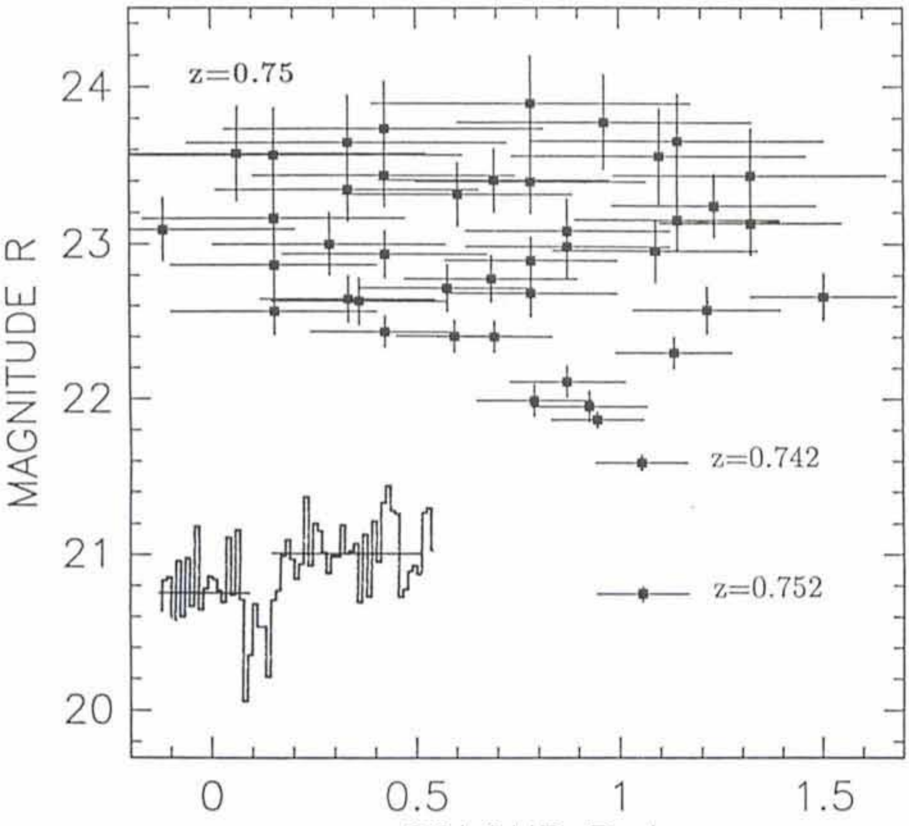

Figure 4: *A colour-magnitude diagram of a cluster at z = 0.75. We find that the blue fraction of objects is very high and that the red objects are slightly bluer than in the absence of evolution. These results should be taken with care, in particular because the contamination by field objects is very uncertain. In the left corner is the 4000 Å break of the first ranked object.*

earlier, possibly in high density peaks of the initial density distribution. In other words, a cluster with a high population of elliptical galaxies may have had high activity in the past, burning most of the gas, while a cluster found with a high degree of activity later would correspond to a slow growing fluctuation. These are the general ideas at this observational stage.

The use of the NTT, EFOSC 2 and a Thomson CCD are very important for the observations of distant clusters. The NTT, a seeing of 0.7 to 0.8 arcsec and a sampling of 0.15 arcsec/pixel made the separation of faint stellar-like objects from galaxies rather easy up to R = 22. To achieve good photometry in R and I, and obtain a spectrum far in the red, it was important to use the THCCD because it has low noise and no fringing in I.

Results on these clusters are still very preliminary. A colour-magnitude diagram of the cluster at z = 0.75, cleaned for stars and foreground objects, is presented in Figure 4. It shows that the R–I colours of red objects are somewhat bluer than if there were no evolution and that the blue-to-red ratio is of the order of 1, both properties suggesting that evolution has been detected (see also in Fig. 4 the rather low 4000 Å break amplitude in the spectrum of the first ranked object). However, the interpretation cannot be so crude for at least two reasons. First, the estimate of the real extent of the contamination by background and remaining foreground objects without multislit spectroscopy is very uncertain, and, second, we do not know if this cluster is representative or very peculiar, as it was detected by the presence of an ultra-steep spectrum radio source.

The trends presented here may be guidelines for a larger programme. Observing faint clusters of galaxies to investigate morphological and photometric evolution was one of the objectives of the wide-field camera of the Hubble Space Telescope (GTO Observing programme, October 1985). Frontier results should be within reach of the NTT and EMMI with a low noise CCD.

High-Resolution Imaging of Globular Cluster Cores

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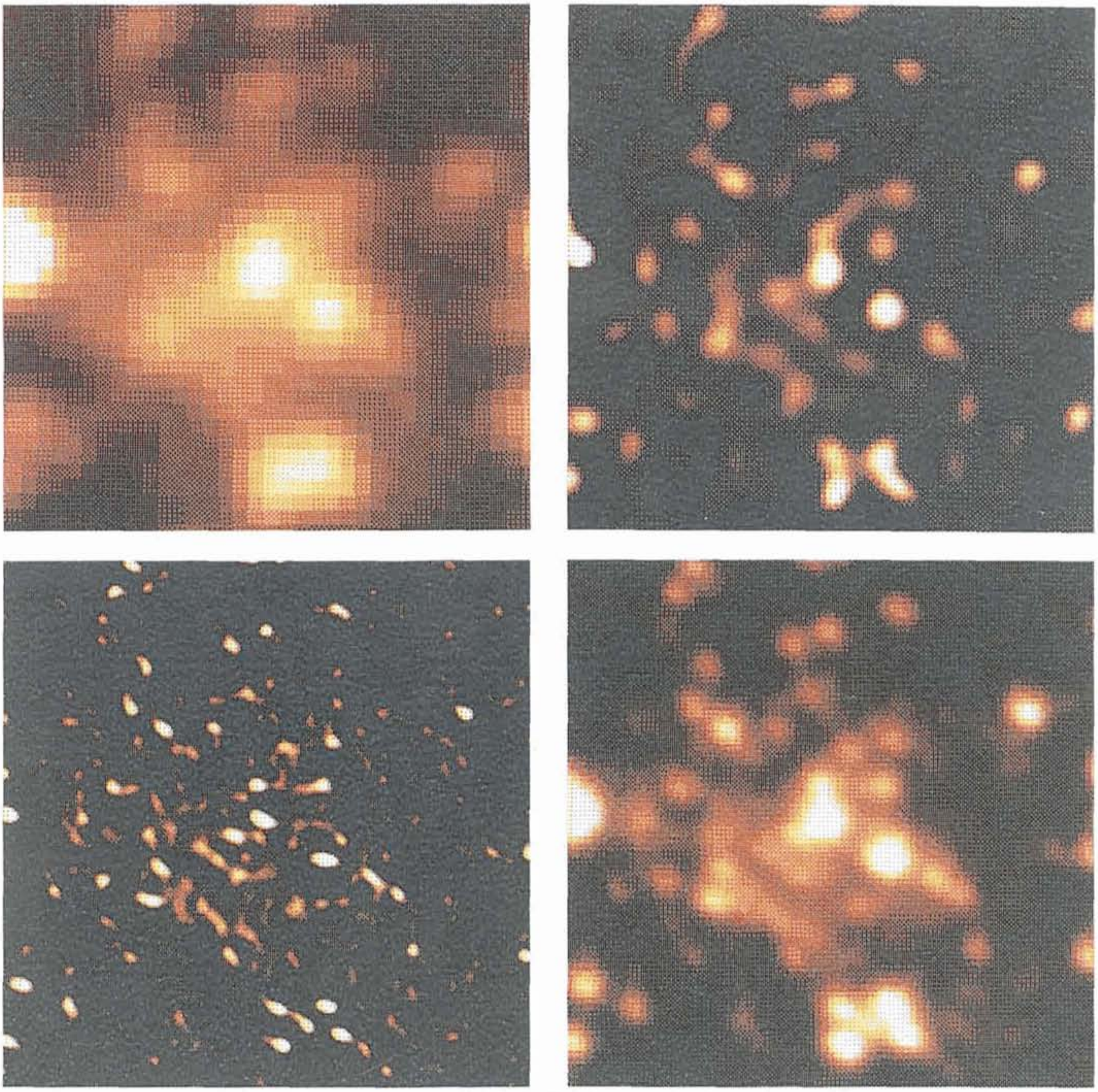
Practically all of ground-based astronomy can benefit from improved angular resolution. Whereas specialized techniques exist (e.g., speckle) or are being developed (e.g., optical interferometry), they are often limited in field size and/or by the available signal level. A significant fraction of optical work relies on CCD imagery of fields of several arcmin, and will probably continue to do so for quite some time. Recent advances in telescope technology (the ESO NTT being the foremost example), careful selection of telescope sites, etc., can do a lot to improve the seeing. But once the hardware is firmly in place, and the data are taken, the only way to improve the resolution is by some image deconvolution technique. Possibly the best among them is the *Maximum Entropy Method.*

A combination of good seeing data and a powerful and reliable seeing deconvolution technique may achieve results from the ground which were once believed to be reserved for space-based observatories. Here we illustrate just such an approach to data taken at ESO as a part of our study of globular cluster cores. There is hardly a more crowded scene than the very centre of a post-core-collapse cluster, such as M30=NGC 7099.

The primary scientific motivation for our study is the discovery of colour and population gradients in the clusters which show the characteristic post-core-collapse morphology (Piotto, King, and Djorgovski, 1988; Djorgovski,



Old and new images of the collapsed core of M30, and their MaxEnt restorations. The field shown is about 13 arcsec square, with north at the top and east to the left. Clockwise from top left: (a) An R-band image obtained in ~ 1.2 arcsec seeing at the ESO 2.2-m telescope, from Piotto et al. (1988). (b) MaxEnt deconvolution of the image shown in (a). (c) An I-band image obtained in ~ 0.5 arcsec seeing at the ESO NTT. Note the excellent correspondence between the stars resolved in the reconstructed image (b) and this one. This comparison establishes the reliability of the deconvolution method. (d) MaxEnt deconvolution of the image shown in (c). The effective "seeing" in this image is about 0.1–0.2 arcsec.

Piotto, and King, 1988; Bailyn et al., 1989). The gradients are always in the sense of becoming bluer inwards, which is the opposite of what may be expected from seeing and crowding effects, and they occur in post-core-collapse, but *not in* King-model-type, clusters. This effect was confirmed by Djorgovski, Piotto, and Mallen-Ornelas (1991), and Djorgovski et al. (1991). Detailed star counts (which are of course limited by the seeing near the cluster centres indicate that the primary cause of the colour gradients is the difference in radial distribution of red giants and subgiants, and horizontal branch stars. It is also possible that there is an increase towards the centre of some population of faint, blue objects, perhaps blue stragglers (Aurière et al., 1990).

Since the phenomenon is clearly confined to clusters with the post-core-collapse morphology, it is likely a consequence of stellar interactions during and after the core collapse. Apparently, dynamical evolution of star clusters can physically modify their stellar populations. Theoretical attempts to understand the origin of gradients have been unsuccessful so far (Djorgovski et al., 1991). Binaries seem most likely to be part of the ultimate explanation of this phenomenon. The process may also be important for the formation of binary and millisecond pulsars in globular clusters. In any case, the key to understanding this phenomenon must be in the nature of stellar populations near the cluster centres. This calls for a substantial increase in angular resolution.

To perform our image restorations, we have implemented a shell which utilizes the Gull-Skilling (1989) MEMSYS-3 package of routines for maximum entropy (MaxEnt) reconstruction of arbitrary sets of data. The new MEMSYS-3 code, and our extensions to it, represent a significant improvement over previous MaxEnt implementations (Weir and Djorgovski, 1991).

A recent application of this system includes restorations of ESO images of the mysterious object R136 in the core of the 30 Doradus nebula (Weir et al., 1991). An especially useful feature of this software is that it allows one to solve for a restored image at subpixel spatial scales, if the S/N is high enough. This ability facilitates the detection of very high resolution structure in the restored image which otherwise might not be apparent due to the large pixel size of the original data. From simulated images and double blind tests, we have never found the method to introduce structure at subpixel scales when it did not actually exist. To restore to such levels, one must be able to adequately interpolate the point spread function (PSF) at the subpixel level. We typically use a PSF determined by the stellar photometry programme Daophot, which achieves a three times higher than nominal sampling estimate of the PSF by forming a composite of stars from the image of interest.

The pictures in Figure 1 are of images obtained (a) on the ESO 2.2-m telescope in ~ 1.2 arcsec seeing, (b) its restoration, (c) an image obtained on the NTT in ~ 0.5 arcsec seeing, and (d) its restoration. This data set provides an excellent means of assessing the power and validity of our deconvolution method by providing us with an estimate of "the truth" (the NTT image) by which to judge the restoration of the poorer quality data (a). We were pleased to find very high correspondence. Virtually all of the maxima in restoration (b), even those which may appear on the surface to be ringing artifacts or noise, actually have counterparts in the independently derived image (c). The faint fuzzy or filamentary structures in (b) are typically how the algorithm represents two or more fainter point sources which it is unable to clearly resolve in the original data. We can thus reliably detect stars at least a magnitude fainter than was possible in the unprocessed data.

From our determination of the power and accuracy of the first restoration, we are able to estimate the degree of resolution and reliability in the deconvolution of the NTT data. We estimate that we are able to reliably distinguish and resolve binaries of equal intensity down to the separations of *0.2 arcsec* or lower throughout the image. The oblong nature of some of the objects in (d) indicates that we are beginning to reach some fundamental limits in resolution, probably due to our inability to form a precise enough estimate of the PSF for all parts of the image. The PSF has been determined in the outer parts of the 2′.5×2′.5 image where the crowding is still quite severe, and the profile of the brightest and most isolated stars can still be contaminated by faint objects. Nonetheless, virtually all of the maxima detected in (d) are easily identifiable (with the proper stretch) in image (c). The principal benefit of deconvolution is in deblending the most crowded groups, to gain a better indication of the number and location of objects in the image.

The next step in our analysis is to construct colour-magnitude diagrams in the cluster centre region, and compare them with those at larger radii. The photometric results of MaxEnt restorations have long been known to be biased in the downward direction. We have found that this degree of bias can be reasonably modeled through Monte Carlo simulations, providing the possibility of statistically correcting for this effect in the image. We prefer, however, the following approach. Given that MaxEnt does an excellent job of object detection and separation, we use the restored image as a high-resolution "finding chart" by which to locate and obtain first estimates of the position and flux of all objects in the image. Next, one feeds these estimates into a least squares PSF fitting package, e.g., Daophot or Romaphot, to obtain unbiased stellar photometry from the original lower resolution images. We have only begun to experiment with this hybrid approach, but the results appear quite promising.

While we will not be able to achieve the resolution possible with speckle methods for bright objects, we do not think we have yet reached the maximum possible resolution attainable via direct imaging and subsequent deconvolution: in fact we are still largely limited by pixel size. Because of the large field of view and long integrations possible with direct imaging, we believe that sophisticated new restoration methods have real promise for providing resolution and depth previously thought achievable only from outside the earth's atmosphere, perhaps at the level of 0.1 arcsec for a broad range of objects.

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References

Aurière, M., Ortolani, S., and Lauzeral, C. 1990, *Nature* **344,** 638.

Bailyn, C., Grindlay, J., Cohn, H., Lugger, H., Stetson, P., and Hesser, J. 1989, *Astron. J.* **98,** 882.

Djorgovski, S., Piotto, G., and King, I.R. 1988, in *Dynamics of Dense Stellar Systems,* CITA Workshop, ed. D. Merritt, p. 147. (Cambridge: Cambridge University Press).

Djorgovski, S., Piotto, G., and Mallen-Ornelas, G. 1991, in Janes, K. (ed.), *Formation and Evolution of Star Clusters,* A.S.P. Conf. Ser. in press.

Djorgovski, S., Piotto, G., Phinney, E.S., and Chernoff, D.F. 1991, submitted to the *Ap. J. Letters.*

Gull, S.F. and Skilling, J. (1989) Quantified Maximum Entropy "MEMSYS 3" User's Manual. Piotto, G., King, I.R., and Djorgovski, S. 1988, *Astron. J.* **96,** 1918.

Weir, N. and Djorgovski, S. 1991, in *Maximum Entropy and Bayesian Methods,* eds. W.T. Grandy, Jr. and L. Schick (Kluwer Academic Publishers, Dordrecht), in press.

Weir, N., Djorgovski, S., and Meylan, G. 1991, *Formation and Evolution of Star Clusters,* ed. K. Janes, A.S.P. Conf. Ser., in press.

IAU Working Group on Photography Meets at ESO

On October 29–30, 1990, the IAU Working Group on Photography (within IAU Commission 9: Instruments) met at the ESO Headquarters in Garching. It was the second time a meeting of this group took place at ESO; last time was in 1978 while the ESO Telescope Division was still located at CERN.

Much has happened within the field of astronomical photography during the past 12 years. CCDs have taken over at many telescopes and to some it may perhaps appear that photography is on its way out of astronomy. However, this is certainly not yet true. Photography is still unequalled when wide fields are observed at high spatial resolution, i.e. whenever areas covering more than a few thousand pixels square are involved. Moreover, the ease of storage and data retrieval from photographical plates should not be underestimated, while the possibility of future digitalization of sky surveys (to provide easy computer access to the information) is a most interesting development. It should of course also be kept in mind that not all observatories have the necessary means to acquire state-of-the-art CCDs. For them, photographic observa-