The Globular Cluster System of M31

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Abstract. This review presents the current status of our knowledge of M31 star clusters. Given the broadness of the subject, I chose to focus on some of its aspects which are not covered by the other participants in this conference.

1. Scientific issues

Globular clusters are studied for their intrinsic properties as well as for the information they give on their parent galaxy. No less than 300 articles address the globular cluster system of M31. I briefly mention here the topics tackled over the years and will come back in more detail to some of them below: their total number and specific frequency, their stellar population: age and metallicity, the distance to M31, the relation between the level of the horizontal branch and metallicity, the search for novae, the bulge/disc/halo cluster properties, the radial distribution of their properties, their luminosity function, their kinematics, dynamics, their true shape, ellipticity, tidal radii, effective radii, the absorption law in M31, the mass and mass distribution of M31, the scenario for the formation of M31. For all these topics, comparisons with our Galaxy and galaxies in the Local Group are usually conducted.

2. Detection

The clear identification and precise location of the clusters is the first step prior to any further investigation. There is a very long list of contributors, and it is nearly impossible to quote them all here. Nonetheless I would like to mention a few historical cornerstones. Hubble (1932) was the first to report the detection on photographic plates of 140 *nebulous* objects, provisionally identified as globular clusters. Thirty years later, in 1962, Vetesnik reported the existence of 257 candidates. As a matter of fact, the total number of "confirmed" clusters has not changed much over the years. What has changed is the degree of confidence that could be put in their "confirmation". In 1976, Alloin, Pelat & Bijaoui started to focus on the inner regions of M31, and identified 8 central globular clusters. Ten years later, Wirth, Smarr & Bruno (1985) increased the list of bulge clusters up to 30 candidates. In 1979, Hodge initiated the search for open clusters, and proposed a list of 403 such objects. One had to wait till 1991 for the first CCD photometry of 82 halo clusters provided by the work of Racine at the CFHT.

As for the contemporary studies of globular clusters, they are largely based on the major study of Battistini et al. (1993). The authors listed a grand total of 1028 globular cluster candidates, with 14 mag $< V <$ 20 mag, in a $3^o \times 3^o$ region (30 kpc x 30 kpc), centered on M31. They established their *best sample*, a term that is now widely used, by selecting clusters with $V \leq 18$ mag and with $B-V \geq 0.58$ mag (this blue limit corresponds to the bluest globular cluster at $B-V = 0.52$ in our Galaxy). This sample regroups 298 objects, comprising 199 confirmed globular clusters, 72 by high resolution imaging, 174 by spectroscopy, 47 by both methods. Limiting the comparison between the Milky Way and M31 to regions with good completeness and little contamination, Battistini et al. (1993) found $N_{M31} / N_{MW} \sim 2.5$. Recently, Barmby et al. (2000) compiled new photometry, spectroscopy and existing data from the literature. Their inventory contains 435 clusters and cluster candidates, including the *best sample*, 268 with 4 or more optical filter photometry, 224 with IR photometry, 200 with velocities, 188 with spectroscopic metallicities. M.G. Lee presents another new survey in this conference.

For the open clusters, Williams and Hodge (2001) provide an updated catalogue of candidates.

3. A view from the IR

The infrared (IR) offers a view of the M31 globular cluster system, which comes closest to the visible.

So far, analyses have dealt mainly with integrated photometry. Cohen & Matthews (1994) gave a good summary of the situation by combining previous studies with 23 new globular clusters, 16 of which have projected distance less than 1.1 kpc from M31 center. Of these earlier studies, we mention in particular Frogel et al. (1980), Sitko (1984), and Bonoli et al. (1992). All studies combined led to a total sample of 84 objects. The mean metallicity in M31 and in our Galaxy is the same to within 0.11 dex, which is within the uncertainties of the two [Fe/H] determinations. There is no evidence among the outer globular clusters for a spatial gradient of metallicity, contrary to what is observed in the globular cluster system of our Galaxy.

Stephens et al. present in these proceedings their HST-NICMOS observations of metal rich globular clusters in M31, a study which opens the era of resolving individual stars in the IR.

As for spectroscopy, Davidge (1990) presented spectra in the interval 1.5–1.8 microns and 2.0–2.4 microns of a few luminous M31 clusters. Since these spectra were noisy, Davidge had to construct a mean spectrum, from which it appeared that the CO bands are similar to the Galactic clusters while CN absorptions look stronger. The CN enhancement in M31 was first mentioned in the visible (Burstein et al. 1984).

4. A view from the UV

Studying the hot phases of the stellar evolution is one strong motivation for observing globular clusters in the UV, another one being the understanding of the connection with the "UV-upturn" population in bulges and elliptical galaxies.

Bohlin et al. (1993) observed 43 clusters with the UIT; 42 were identified in the near UV (2490 Å) and only 10 in the far UV (1520 Å). Their data suggest that the M31 clusters are close counterparts of Galactic globulars.

Cacciari et al. (1982) and Cowley & Burstein (1988) obtained the first spectra of a dozen of the brightest clusters in M31, at rather low resolution. Some clusters seem to exhibit residual flux below 3000 Å, more than that expected from the bright evolved stars in the clusters. These pioneering observations were still at low signal to noise and triggered discussions (Crotts et al. 1990).

The Hubble Space Telescope has opened a new era: the spectral resolution of the UV data can now match that obtained in the visible. As a start, Ponder et al. (1998) got HST/FOS integrated UV spectra for 4 M31 clusters. Interestingly, the near-UV indices involving nitrogen show an enhancement relative to Galactic stars (disk and halo). As in the visible, there is yet no clear explanation for this phenomenon.

5.   A view from the X-rays

It seems that there is a promising field of research in the X-rays. This domain allows a direct insight into the composition of the globular clusters' stellar population.

The Einstein Satellite has brought a first set of significant information (Battistini et al. 1982, Trinchieri & Fabbiano 1991). However, ROSAT gave a more general view (Supper et al. 1997, after Primini et al. 1993), since the ROSAT PSPC deep survey could cover the whole galaxy, with a total integration time about ten times greater than that of the Einstein observations. In total, 396 sources were found in the ROSAT PSPC first survey of M31, and 27 of these ROSAT sources were identified with globular clusters. The fraction of X-ray bright clusters among the total cluster population looked similar in M31 and in our Galaxy. For the two galaxies, the maximum luminosity of X-ray bright globular clusters looked also comparable. With the second ROSAT PSPC deep survey, Supper et al. (2001) update and confirm these results. However, *Chandra* results, with observation of 30 clusters, as presented by Di Stefano et al. (2001), seems to contradict this view. Indeed, the authors find a higher peak in luminosity and a larger fraction of high luminosity clusters.

At this stage, it is difficult to distinguish for which reason such opposite conclusions can be reached. The samples and statistical analyses are different. Further investigation seems necessary.

Very interestingly, the X-ray technology now allows rather good spectroscopy and this first step is reported by Trinchieri et al (1999) with the observation of 8 clusters. The detected sources with BeppoSAX have high X–ray luminosity ($L_X \geq 5 \times 10^{37}$ erg s^{-1} in the 2-10 keV band). This suggests that they are most likely low-mass-X-ray binaries. Most of them have a similar spectrum, that can be described with a single temperature component with kT$\sim 6 - 9$ keV. Contrary to a recent proposal, no trend shows up between the soft X–ray properties and the cluster metallicities.
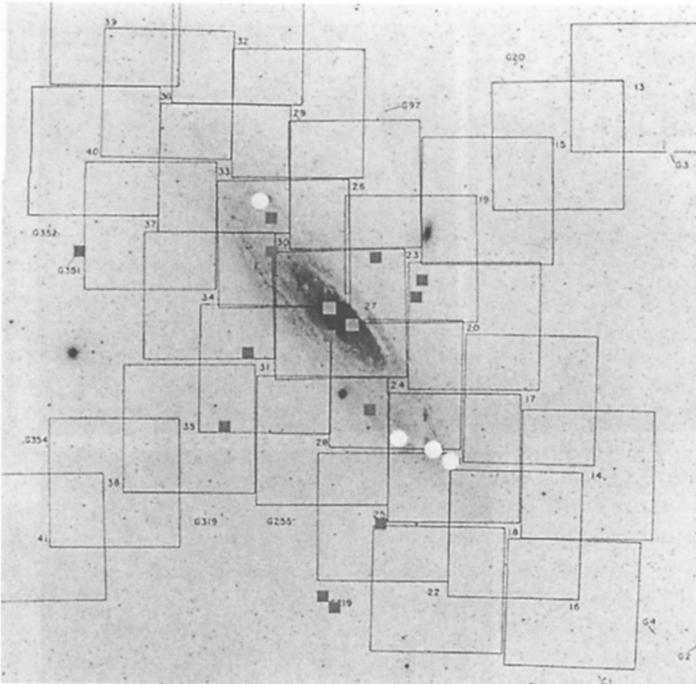
Figure 1.   The M31 clusters for which color-magnitude diagrams have been obtained, at the time of Symposium. Overplotted on the M31 Atlas of Hodge (1961), the squares locate the observed globular clusters, while the circles indicate the position of the observed young clusters

6.   A view with the Hubble Space Telescope

At the time of this Symposium, about twenty M31 clusters have been imaged by the Hubble Space Telescope with enough spatial resolution and photometric quality so that their color-magnitude diagrams could be built. Figure 1 indicates their location in projection over M31. Even if the statistics remain modest, halo, disk and bulge cluster populations have been sampled.

Figure 2 displays a variety of cluster morphologies. Thanks to the courtesy of P. Hodge and B. Williams, the first two upper images are young open and compact clusters, viz. G44 and G38. Below, on the left hand side, thanks to the courtesy of C. Cacciari, L. Federici and F. Fusi Pecci, the disk globular cluster G219. On the right side, G1, the most distant halo cluster. The image is a composite of V and I images (Meylan et al. 2001). This cluster is very bright and massive, and displays a significant flattening. Meylan details some of its outstanding properties in these proceedings. G177, at the bottom of the figure, is a bulge cluster. It is conspicuous that the field surrounding this bulge cluster is significantly more populated than the fields surrounding the other clusters. Due to dynamical interaction with the bulge, G177 has probably lost a significant
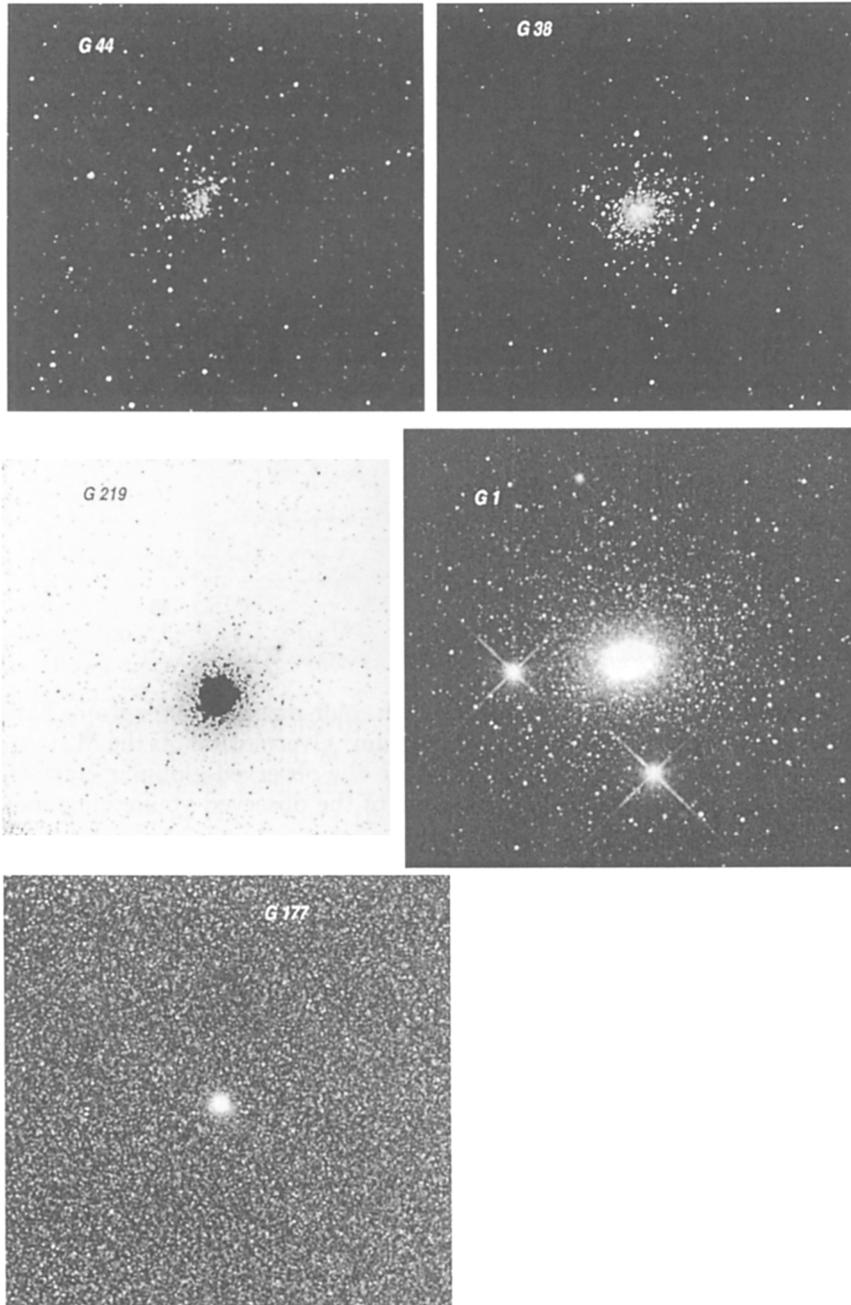
Figure 2.   A sample of 5 M31 globular clusters observed with HST/WFPC2: the young clusters G44 and G38, the disk cluster G219, G1 located in the outer halo, and the bulge cluster G177.

fraction of the stars in its envelope. Its stellar population is very red, as would be an old and metal rich stellar system.

6.1. An example of color-magnitude diagrams: three bulge star clusters

At the distance of M31, the best color-magnitude diagrams reach stars about one to two magnitudes below the horizontal branch level (I $\sim$ 24.5 mag). See, for example, Ajhar et al. (1996), Fusi Pecci et al. (1996), Rich et al. (1996), and Holland et al. (1997). See also B. Williams in these proceedings for the young star clusters.

As seen in Figure 1, most clusters observed with HST are located in the disk and halo of M31. Jablonka et al. (2000) have focused on three clusters projected at distances between slightly less and slightly more than 1 kpc from the nucleus of M31. The cluster G177 seen in Figure 2 is one of them. Given the extreme density of field stars in the bulge of M31 (from 30 to 55 stars per arcsec^2 for V $\leq$ 26.5 mag and I $\leq$ 24.5 mag) and the compactness of the clusters, we adopted the MCS deconvolution technique (Magain, Courbin & Sohy, 1998). The principle of this method is to consider that, in order to satisfy the sampling theorem, the deconvolution must be conducted with a PSF which is narrower than the observed one. One of its appreciable advantages is that it enables the user to perform photometry on the deconvolved images. With this strategy we succeeded in disentangling field from cluster stars, although marginally for the innermost cluster G198. Comparison between field and cluster star color-magnitude diagrams confirms that these clusters were formed from the same material as the field stars, early in the formation of M31.

6.2. Surface-brightness profiles

The precision achieved with the HST is such that the questions addressed via the surface-brightness profiles resemble more and more those tackled for the clusters in our Galaxy. The structural parameters are derived (Fusi Pecci et al. 1994 ; Grillmair et al. 1996); tidal radii are computed (Cohen & Freeman 1991); even a core collapse cluster has been identified (Bendinelli et al. 1993).

6.3. Mass-to-light ratios

Obtaining the velocity dispersion of the globular clusters and combining them with structural and photometric parameters allows one to measure the M/L ratios, to explore the correlations of cluster properties, and to compare them with the equivalent correlations for the Galactic globular clusters. Two contemporary works started to address this aspect: Dubath & Grillmair (1997) and Djorgovski et al. (1997). The latter, with 27 clusters, certainly gather the largest sample. The authors investigated the correlations in two parameter planes constructed with the central velocity dispersions and central surface brightnesses or absolute magnitudes, both in V and K bands. They stress that the M31 globular clusters smoothly continue and extend to higher luminosities the trends drawn by the Galactic clusters. Moreover, at the same metallicity, Galactic and M31 clusters have the same M/L ratios.

The so far most precise dynamical study of a globular cluster in M31, viz. G1, based on its surface-brightness profile and central velocity dispersion, has been recently published by Meylan et al. (2001 and these proceedings).

7. Conclusion

It clearly appears that one will gain in increasing the size of the cluster samples for which the quality of the data will catch up with what is available for the clusters in our Galaxy, as one started with the HST. The answer to the question of the universality of the cluster properties is at this price. Meanwhile, the opening of new wavelength domains with good sensitivity and improvement of spatial/spectral resolutions certainly give to the study of globular clusters in M31 some fresh air! This is becoming a new domain of investigation in which excitement for new insight is genuine.

References

Ajhar E.A., Grillmair C.J., Lauer T.R. et al., 1996, AJ, 111, 1110
Barmby P., Huchra J.P., Brodie J.P. et al. 2000, ApJ, 119, 247
Battistini P.L., Bonoli F., Pecci F.F. et al., 1982 A&A 113 39
Battistini P.L., Bonoli F., Casavecchia M. et al. 1993, A&A, 272
Bendinelli O.,Cacciari C., Djorgovski S. et al., 1993, ApJ, 409, L17
Bohlin R.C., Deutsch E.W., McQuade K.A. et al. 1993, ApJ, 417, 127
Bohlin R.C., Cornett R.H., Hill J.K. et al. 1988, ApJ, 334, 657
Bonoli F., Delpino F., Federici L. et al. 1992, A&AS, 96, 163
Burstein D., Faber S.M., Gaskell C.M., Krumm N., 1984, ApJ, 287, 586
Cacciari C., Cassatella A., Bianchi L. et al., 1982, ApJ, 261, 77
Cohen J.G., Freeman K.C., 1991, AJ, 101, 483
Cohen J.G., Matthews K., 1994, AJ, 108, 128
Cowley A.P., Burstein D., 1988, AJ, 95, 1071
Crotts A.P.S., Kron R.G., Cacciari C., Fusi Pecci F., 1990, AJ, 100, 141
Davidge T.J., 1990, ApJ, 351, L37
Di Stefano R., Kong A.K.H., Garcia M.R., Barmby P., 2001, astro-ph/0106254
Djorgovski S.G., Gal R.R., McCarthy J.K. et al., 1997, ApJ, 474, L19
Dubath P., Grillmair C.J., 1997, A&A, 321, 379
Frogel J.A., Persson S.E., Cohen J.G,.1980, ApJ, 240 ,785
Fusi Pecci F., Battistini P., Bendinelli O. et al., 1994 A&A 284 349
Fusi Pecci F., Buonanno R., Cacciari C. et al., 1996, AJ, 112, 1461
Grillmair C.J., Ajhar E.A., Faber S.M. et al., 1996 AJ 111 2293
Holland S., Fahlman G.G., Richer H.B., 1997, AJ, 114, 1488
Jablonka P., Courbin F., Meylan G. et al., 2000, A&A, 359, 131
Magain P., Courbin F., Sohy S., 1998, ApJ, 494, 472
Ponder J.M., Burstein D., O'Connell R.W. et al., 1998, AJ, 116, 2297

Primini F.A., Forman W., Jones C., 1993, ApJ, 410, 615

Racine R., 1991, AJ, 101, 865

Rich R.M., Mighell K.J., Freedman W.L., Neill J.D., 1996 AJ 111 768

Sitko, M.L., 1984, ApJ, 286, 209

Supper R., Hasinger G., Pietsch W. et al., 1996, AJ, 112, 1461

Supper R., Hasinger G., Lewin W.H.G. et al., 2001, A&A 373, 63-99

Trinchieri G., Fabbiano G., 1991, ApJ, 382, 82

Trinchieri G., Israel G.L., Chiappetti L., et al. 1999, A&A, 348, 43

Vetesnik M., 1962, BAICz, 13, 180

Williams B.F., Hodge P.W., 2001, ApJ, 559, 851

Discussion

P. Barmby: More than 20 globular clusters in M31 have been imaged with HST. If you look through the HST archive, you find that there are more like 60 M31 globulars in HST fields. I've been working on this data and I now have structural parameters for all of these clusters, over a wide range of cluster luminosities and distances from M31.