the population I or population II stars measurements. If the population II value of log N(Li) ≈ 2 (Spite and Spite, 1982) represents the cosmological value, a model is necessary to explain the values of log N(Li) ≈ 3 found in disk population I stars (Boesgaard and Steigman, 1985), which means an enrichment of a factor 10 between the two populations. These Li-rich giants are perhaps the Li enriching agent in the Galaxy.

References

Batalha, C., Gregorio-Hetem, J., Barbuy, B.: 1992, in preparation.

Boesgaard, A. M., Steigman, G.: 1985, *ARA & A* **23**, 319.

Finkenzeller, U., Basri, G.: 1987, *ApJ* **318**, 823.

Gregorio-Hetem, J., Lepine, J.R.D., Quast, G.R., Torres, C.A.O, de la Reza, R.: 1992, *AJ* **103**, 549.

de la Reza, R., Torres, C.A.O., Quast, G., Castilho, B.V., Vieira, G.L.: 1989, *ApJ* **343**, L61.

Spite, F., Spite, M.: 1982, *A&A* **115**, 357.

IR Stellar Photometry in Globular Clusters Using IRAC2

M.D. GUARNIERI[1,2], A. MONETI[3], V. TESTA[4], L. ORIGLIA[5,2], F.R. FERRARO[6], F. FUSI PECCI[6]

[1]Istituto di Fisica Generale, Università di Torino, Italy; [2]Osservatorio Astronomico, Torino, Italy; [3]European Southern Observatory, La Silla, Chile; [4]Dipartimento di Astronomia, Università di Bologna, Italy; [5]Dipartimento di Astronomia, Università di Firenze, Italy; [6]Osservatorio Astronomico, Bologna, Italy

1. Introduction

Globular clusters represent the *oldest, simple* population in galaxies. Hence, the study of their properties yields crucial information on the early evolutionary phases of the parent galaxy. Moreover, they are the best *laboratory* to study stellar evolution and one of the most powerful tools to grasp basic cosmological problems, like for instance the definition of the distance and time scales.

In fact, on the one hand, the detailed comparison between stellar evolutionary tracks and observed colour-magnitude (c-m) and colour-colour (c-c) diagrams allows us to check the reliability of the theoretical models (which actually are the engine of the *stellar clock*) and, on the other, the correct measure of the turn-off luminosity of the main sequence in individual clusters which is the crucial item to determine precisely their ages and, thus, to put significant constraints to the age of the Universe.

The availability of infrared (IR) magnitudes may be extremely useful in this task, particularly if combined with optical data. For instance, the V-K colour is an excellent indicator of effective temperature (T_{eff}), being relatively insensitive to metallicity and having a long wavelength baseline. Besides, extinction is much lower in the IR than in the optical bands. Finally, in the IR the contrast between stars to measure and the unresolved background is different and in particular, for stars populating the giant branch, is greater than in any optical region.

Though the significant advantages of observing individual globular cluster stars in the near IR are well known for many years (see for references Frogel et al., 1983), the technical limits intrinsic to the available detectors (single-channel aperture photometers) have unfortunately restricted in the past the observations to a few bright stars in the external regions of a small sample of clusters (Frogel et al. 1983, Arribas *et al.* 1991 and references therein).

The recent introduction of the IR arrays has opened new perspectives. In particular, the availability of new cameras, based on 256 × 256 arrays having pixel sizes and performances close to those of optical CCD's, will surely exploit soon the great potential impact of IR observations of large samples of globular cluster stars.

We present here the main outlines of our global project and the first results of a photometric survey of Galactic globular clusters started with IRAC2, the new

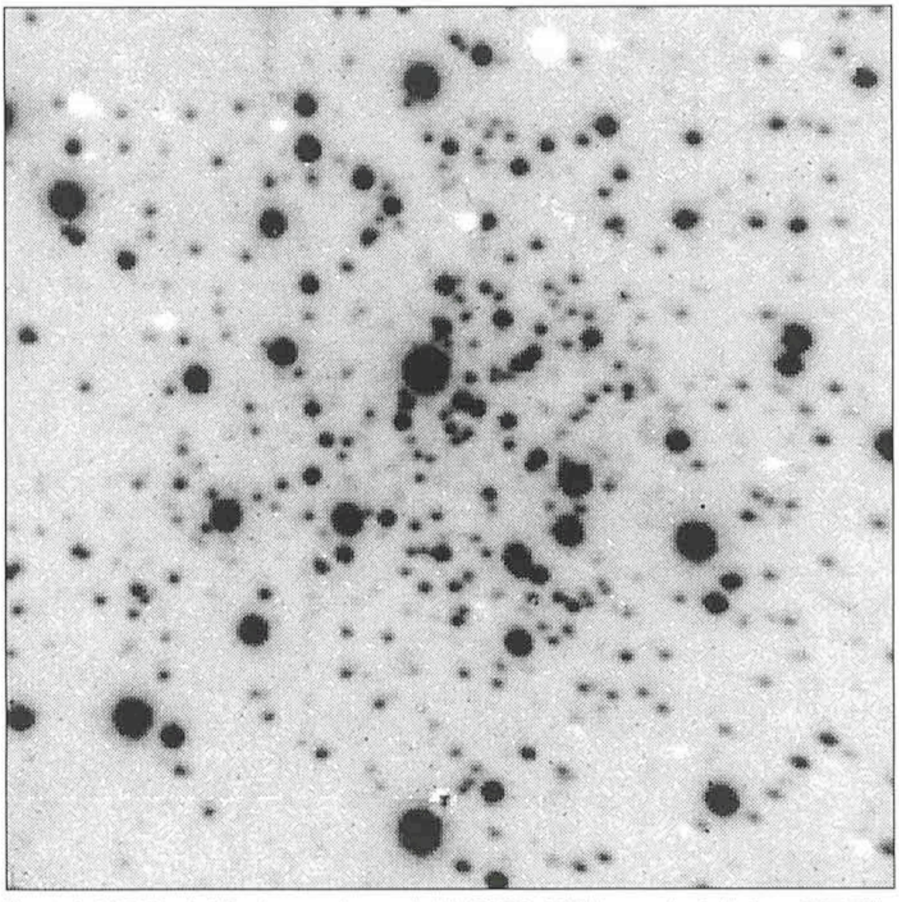

Figure 1: *M69 Central Region as observed with IRAC2, 0.27"/px mode, field size ~70×70".*

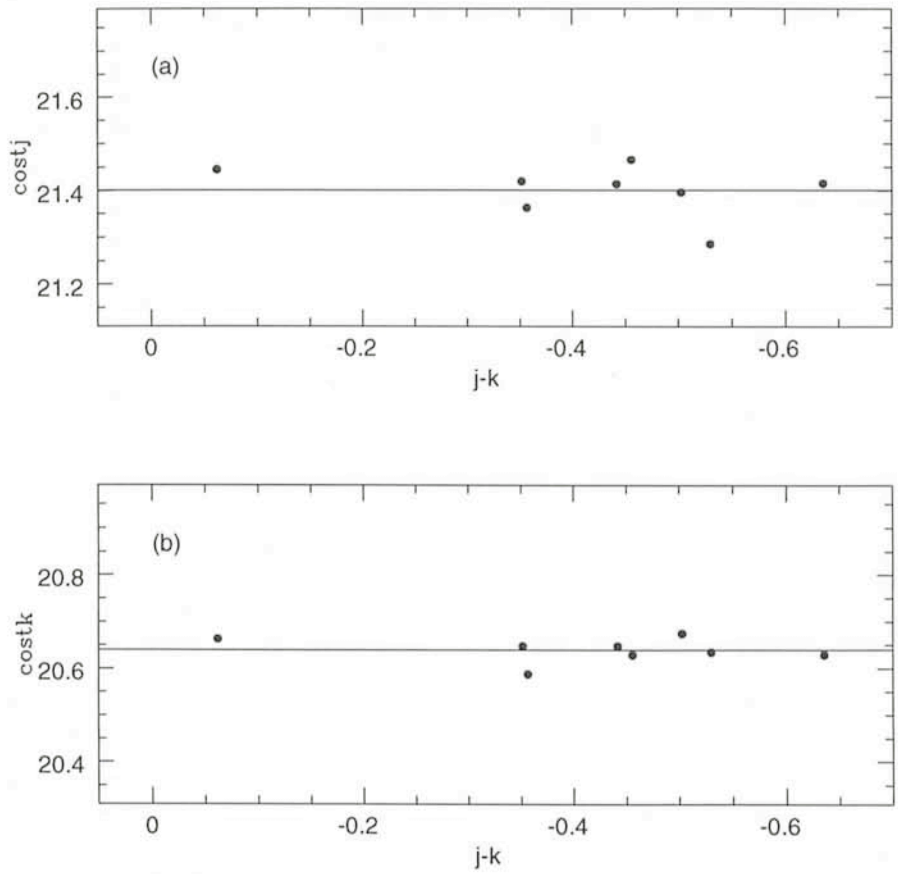

Figure 2a,b: *Provisional calibration curves.*

highly performing IR camera developed at ESO. In particular, we show the preliminary results obtained for the low-latitude, metal rich-cluster M69 = NGC 6637. Since JHK data obtained using a Rockwell 256 × 256 NICMOS3 array at the 3.6-m CFHT have already been reported for this cluster by Davidge and Simons (1991), we decided to observe it first and reduce immediately the data for making useful comparisons and to improve at best our observing and reduction procedures.

A complete presentation of the observational strategy and data reduction techniques will be given in a forthcoming paper (Guarnieri et al., 1993) together with a preliminary discussion of the results.

2. Main Outlines of the Project and Observational Strategy

From the IR survey of the brightest stars in about 30 Galactic globular clusters, Frogel et al. (1983) got the first quantitative, detailed description of their upper giant branches with varying metal content. In summary, they showed that the absolute locations of the globular cluster giant branches correlate with metallicity, the observed luminosities of the brightest giants are in agreement with the theoretical model predictions, and, finally, that the integrated light measurements of the cluster as a whole correlate with the cluster parameters determined from measurements of its brightest individual members in a way that can be understood within the current knowledge of stellar evolution. Based on these facts, the same group has also systematically used integrated near-IR data for a sample of globular clusters in the Milky Way, in the Magellanic Clouds, and in M31 to investigate their stellar content and to compare them with elliptical galaxies.

Though very important, the data-base used by Frogel and co-workers includes however only about 350 stars in total. Therefore, due to the small number of stars observed in each cluster, the significance of some results is somewhat reduced, and problems like the precise estimate of the giant tip luminosity and the determination of an accurate mean ridge line down to the turnoff could hardly be faced.

Hence, the first obvious use of the new IR imagers is to secure observations of much wider samples of stars in many clusters with varying cluster metallicity, galactocentric location, age, etc. Moreover, it has been shown (Longmore et al., 1990; Buckley and Longmore, 1992) that it will now be possible to obtain fairly accurate and very deep IR photometry (2–3 mag below the turnoff, at K ~ 20) in the closest clusters. Thus, a completely new window can be opened on the problem of the determination of cluster distances and ages. In this respect, it is also important to recall that the conversion of two sets of the most frequently used isochrones in the IR planes carried out by Bell (1992) will permit a direct, stringent comparison between the observed and theoretical quantities.

Within this new exciting scenario, and exploiting the exceptional capabilities offered by IRAC2, we have started a long-term project intended to secure near IR photometry (JHK) of very wide samples of stars in many Galactic globular clusters down to the main sequence with the specific aim of touching upon the following items:

● *(i) The actual extent in luminosity and the location in temperature of the giant branch.* This can give a quantitative determination of the luminosity of the stars at the *helium flash* with varying metallicity, and set strong constraints on mass loss and on the masses of currently forming White Dwarfs. Moreover, one could also check the reliability of the location of theoretical models in the observational plane and eventually their scaling with metallicity, getting for instance direct tests of the dependence of the mixing length parameter α and colour-temperature transformations on metallicity. Incidentally, one will also get a consistency check of the various metallicity scales, and an indirect estimate of the actual influence of the horizontal branch morphology on the metallicity derived from integrated cluster observations (see Zinn and West, 1984).

● *(ii) The calibration of a new, very accurate method for the determination of the cluster distance scale.* Once the small number effects disappear, thanks to the complete observations of the giant branch stars in the cluster cores, the luminosities of the brightest objects are *bona fide* indicators of the actual giant branch tip whose absolute luminosity is expected to be constant for fixed chemical composition (see the Sweigart and Gross [1978] models). Hence, very accurate relative distance moduli (to better than ±0.1mag) can be obtained by simply imposing the coincidence of the RGB tips in clusters having similar abundances (Crocker and Rood, 1984). For instance, this will probably yield the solution of the long-standing problem of the *second parameter* (clusters with similar metallicity but very different HB morphologies). Moreover, the use of the various c-c diagrams will illuminate the origin of the discrepancy, if any. It will also be possible to use the so-called "IR flux method" (Blackwell and Shallis, 1977, Blackwell et al.,

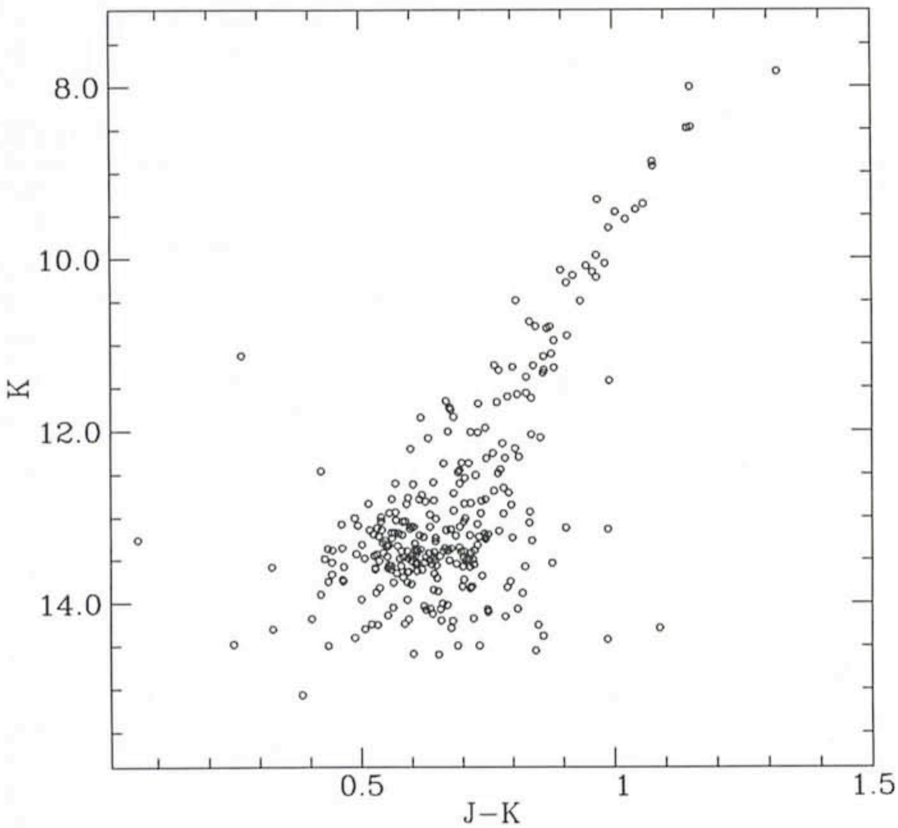

Figure 3: *M69 Colour-Magnitude diagram of the high-resolution central region.*

1980 and Arribas and Martinez Roger, 1987) to get an independent estimate of the distance for comparison.

● *(iii) The study of the turnoff region and the age.* It is well known that the luminosity and the temperature of the main-sequence turnoff in the c-m diagram are very sensitive to the absolute age, but they depend also on the chemical composition and mixing length. It is also known that a major uncertainty in the age determination is related to the knowledge of the distance (Renzini, 1991), often further complicated by an insufficiently accurate measure of the interstellar reddening. Taking into account the results achieved from point (ii) above and, as discussed in detail by Longmore et al. (1990), Bell (1992), Buckley and Longmore, (1992), by combining optical and IR magnitudes of equivalent photometric accuracy it will be feasible to constrain significantly the possible range of the various parameters involved (for instance via the comparison and compatibility tests of the various c-m and c-c diagrams). The long-standing problem that the most frequently used isochrones computed by VandenBerg and Bell (1985) transformed into the observational plane seem to show a systematic shift of 0.02–0.03 mag blueward in B-V (VandenBerg, 1986) could be eventually solved. In particular, it is not clear whether the shift could be due to poor transformations between the two planes or to the models themselves. The availability of the IR colours will clarify this issue or other similar ones because V-K is an excellent indicator of effective temperature and the various c-c diagrams will give hints on the cause of the shift, if any.

● *(iv) The study of the contribution of the various evolutionary stages to the cluster integrated light in each photometric band and bolometrically.* A proper examination of this item requires the use of very populous and *complete* samples which can only be achieved by mapping with the new large arrays vast areas of the cluster, including the central regions. This represents a big observational and reductional effort, but it is very important in view of the use of globular clusters as templates in the stellar population synthesis techniques. In particular, the IR observations are essential when observing very metal-rich clusters. These clusters are projected onto the Galactic bulge and are unique homogeneous samples of bulge population. Their optical c-m diagrams are dominated by blanketing effects giving origin to a turnover on the giant branches (Ortolani et al., 1990). At present there are no models that correctly fit these features in spite of recent efforts to produce new isochrones for solar abundance low-mass stars. The major difficulty seems to be the transformation from the theoretical to the obser-

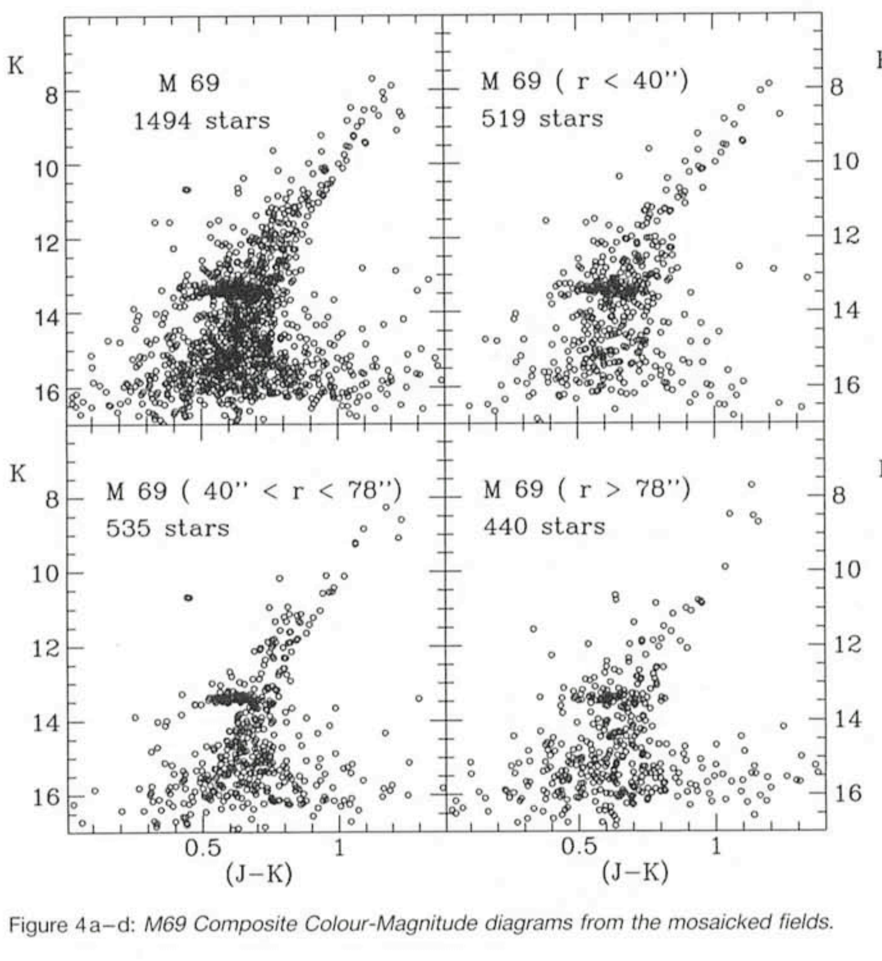

Figure 4a–d: *M69 Composite Colour-Magnitude diagrams from the mosaicked fields.*

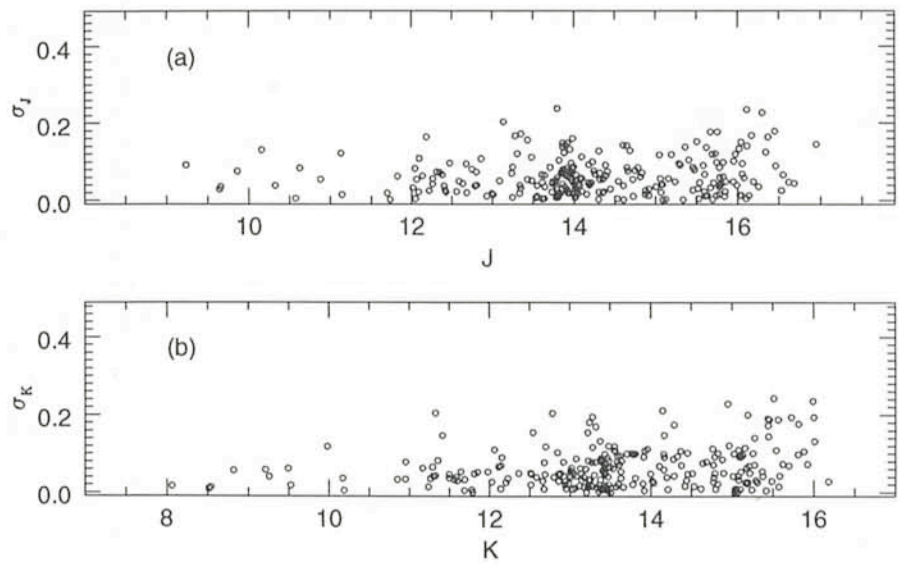

Figure 5a, b: *Internal errors overall behaviour.*

vational plane due to the heavy blanketing effect. It is clear that only bolometric luminosities and effective temperature determinations via combined optical-IR measurements can improve the current theoretical research in this field.

Concerning the observational strategy, as said, the IR arrays provide the best way to get unbiased samples of stars over a wide range of magnitude. In particular, IRAC2 is optimal to study the Galactic globular clusters offering the facility to vary the pixel scale. Therefore, for each cluster we have planned to take a mosaic exposure made by one field centred on the cluster observed with high spatial resolution (0.27″/px) plus four fields with a common vertex in the cluster centre, partially overlapping one each other and with the central field. Moreover, to reach the faintest possible magnitude limit in the K-band, we have selected one of the four fields off centre and planned to secure further specific exposures. Finally, for each cluster a few other fields will be observed to survey the stars already observed by Frogel and collaborators for comparison.

In summary, the brightest stars in most of the clusters we have planned to observe have magnitudes V ~ 11–12 and colours *V–K* ~ 2–4; the faintest objects are about 9 magnitudes fainter. Hence, assuming that about 20–50 stars populate the upper 1.5-mag region of the giant branch in each cluster (this number has been computed taking into account the integrated luminosity of the clusters and the giant branch evolutionary phases, see Renzini and Fusi Pecci, 1988), we can get sufficiently populous samples and guarantee good statistics. On the other hand, thanks to the possibility of varying the scale of the camera, this procedure guarantees also a sufficient spatial resolution and photometric sampling to deal with the central crowded regions. Moreover, the availability of overlapping areas will allow us to carry out various tests about the photometric accuracy and the degree of completeness actually achieved in the reductions.

3. Observations and Data Reduction

The observations of M69 described here were made on June 10, 1992 with the newly commissioned "IRAC2" mounted on the ESO/MPI 2.2-m telescope. For a detailed description of IRAC2 see Moorwood et al. (1992). The following observations were performed: (i) high resolution (0.27″/pixel) J and K images of the cluster centre; (ii) 4 fields centred on the corners of a ~ 100″ × 100″ square in J and K at medium resolution (0.49″/pixel). Integration times were 60 co-adds × 1 sec for both (i) and (ii). Separate sky frames were obtained with the same integration times ~ 10′ away from the cluster centre. Figure 1 shows a plot of the central frame obtained in the K-band.

Faint photometric standard stars (from SAAO, kindly provided by Dr. Ian Glass) were observed for calibration, and flat fields were obtained on the fading or brightening sky at sunset and at sunrise. For each filter/lens combination, several images were obtained with a fixed integration time, and an image with little signal was subtracted from an image with high signal in order to subtract possible signal arising from the instrument and/or the telescope and to be left with an image of *pure flat field* (see also Moorwood et al., 1992). All observations were carried out close to the zenith and with photometric sky; the average seeing was slightly less than 1″.

Source images were reduced by subtracting the corresponding sky and with it the fixed pattern (or bias) and dark current. When several sky frames were available, these were combined via a stack median filter to remove field stars. These difference images were then divided by a normalized flat field.

Photometry was carried out using ROMAFOT (Buonanno et al., 1979, 1983), a crowded field photometry package. ROMAFOT fits a Moffat function to the stellar profile in order to determine its volume and hence the instrumental magnitude

$$M_{inst.} = -2.5 \times \log(\text{Volume})$$

That is:

$$M_{inst.} = -2.5 \times \log(\text{Volume}) = -2.5 \times \log[(\pi h^2 \sigma)/(\beta - 1)]$$

where

h = height of the stellar component

σ and β = Moffat function parameters.

The zero point of the calibrations was obtained by making aperture photometry on an uncrowded sample of bright stars located in the outer regions of the fields and matched to 8 SAAO standards observed in the same nights with the same set-up. They have been repeatedly observed during the same night, yielding a r.m.s scatter always less than 0.02 mag. In particular, two of them have been observed also in the other 3 nights. The *internal* scatter of the various measures is very low. For the star HD 202964 we got σ_K = 0.008 and σ_J = 0.014 mag, while for HD 194107 we had 0.032 and 0.011 mag, respectively.

Concerning the calibration of the central high-resolution field, since no safe bright uncrowded stars were available, we have used the stars in common with the overlapping low-resolution regions to transfer the calibration.

The complete description of the calibration will be given in the full paper in preparation. Figure 2 presents the calibration curves used to determine the photometric zero-point here provisionally adopted.

4. The Preliminary IR Colour-Magnitude Diagrams

The IR c-m diagram we present in Figure 3 includes the stars identified in the central field and observed with the best pixel-scale (0.27″/px). By inspecting the plot, we see immediately that the giant branch is highly populated and well defined. In fact, even observing the very central crowded regions of the

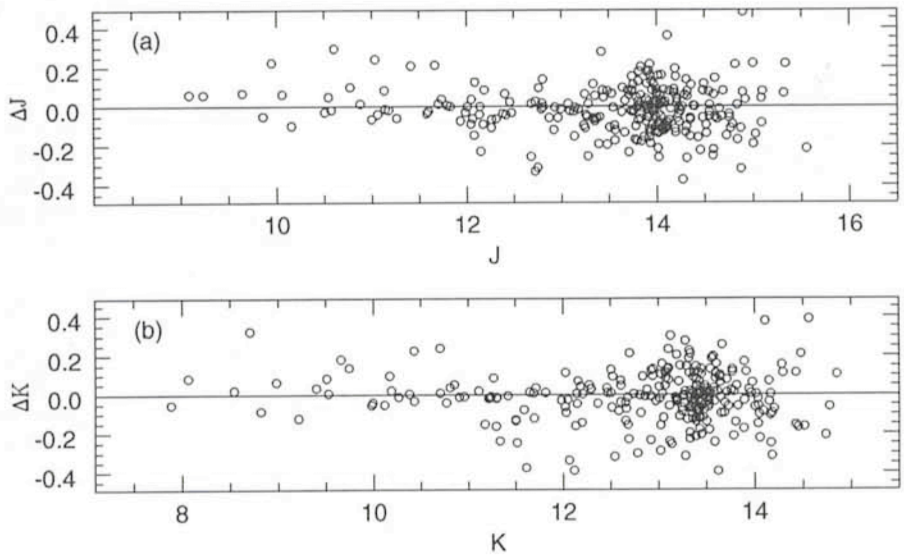

Figure 6a, b: *Plot of the residuals in magnitude for the stars measured on both high-resolution central region and low-resolution mosaicked fields.*

cluster, it is now possible to determine a reliable mean ridge line up to the giant branch tip. Note that also the Horizontal Branch (HB) has clearly been reached in this central quite short exposures, and a mean locus could already be drawn using only these data.

In Figure 4a–d, we present the IR c-m diagrams obtained from the reduction of the four mosaicked fields observed with the larger pixel-scale, including also the central region overlapping the high-resolution central survey. As said, these exposures are deeper and, hence, a deeper K-limit has been reached, almost close to the expected turnoff region.

In particular, in Figure 4a we present the c-m diagram for all the 1497 measured stars (no completeness tests have been carried out yet), while c-m diagrams for radial bins are shown in Figure 4b,c,d.

These IR c-m diagrams seem to be suitable to carry out the kind of analysis we aimed at. In particular, the Red Giant Branch (RGB) is well traced up to the tip, and it can also be possible to locate the Asymptotic Giant Branch (AGB) as a quite scattered distribution of stars above the HB and bluer than the RGB. Note that in these plots the HB is tightly defined and narrow, yielding a very precise average luminosity, $K = 13.4 \pm 0.05$. It is very red and stubby, as expected for metal rich globular clusters. The Subgiant Branch (SGB) is wide due to the increasing photometric scatter and to the possible presence of field objects which can also be found at brighter magnitude levels, located outside the main branches (but their photometry will be specifically checked). To confirm the high statistical significance achievable with this new IR c-m diagrams, it may also be noted that a hint for the presence of the expected RGB-bump (see Fusi Pecci et al., 1990) can already be found in the present preliminary study at $K \sim 13.55$.

A complete analysis and discussion of these data will be the subject of the forth-coming paper (Guarnieri *et al.*, 1993).

5. Photometric Errors and Comparison with Previous IR Data

The preliminary analysis we performed here shows quite convincingly that, by using IRAC2, it will be possible to carry out a wide and very accurate new IR survey in the Galactic globular clusters, measuring very wide samples of post-Main Sequence stars up to the cluster centre (at least for the clusters with low and intermediate concentration). Moreover, taking advantage of the possibility of varying the pixel-scale, it will also be possible to study the radial behaviour of the photometric errors and of the degree of completeness. This item is crucial for getting statistically significant luminosity functions for comparisons with the theoretical models.

For sake of example, we report here two plots to show the variation of the estimated internal photometric errors with varying magnitude and pixel size. Then, we present a comparison of our magnitudes with those listed by Davidge and Simons (1991) for a subset of stars in common.

Figure 5 presents the distributions of the *internal* errors in the photometry of the stars located in the overlapping areas of the mosaicked fields, computed using the formula given in Ferraro et al. (1991) and plotted versus the final J and K magnitudes obtained for each star. No specific segregation has been made among crowded and uncrowded images. As can be seen, most of the stars display errors less than 0.1 mag even at quite faint magnitudes, and even on the crowded objects the internal errors are smaller than 0.2 mag.

The results of another interesting test carried out using the available data are shown in Figure 6. There, we report the plots of the residuals of the magnitudes obtained in the same band for the stars in common in the overlapping central regions observed with the two different pixel-scales. From the plot, the existence of a scatter becomes evident which tends to increase up to 0.3–0.4 magnitudes at the faint limits. The size of these residuals is quite high and it would require a further, more detailed analysis. However, a quick preliminary inspection has already revealed that the distribution of the residuals is essentially driven by the relative depth of the used exposures (the high-resolution ones are less deep) and by three basic groups of stars, i.e. (1) the sufficiently bright and uncrowded objects, which yield very small residuals; (2) the very crowded objects, which usually lead to high values for the residuals independent of the brightness; (3) the faint objects, whose residuals may be large or small depending on their location with respect to brighter nearby companions. This overall trend clearly indicates that the use of a higher spatial resolution in the central regions may be crucial to manage the crowded objects as, besides the incidence on the degree of completeness (still to test however), it may affect the obtained magnitudes for the most crowded objects up to a few tenths of a magnitude.

Finally, to have an independent check of the reliability of the magnitudes and colours obtained from these preliminary reductions, we have compared our results with those presented by Davidge and Simons (1991) for the stars in common. To carry out this preliminary comparison we have not aimed at getting a complete overlay (which is currently in progress), but we have simply identified a first subset of stars produced by making a rough coincidence of their published coordinates transformed to our internal reference system. This implies that we cannot yet say anything about the relative degree of completeness, nor on the actual ability to resolve blended images. However, the results of the preliminary comparisons shown in Figure 7 a–c are already very encouraging. The agreement between the two sets of measurements is excellent for the bright stars both in J and in K, and it is still good down to the HB level. Taking into account the fact that the data presented by Davidge and Simons (1991) reach a magnitude limit brighter than the measures here presented, the above comparisons seem to indicate that for the stars in common displaying a sufficient S/N in both photometries, the computed magnitudes agree very well. Moreover, although we have not examined the issue in detail, it seems also that the agreement is quite independent of the crowding. Since both observations were carried out with similar scales (0.27 and 0.29″/px here and DS, respectively), it may also suggest that crowding problems have been similarly dealt with in the two studies.

The colour comparison (see Fig. 7c) is slightly less good. There is some indication for the existence of a weak systematic trend which has to be further studied. It has certainly to be ascribed to the different observational set-up and standard stars used, and further measurements of many more standards are necessary to determine a reliable colour transformation from one system to the other.

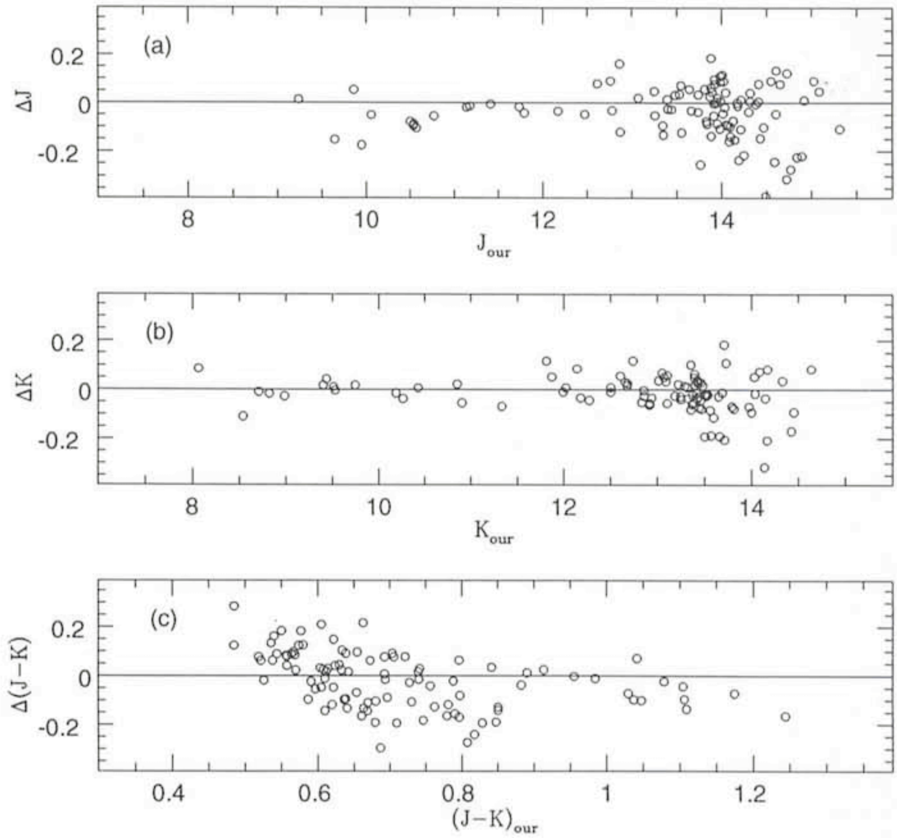

Figure 7a–c: *Plot of the residuals (Davidge and Simons – Ours) versus our values for the subset of common stars.*

6. Preliminary Conclusions and Future Prospects

The present preliminary study has confirmed that the new infrared camera IRAC2 now available for use at ESO is perfectly suitable to satisfy all the basic requirements put forward by a very accurate and deep IR photometry of wide samples of individual stars, even in the central regions of most of the Galactic globular clusters.

After securing a proper set of frames and using a reduction package purposely aimed at dealing with crowded fields (like ROMAFOT or DAOPHOT), we believe it is now possible to obtain the description of the whole c-m diagram of the cluster in the IR and also in the combined IR-optical planes down to a few magnitudes below the turnoff with a remarkable internal accuracy (~ 0.1 mag) at K ~ 20.

A variety of problems related to a *quantitative* check of the stellar evolutionary models and to a significant improvement in the cluster distance and age determinations can now be successfully addressed.

Acknowledgements

We would like to thank the ESO organization for the allocation of observing time and for giving us the chance to be the first IRAC2 users. We also thank Hans Gemperlein for the help during the observing run.

References

Arribas, S. and Martinez Roger C. 1987 *Astron. Astrophys.* **178**,106.

Arribas, S., Caputo, F. and Martinez Roger C. 1991 *Astron. Astrophys. Suppl. Ser.*, **88**, 19.

Bell, R.A. 1992, *Mon. Not. R. Astr. Soc.* **257**, 423.

Blackwell, D.E. and Shallis, M.J. 1977, *Mon. Not. R. Astr. Soc.* **180**, 177.

Blackwell, D.E., Pedford, A.D. and Shallis, M.J. 1980. *Astron. Astrophys.*, **82**, 249.

Buckley, D.R.V. and Longmore, A.J. 1992. *Mon. Not. R. Astr. Soc.*, **257**, 731.

Buonanno, R., Corsi, C.E., De Biase, G.A. and Ferraro, I. 1979. In *Image processing in Astronomy*, eds. G. Sedmak, M. Capaccioli and R. J. Allen, Trieste Obs., p. 354.

Buonanno, R., Buscema, G., Corsi, C.E., Ferraro, I. and Iannicola, G. 1983. *Astron. Astrophys.*, **126**, 278.

Crocker, D.A. and Rood. R.T. 1984. in *Observational Tests of the Stellar Evolution Theory*, eds. A. Maeder and A. Renzini, (Reidel: Dordrecht), p. 159.

Davidge, T.J. and Simons, D.A. 1991. *Astron. J.*, **101**,1720.

Ferraro, F.R., Clementini, G., Fusi Pecci, F. and Buonanno, R. 1991. *Mon. Not. R. Astr. Soc.*, **252**, 357.

Frogel, J.A., Cohen, J.G. and Persson, S.E. 1983. *Astrophys. J.*, **275**, 773.

Fusi Pecci, F., Ferraro, F.R., Crocker, D.A., Rood, R.T. and Buonanno, R. 1990. *Astron. Astrophys.* **238**, 95.

Guarnieri, M.D., *et. al.*, 1993. In preparation.

Longmore, A.J., Dixon, R.I. and Guarnieri, M.D. 1990, in *Astrophysics with Infrared Arrays*, ed. R. Elston, A.S.P. Conf. **14**, 121.

Moorwood A., *et. al.* 1992. *The Messenger*, **69**, 61.

Ortolani, S., Barbuy, B. and Bica, E. 1990. *Astron. Astrophys.*, **236**, 362.

Renzini, A., *1991*. In *Observational Tests of Cosmological Inflation,* NATO ASI Series C, Vol. 348, 131.

Renzini, A. and Fusi Pecci, F. 1988. *Ann. Rev. Astron. Astrophys.*, **26**, 199.

Sweigart, A.V. and Gross, P.G. 1978. *Astrophys. J. Suppl.*, **36**, 405.

VandenBerg, D.A. and Bell, R.A. 1985. *Astrophys. J. Suppl.*, **58**, 561.

VandenBerg, D.A. 1986. *Mem. S.A.It.*, **57**, 373.

Zinn, R.J. and West, M.J. 1984. *Astrophys. J. Suppl.*, **55**, 45.