K.C., Mayor, M., Seitzer, P., 1997, ApJ, 487, L187
Odenkirchen, M., Grebel, E.K., Rockosi, C.M., 2001, ApJ, 548, 165
Odenkirchen, M., Grebel, E.K., Dehnen, W., et al., 2002, AJ, 124, 1497
Pancino, E., Ferraro, F.R., Bellazzini, M., et al., 2000, ApJ, 534, L83
Piotto, G., Zoccali, M., King, I. R., et al., 1999a, AJ, 117, 264
Piotto, G., Zoccali, M., King, I. R., et al., 1999b, AJ, 118, 1727
Piotto, G., 2002, in the Liège International Astrophysics Colloquium on The Galactic Halo: from Globular Clusters to Field Stars, p. 471
Piotto, G., King, I. R., Djorgovski, S. G., et al., 2002, A&A, 391, 945
Portegies Zwart, S.F., Makino, J., McMillan, S.L.W., Hut, P., 2002, ApJ, 565, 265
Preibisch, T., Zinnecker, H., 2002, AJ, 123, 1613
Raimondo, G., Castellani, V., Cassisi, S., et al., G. 2002, ApJ, 569, 975
Ramírez, S.V., Cohen, J.G., 2002, AJ, 123, 3277
Recio-Blanco, A., Piotto, G., Aparicio, A., Renzini, A., 2002, ApJ, 572, L71
Rosenberg, A., Piotto, G., Saviane, I. Aparicio, A., 2000a, A&AS, 144, 5
Rosenberg, A., Aparicio, A., Saviane, I., Piotto, G., 2000b, A&AS, 145, 451
Siegel, M. H., Majewski, S. R., Cudworth, K. M., Takamiya, M., 2001, AJ, 121, 935
van Leeuwen F., Le Poole R.S., Reijns R.A., Freeman K.C., de Zeeuw P.T., 2000, A&A, 360, 472
Smith, V.V., Suntzeff, N.B., Cunha, K., et al.., 2000, AJ, 119, 1239
Zoccali, M., Cassisi, S., Piotto, G., et al., 1999, ApJ, 518, L49
Zoccali, M., Cassisi, S., Bono, G., et al., 2000, ApJ, 538, L289
Zoccali, M., Piotto, G., 2000, A&A, 358, 943