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Globular Clusters in the IR

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Abstract. IR photometry and spectroscopy are primary tools to investigate the physical and chemical properties of red stellar populations. Some of the most recent results applied to the study of Galactic Globular Clusters will be briefly reviewed.

Key words. Red stellar populations – IR photometry & spectroscopy – metallicity & distance scales – mass loss – abundances

1. Introduction

Globular Clusters (GCs) are the oldest stellar populations in our Galaxy, hence they are fundamental tracers of its formation and evolution history. As simple stellar populations, they also represent ideal laboratories to study stellar evolution and dynamics and ideal population templates to model galaxy evolution. The most efficient and fruitful way to study their stellar content in the various evolutionary stages is a multi-wavelength approach, which allows one to characterize the physical and chemical properties of stars with different temperatures and luminosities in the most suitable spectral range, from the UV to the IR (see e.g. Ferraro 2002).

Evolved red sequences, like the Red (RGB) and the Asymptotic (AGB) Giant Branches, characterized by low temperatures, can indeed be better investigated in the IR, where they emit most of their light. Also, in the IR, the luminosity contrast between the red giants and the warmer Main Sequence population is larger than at any other wavelength, drastically reducing the crowding effect even in the innermost core regions of the clusters. Moreover, the much lower IR extinction allows one to study in a homogeneous way not only the halo, metal poor but also the disk/bulge metal rich populations, affected by severe reddening. Finally, in the IR one can directly observe circumstellar envelopes, which univocally trace the occurrence of mass loss processes during the RGB and AGB evolutionary stages. In recent years, the last generation of IR imagers and spectrometers is providing the necessary resolution and sensitivity to perform *i*) systematic and homogeneous surveys of the Galactic red stellar populations and *ii*) quantitative investigation of their physical, chemical and evolutionary properties by analyzing suitable Color-Magnitude Diagrams (CMDs), Luminosity Functions (LFs) and medium-to-high resolution spectra.

2. Near-IR CMDs and LFs: metallicity and distance scales

Near-IR CMDs of GCs are powerful tools to characterize the location and morphology of

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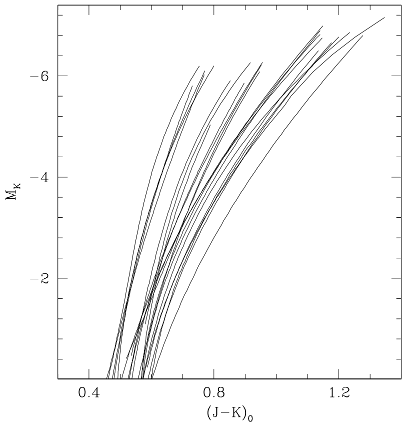

Fig. 1. Homogeneous set of RGB ridge lines in the $M_K, (J - K)_0$ absolute plane for a complete set of Galactic GCs observed at ESO-NTT with SOFI, spanning the whole range of metallicities up to solar values (see Ferraro et al. 2000; Valenti, Ferraro & Origlia 2004).

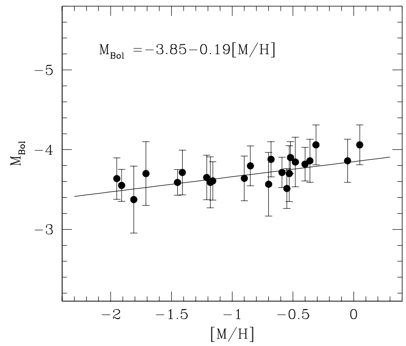

Fig. 2. The RGB Tip bolometric luminosity as a function of the global metallicity, as calibrated by means of a complete sample of Galactic GCs spanning the whole range of metallicities (see Ferraro et al. 2000; Valenti, Ferraro & Origlia 2004). The straight line is the best-fit relation.

the RGB. When a homogeneous set of RGB ridge lines spanning the whole range of metallicities is available (see Fig. 1), a number of useful relations linking the colors at fixed magnitudes or the magnitudes at fixed colors with the cluster metallicity can be easily calibrated (see e.g. Kuchinski et al. 1995; Kuchinski & Frogel 1995; Ferraro et al. 2000; Valenti, Ferraro & Origlia 2004), providing a suitable photometric metallicity scale. Another powerful metallicity indicator over the full range of metallicities is the RGB slope, since it is independent of the cluster distance and reddening. In the near-IR CMDs the RGB can indeed be reasonably approximated by a straight line also at metallicity in excess of solar and its slope linearly increases with increasing metallicity. In addition, the near-IR LFs of GCs allows the characterization of two major RGB evolutionary features, namely the Bump and Tip, with varying the cluster metallicity.

The Bump is a feature predicted by theoretical models at some point during the RGB evolution and it marks the occurrence of a deep penetration of the convective envelope and the subsequent retreat from the advancing H-burning shell, which leaves a discontinuity in the H-abundance profile. Fusi Pecci et al. (1990) and more recently several other authors (see e.g. Ferraro et al. 1999; Zoccali et al. 1999; Zoccali & Piotto 2000; Ferraro et al. 2000; Cho & Lee 2002; Riello et al. 2003; Valenti, Ferraro & Origlia 2004; Sollima et al. 2004) show how this feature can be safely identified in most of the current generation of optical and IR CMDs of GCs and also in other stellar systems (see e.g Bellazzini et al. 2001, 2002; Monaco et al. 2002).

From the observational point of view, the Bump is recognizable as a peak in the differential LF and a slope change in the integrated LF: its luminosity rapidly decreases by increasing metallicity. The evolution along the RGB ends suddenly at the so-called RGB Tip, when He ignites in the electron-degenerate core. The luminosity of the RGB Tip is constant for a given metallicity, hence it represents a powerful standard candle for old stellar populations and its calibration is of primary importance. In the

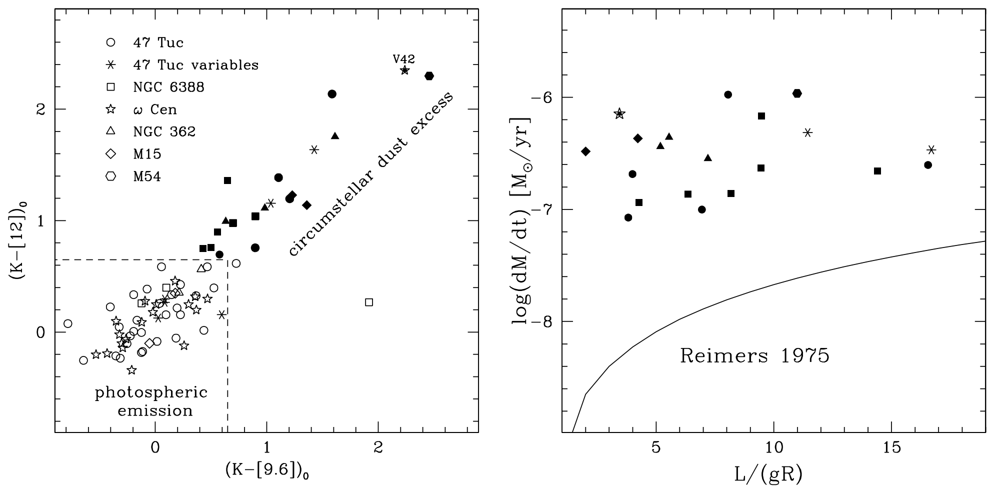

Fig. 3. Left panel: De-reddened $(K-[12])_0$, $(K-[9.6])_0$ color–color diagram of the ISOCAM point sources detected in the observed globular clusters (from Origlia et al. 2002). The dashed box indicates the region where the 12 μm emission is still dominated by the stellar photosphere. Right Panel: Mass loss rates for the giant stars with dust excess as a function of stellar parameters. The empirical law by Reimers (1975), recently revised by Catelan (2000) and calibrated on Population I giants of relatively low luminosity, is shown for comparison.

near-IR bands as well as in bolometric (see Fig. 2) it linearly increases by increasing the stellar metallicity (Ferraro et al. 2000; Valenti, Ferraro & Origlia 2004; Bellazzini et al. 2004). By coupling the fact that it is very luminous and it works at all metallicities, this standard candle turns to be particularly suitable to estimate distances to any resolved stellar system in the Local Group and beyond.

3. Mass loss

Stellar mass loss is a physical phenomenon still poorly understood, preventing our full knowledge of the late stages of stellar evolution. A quantitative understanding of the physics of mass loss processes and the precise knowledge of the intra-cluster matter content and distribution is crucial for the study of Population II stellar systems and their impact on the Galaxy evolution. It also has major astrophysical implications on related problems such as the UV excess found in elliptical galaxies (see e.g. Greggio & Renzini 1990; Dorman et al. 1995) and the possible interaction between the intra-cluster medium and the hot halo gas (see e.g. Faulkner & Smith 1991).

Circumstellar envelopes of gas and dust are unambiguous signatures of the occurrence of mass loss processes. The mid-IR spectral range is particularly efficient to detect warm dust around giant stars, hence to constrain mass loss rates and timescales. A pilot deep survey of 5 massive Galactic GCs (Origlia et al. 2002) in the 10 μm window has been performed using ISOCAM (Cesarsky et al. 1996). Fig. 3 shows the observed $(K-[12])_0$, $(K-[9.6])_0$ color–color diagram and the inferred mass loss rates for those sources with mid-IR excess. Circumstellar dust has been found in about 20% of stars close to the RGB Tip, suggesting episodic mass loss processes with typical rates in the $10^{-7} < dM/dt < 10^{-6} M_\odot\,yr^{-1}$ range, and without a crucial dependence on the cluster metallicity.

4. IR spectra: stellar abundances

The near IR spectra of cool giants show many atomic and molecular features in absorption,

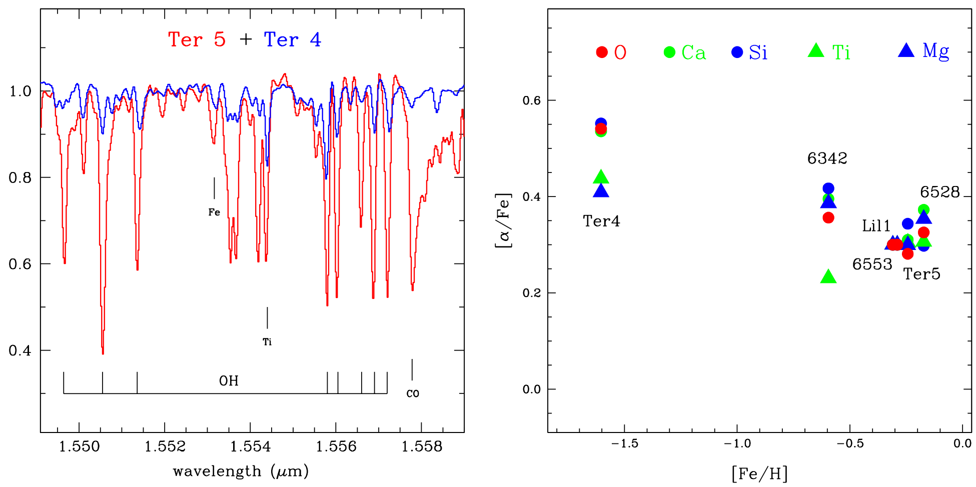

Fig. 4. Left panel: portion of the NIRSPEC H–band spectrum around 1.555 μm of two giants in the core region of the Terzan 4 and Terzan 5 bulge GCs. A few major atomic lines and molecular bands of interest are marked. Right Panel: [α/Fe] *vs* [Fe/H] abundance ratios for 6 bulge GCs in our sample.

allowing accurate abundance estimates of Fe, C, O and other α-elements, particularly in the high metallicity domain. It is worth mentioning that since a long time the IR CO and OH molecular bands are known to provide the most robust estimates of Oxygen and Carbon abundances and their isotopic ratios in cool stars (see e.g. Thompson & Johnson 1974; Lambert et al. 1984; Wallace & Hinkle 1996). A reasonable number of the near-IR atomic and molecular lines are strong, and not affected by severe blending, hence they can be also measured at low-medium resolution (see e.g. Origlia et al. 2003; Shetrone 2003; Smith, Terndrup & Suntzeff 2002; Stephens & Frogel 2004, and references therein), making them powerful abundance tracers also in more distant stellar clusters and galaxies (see e.g. Origlia et al. 1997).

Oxygen is a key element to trace the chemical enrichment history in several astrophysical contexts. However, the determination of its abundance in giant stars is still controversial since the major UV and optical diagnostics yield somewhat different results. Systematic calibration off-sets, non-LTE effects and TiO and CN blends in the coolest giants can severely affect both the optical [OI] and OI-triplet lines and the electronic OH molecular transitions in the UV (see e.g. Hill 2001, and references therein) making IR roto-vibrational OH lines the most reliable diagnostics (see e.g. Balachandran & Carney 1996; Meléndez, Barbuy & Spite 2001). The direct measurement of the $^{12}C/^{13}C$ abundance ratio provide major clues on the efficiency of the mixing processes in the stellar interiors (see e.g. Cavallo, Sweigart & Bell 1998; Boothroyd & Sackmann 1999; Weiss, Denissenkov, & Charbonnel 2000, and references therein).

The last generation of high resolution optical spectrographs with multi-object capabilities represent powerful instruments for the systematic screening of the abundance patterns in the Galactic halo GCs. A systematic study of the Galactic bulge started only in the last decade but it remains still largely unexplored, since the high and variable foreground extinction, the severe crowding and the high metal content which implies a high level of molecular blending and blanketing make almost prohibitive any kind of optical observations. The use of the new generation of medium-to-high resolution spectrograph extended to the near IR spectral range is thus crucial to perform a systematic spectroscopic screening of the bulge population (see e.g. Origlia, Rich & Castro 2002; Meléndez et al. 2003; Origlia & Rich 2004). Fig. 4 shows an example of high resolution H-band spectra around 1.555 μm, obtained with NIRSPEC, a high throughput IR echelle spectrograph at the Keck Observatory (McLean 1998) and the [α/Fe] trend with [Fe/H] for a sample of bulge GCs (Origlia, Rich & Castro 2002; Origlia & Rich 2004). A significant α-enhancement is constantly present even toward the highest metallicities, somewhat contrary to the disk population which shows solar [α/Fe].

5. Future perspectives

The beginning of the 21th century has been and will be extremely attractive for IR ground-based and space astronomy. Innovative instruments with large field, high spatial and spectral resolution, adaptive optics, integral field and/or multi-object capabilities became recently operational or are under construction, with a huge impact on major astrophysical fields regarding the origin and evolution of the Local as well as the high redshift Universe.

The study of stellar populations and galaxy evolution will strongly benefit from highly efficient IR imagers and spectrometers. Crucial information on *i*) the chemical and kinematic properties of resolved as well as integrated stellar systems (like e.g. extragalactic stellar clusters, distant galaxies) also in the most extreme environments (as for example the nuclear regions of galaxies), *ii*) the interactions with the circum - and inter - stellar medium of the host galaxies, *iii*) the formation and evolution of galactic [sub]structures will be obtained.

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References

Balachandran, S. C., & Carney, B. W 1996, AJ, 111, 946
Bellazzini, M., Ferraro, F. R. & Pancino, E. 2001, MNRAS, 327,15
Bellazzini, M., Ferraro, F. R., Origlia, L., Pancino, E., Monaco, L. & Oliva, E. 2002, AJ, 124,3222
Bellazzini, M., Ferraro, F. R., Sollima, A., Pancino, E. & Origlia, L. 2004, A&A, astro-ph/
Boothroyd, A. I., & Sackmann, I. J. 1999, 1999, ApJ, 510, 232
Catelan, M. 2000, ApJ, 531, 826
Cavallo, R. M., Sweigart, A. V., & Bell, R. A. 1998, ApJ, 492, 575
Cesarsky, C.J., Abergel, A., Agnese, P. et al. 1996, A&A, 315, L32
Cho, D. H. & Lee, S. G. 2002, AJ, 124, 977
Dorman, B., O'Connell, R. W., & Rood, R. T. 1995, ApJ, 442, 105
Faulkner, D. J., & Smith, G. H. 1991, ApJ, 380, 441
Ferraro, F. R., Messineo, Fusi Pecci, F., De Palo, M. A., Straniero, O., Chieffi, A. & Limongi, M. 1999, AJ, 118, 1738
Ferraro, F. R., Montegriffo, P., Origlia, L., & Fusi Pecci, F. 2000, AJ, 119, 1282
Ferraro, F. R. 2002, ASP Conf. Ser., 274, 268
Fusi Pecci, F., Ferraro, F. R., Crocker, D. A., Rodd, T. R. & Buonanno, R. 1990, A&A, 238, 95
Greggio, L., & Renzini, A. 1990, ApJ, 364, 35
Kuchinski, L. E. & Frogel, J. A. 1995, AJ, 110,284
Kuchinski, L. E., Frogel, J. A., Terndrup, D. M. & Persson, S. E. 1995, AJ, 109,1131
Hill, V. 2001, ApSSS, 277, 137
Lambert, D. L., Brown, J. A., Hinkle, K. H., & Johnson, H. R. 1984, ApJ, 284, 223
McLean, I. et al. 1998, SPIE, 3354, 566
Meléndez, J., Barbuy, B., & Spite, F. 2001, ApJ, 556, 858
Meléndez, J., Barbuy, B., Bica, E., Zoccali, M., Ortolani, S., Renzini, A., & Hill, V. 2003, A&A, 411, 417
Monaco, L., Ferraro, F. R., Bellazzini, M. & Pancino, E. 2002, AJ, 578, 50

Origlia, L., Ferraro, F. R., Fusi Pecci, F., & Oliva, E. 1997, A&A, 321, 859
Origlia, L., Rich, R. M., & Castro, S. 2002, AJ, 123, 1559
Origlia, L., Ferraro, F. R., Fusi Pecci, F., & Rood, R. T. 2002, ApJ, 571, 458
Origlia, L., Ferraro, F. R., Bellazzini, M., & Pancino, E. 2003, ApJ, 591, 916
Origlia, L., & Rich, R. M. 2004, AJ, astro-ph/
Reimers D. 1975, Mem. Soc. R. Sci. Liège 6 Ser., 8, 369
Riello, M., Cassisi, S., Piotto, G., De Angeli, F., Salaris, M., Pietrinferni, A., Bono, G. & Zoccali, M. 2003, A&A, 410, 553
Shetrone, M. D. 2003, ApJ, 585, 45
Smith V. V., Terndrup, D. M., & Suntzeff, N. B. 2002, ApJ, 579, 83
Stephens, A. W., & Frogel, J. A. 2004, AJ, 127, 925
Sollima, A., Ferraro, F. R., Origlia, L., Pancino, E. & Bellazzini, M. 2004M A&A, astro-ph/
Thompson, R. I., & Johnson, H. L. 1974, ApJ, 193, 147
Valenti, E., Ferraro, F.R., & Origlia, L. 2004, MNRAS, astro-ph/
Wallace, L., & Hinkle, K. 1996, ApJS, 107, 312
Weiss, A., Denissenkov, P. A., & Charbonnel, C. 2000, A&A, 356, 181
Zoccali, M., Cassisi, S., Piotto, G., Bono, G. & Salaris, M. 1999, AJ, 518, 49
Zoccali, M. & Piotto, G. 2000, A&A, 358,943