CCD Photometry of Globular Clusters

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The Subject

In a similar way that humans inhabit our planet, stars are distributed in galaxies. There are regions where their density is low, such being the case where our sun exists, or places where the population is large and highly concentrated, the counterparts of the Tokios, New Yorks, denominated in the astronomical world as globular clusters, because of their globular appearance rendered by their gravitational field. Their stellar population ranges in the order of the tens of thousands up to beyond a million. About 140 of these objects are seen in our Galaxy and a few others may be hiding, obscured by the dust in the plane of the Galaxy. The majority are placed towards the direction of the galactic centre, and hence ideally situated to be observed from the southern hemisphere.

The study of globular clusters provides most relevant information, such as the minimum age of the Universe, as they are the oldest known objects, supposedly formed in the early stages of the contraction of the galaxy, percentagewise very soon following the birth of the Universe. It explains furthermore the process of stellar evolution, due to the fact that we can analyse a large sample of coeval stars all placed at the same distance; provides knowledge of the chemical composition of the original material which prevailed during the "first epoch", as well as their mass, and location within our Galaxy, and neighbouring galaxies, such as the Magellanic Clouds, close enough to scrutinize these objects.

The observations of globular clusters are performed with high-precision photometry, measuring the luminosity and the colour of a sample of stars, ideally placed not so near the cluster's centre, as to avoid the high contamination; and not so far from the nucleus, as to elude intruders from the field. The plot derived from such observations is called the colour-magnitude diagram, which is a fundamental tool in understanding the evolution of stars in these objects. It informs us on the relation magnitude as a function of the stellar colour, which can be transformed with good approximation to those theoretically derived for their luminosity and temperatures. As it is assumed that all stars in a cluster shared a common origin, their location in the colour-magnitude diagram is due to the fact that the more massive the star is, the faster it evolves, hence the different regions of the diagram, correspond to the various phases of their lives.

The theoretical tracks of different masses for identical ages provide the isochrones, in whose extension the various masses are placed on the hypothesis of a common origin. The calculation of these models provides the evolution in time of the stellar temperature and luminosity for a homogeneous chemical composition. From the comparison of the observed colour-magnitude diagrams with the isochrones we can deduce the age of the cluster. In order to be able to make these comparisons we need to know the chemical composition, distance and reddening of the cluster, and the transformation of the physical parameters of luminosity and temperature ought to be well defined.

History

In the mid-sixties, when I began to study astronomy, I gave careful thought to the kind of research that might be carried out from Chile. At that time, the European Southern Observatory was just being started. I was primarily interested in photometry, and the beautiful work on globular clusters that Allan Sandage had recently done at the Mount Wilson and Palomar Observatories had impressed me greatly, so I decided to stop off in Pasadena and talk with the expert. It was then and there that the decision was made: do photometry on the many globular clusters that lie at negative declinations (65 per cent are south of –20°). At the time, globular cluster photometry in the Southern Hemisphere was almost a virgin field, and almost any cluster that one worked on was being studied for the first time. It was possible to reach below the horizontal branch, home of the RR Lyrae stars, thereby allowing one to derive reasonably reliable distances and interstellar reddening for these objects. The approximate metallicities could also be determined.

The early photometry was carried out in two steps: first, a dozen or so stars were measured photoelectrically (UBV usually), covering as wide a range of colour and magnitude as possible. Then photographs were taken and star images measured with a suitable photometer. Later, when it became available at the ESO 3.6-m telescope, a small thin-wedge prism could be placed before the objective, thereby producing a second, much fainter image of each star. Thus, in a boot-strap manner, the relatively bright photoelectric sequence could be extended to fainter magnitudes. Then came CCDs. Suddenly it became possible to carry out photometry with a substantially higher precision owing to the stability and the linearity of this marvellous detector, especially at low light levels. Also, its sensitivity range extended beyond 1 micron making it possible to work with ease in more colours than B and V which had been the workhorse wavelength bands for many years.

In 1981, following two decades of professorship at Harvard, the American astronomer William Liller moved permanently to Chile at a time when CCDs were still not user-available at ESO. We had known each other since 1968, and because of his interest in globular clusters, we began to collaborate, initially using the now old-fashioned techniques, but then changing over to CCDs when they became available. We shall describe herewith the results of our recent work.

Current Status of Research

Colour-magnitude diagrams reaching down to the main sequence have been obtained for about 40 globular clusters in the Galaxy. The primary motivation for this research has been the determination of the ages of the clusters found by matching the observed V, (B-V) diagram to the theoretically derived luminosity-temperature relationship converted to the observed parameters. Initially, it was not clear if globular clusters had a substantial spread in ages which would imply a gradual formation of the halo of the Galaxy, or if the ages were all similar which would lead one to conclude that there was a rather abrupt galactic collapse. However, improved work of recent years, both observational and theoretical, has made it clear that there is a small spread in the ages of globular clusters, perhaps no more than 2 billion years, an average age somewhere between 16 and 18 Gyrs. As we have said, one of the most important aspects of these results is that it bears directly on the age of the Universe and the value of the Hubble Constant since globular clusters are among the oldest known objects in existence. Therefore, establishing firmly and accurately the age of the oldest clusters would set an upper limit on the Hubble Constant, the exact value of which continues to be very

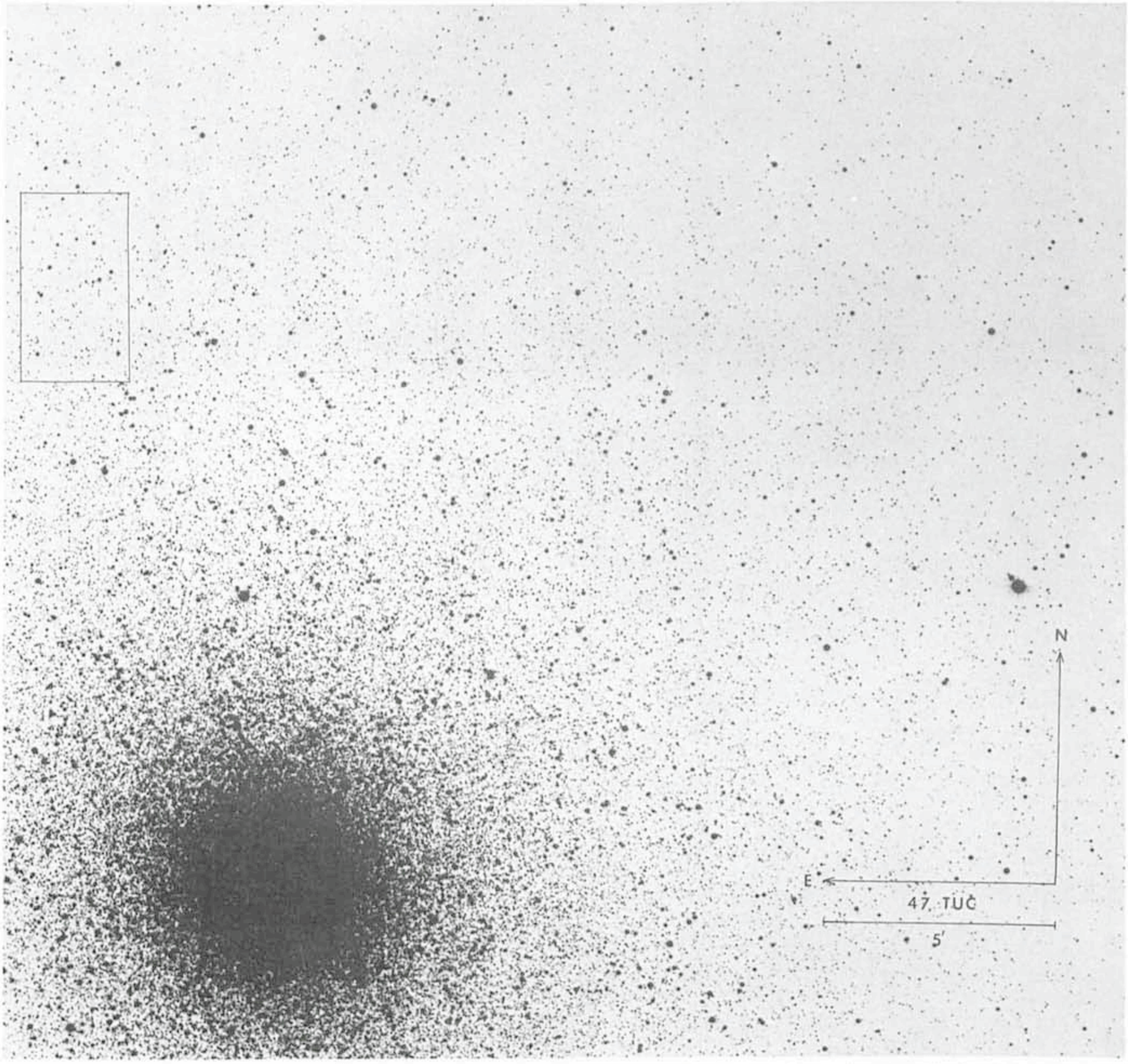
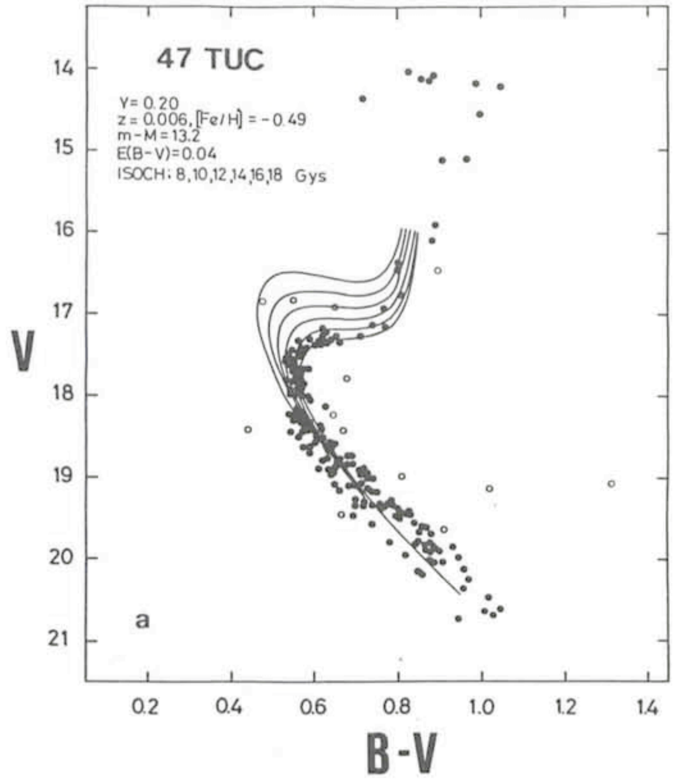
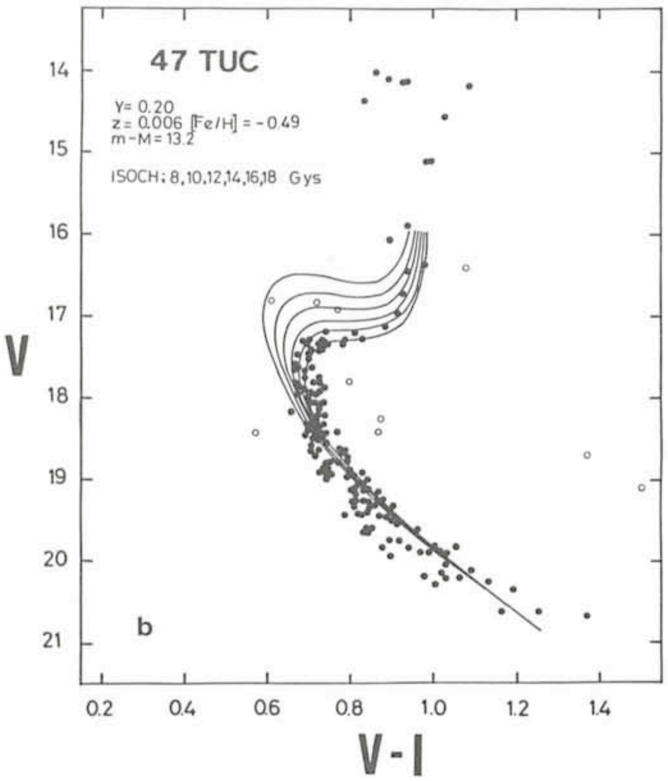


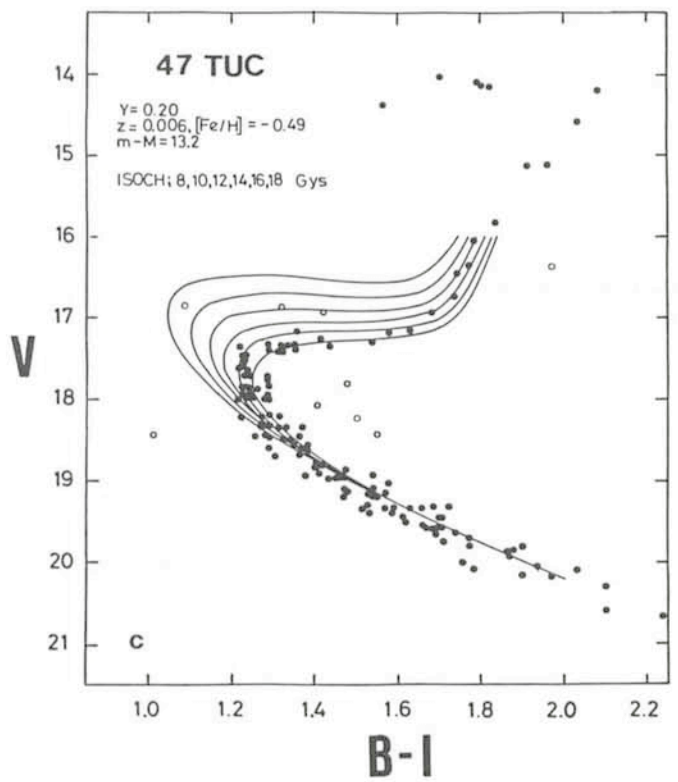
Figure 1: *The northwest sector of the globular cluster 47 Tucanae. The reproduction is from a 14-minute yellow plate (IIa-D + GG 495) obtained with the ESO 3.6-m telescope. Notice the secondary images produced by the Pickering-Racine wedge, displaced 14 arcsec towards the northeast of the brighter primary images. The general view shows the typical field that can be analysed with photographic techniques. The rectangle of 4 × 2.5 arcmin shows the region actually studied with the CCD camera.*

much under discussion at the present time.

One of the weaknesses of the extremely popular and often-used BV photometric system is that metallic line absorption in the blue and violet can be considerable. Thus, the interpretation of observations with stellar evolution theory rests heavily on model stellar atmospheres which are needed to predict the effects of this extinction in stars where often the metallicity is not well known. The metallicity of globular clusters, usually expressed by the parameter [Fe/H], has a range of over two orders of magnitudes, making a precise knowledge of absorption line effects imperative. Fortunately, VandenBerg and Bell have now carried out the difficult calculations needed to predict the location of isochrones in longer wavelength bands where metallic absorption is much less than in the blue. This work came largely as a response to the appearance of the modern generation of electronic detectors, especially the charge-coupled device (CCD), which has made it possible to carry out improved photometry at magnitudes fainter than photographic limits and at wavelengths extending into the near infrared. Besides the obvious advantage of reducing uncertainties arising from poorly known metallicities, use of the red and infrared wavelengths (R and I bands) makes possible an enlarged colour baseline which enhances effects seen less clearly with a smaller range in colour. An additional benefit of this multi-colour approach is that observational uncertainties are reduced by having several independently derived CMDs of the same cluster. With separate evaluations of the age of a single cluster, one not only can assess more reliably the accuracy of the final result, but also can derive ages with a higher precision than attained previously or with only two colours. Consequently, for the past several years we have had underway a programme of BVRI photometry of globular clusters using CCDs and new powerful reduction software. The main thrust of this programme is to concentrate on







Figures 2 (a, b, c):
a. The observed V vs B-V colour magnitude diagram of 47 Tuc, fitted to the isochrones of VandenBerg and Bell for Y = 0.2, Z = 0.006, ([Fe/H] = −0.49), α = 1.65, and ages 8–18 billion years. The isochrones were shifted to represent a cluster with $(m\text{-}M)_V$ = 13.2 and E(B-V) = 0.04.
b. The observed V vs V-I colour magnitude diagram of 47 Tuc, fitted to the isochrones of VandenBerg and Bell for Y = 0.2, Z = 0.006, ([Fe/H] = −0.49) α = 1.65, and ages 8–18 billion years. The isochrones were shifted to represent a cluster with $(m\text{-}M)_V$ = 13.2 and E(V-I) = 0.05.
c. The observed V vs B-I colour magnitude diagram of 47 Tuc, fitted to the isochrones of VandenBerg and Bell for Y = 0.2, Z = 0.006, ([Fe/H] = −0.49) α = 1.65, and ages 8–18 billion years. The isochrones were shifted to represent a cluster with $(m\text{-}M)_V$ = 13.2 and E(B-I) = 0.09.

relatively nearby clusters so that we can reach well below the main sequence turnoff with medium-sized telescopes.

We have now completed BVRI reductions on clusters: NGC 104 (47 Tuc), NGC 2298, NGC 3201, NGC 5139 (Omega Cen), NGC 6121 (M 4), and NGC 6362. All observations were made with the superb CCD system of the 1.54-metre Danish Telescope at La Silla. An additional eight globulars have now been observed in these four colours with a CCD at the 2.2-metre Max-Planck telescope at La Silla, and these data are currently being reduced at the computer centre at La Silla and analysed at the Isaac Newton Institute in Santiago. In order to minimize the errors that arise from comparing cluster fields with standards in other parts of the sky, we have set up photo-electric standards in the same cluster fields observed with the CCD. Thus, the effects of inaccurately known or varying atmospheric extinction are totally avoided. Because we can use smaller telescopes to set up the standards (most often the ESO 1-metre reflector), valuable large telescope time is not wasted moving back and forth between widely separated fields.

Observations

The camera that we have used at the Cassegrain focus of the Danish 1.54-metre telescope uses a CCD with 512 × 320 pixels. Each 30 × 30 micron pixel corresponds to an area on the sky of 0.47 × 0.47 arcsec; thus, the total field is 4.0 × 2.5 arcmin. Typically, the number of exposures of the BVRI frames obtained for each cluster ranged from a few seconds to several minutes in order to cover the full range of magnitudes without image saturation. Field positions were chosen, following careful inspection of deep photographs, as the best compromise between maximum cluster membership and workable contamination caused by crowding of im-

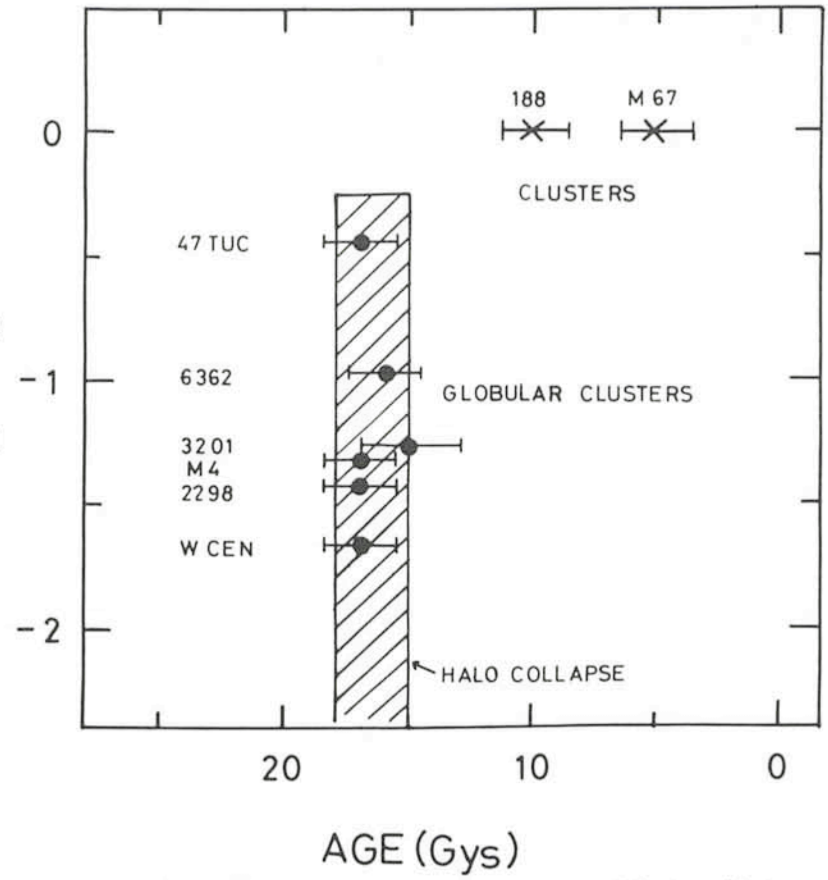


Figure 3: *Age versus metallicity for our studied globular clusters and the two oldest open clusters (NGC 188 and M67).*

ages. All reductions have been carried out at La Silla using the MIDAS/INVENTORY software employing point spread function techniques. Precise colour equations have now been established for the CCD telescope system based on 140 BVRI frames and a total of 40 standard stars with a large range of colour.

The Results

As an example, we will discuss in somewhat more detail the results for 47 Tucanae, the second brightest globular cluster in the sky. With a total population of more than one million stars, and at a distance of 13 thousand light-years, the object is faintly visible with the naked eye northwest of the South Magellanic Cloud. The cluster is shown in Figure 1, from a plate obtained by us at the ESO 3.6-m telescope. About two hundred stars were measured in a 4.0′ × 2.5′ field, and the MIDAS/INVENTORY reductions yielded the V vs B-V, V vs V-I, and V vs B-I CMDs shown in Figures 2a–2c. These diagrams also include the theoretical isochrones of VandenBerg and Bell for ages ranging from 8 to 18 Gyrs. From the figures we can see that the brightest stars investigated in our field are four red horizontal branch stars at a mean magnitude of V = 14.07. While no red giants are present in the field, the sub-giant branch and the main sequence are well defined in all diagrams. The magnitudes of the main sequence turnoff points in the three colours all fall very close to V_{TO} = 17.6 ± 0.1.

The VandenBerg and Bell BVRI isochrones are presented with the helium content alternatives of Y = 0.2 and Y = 0.3, and abundance alternatives of [Fe/H] = −0.79 (Z = 0.003) and [Fe/H] = −0.49 (Z = 0.006) for α = 1.65. The reddening value for 47 Tuc is well determined at E(B-V) = 0.04 ± 0.02 from which we derive E(V-I) = 0.05 ± 0.02 and E(B-I) = 0.09 ± 0.02. The best fit for all the isochrones shown in Figures 2a, 2b, and 2c results from Y = 0.2, [Fe/H] = −0.49, with E(B-V) = 0.04 ± 0.02 and a distance modulus of $(m-M)_v$ = 13.2. In all three colour-indices we find that the isochrones match the CMDs best for an age 17 ± 2 × 10^9y. The V vs B-I CMD in Figure 2c shows the good sequence definition provided by the use of the extreme bands as colour-indices. Using the horizontal branch magnitude of V(HB) = 14.05, we find that the absolute magnitude of the red horizontal branch is M_v (HB) = 0.85 with an uncertainty around ± 0.1. This result clearly suggests that indeed the intrinsic brightness of horizontal branch stars is fainter for metal rich clusters than the canonical value of M_v (HB) = 0.6.

In Figure 3 we have plotted the ages vs metallicity of these clusters plus the two oldest known open galactic clusters: M67 and NGC 188. We can observe that the ages derived for all of them are 17 ± 2 × 10^9 years, hinting that the globular cluster system might be coeval, and that the epoch of the galactic contraction was short. These ages set a lower limit for the age of the universe and thus an upper limit for the Hubble constant of H_o = 58 ± 5 km s^{-1} Mpc^{-1}, assuming q_o = 0.

ESO and La Silla

For nearly two decades I have been observing from La Silla, for a total of around 300 nights, witnessing the dramatic rate of improvement of astronomical technology and accumulating data that have given birth to about one hundred scientific papers. It is a moment to pause, both to express my gratitude to the many friends that have enabled me to take part in this formidable adventure, as well as to make public my recognition to the thirteen years leadership of Lodewijk Woltjer and his key collaborators who have made La Silla what it now is: the best astronomical observatory in the world, a line of excellence assured to be sustained and expanded by the current administration and the advent of the VLT, the visionary vanguardship of European astronomy.

Correction

We are sorry to inform you that some IRAS measurements listed in Table 1 of our article "IRAS Molecular Clouds in the Hot Local Interstellar Medium" (P. Andreani, R. Ferlet, R. Lallement, and A. Vidal-Madjar), published on page 47 in the last issue of the *Messenger* (No. 52), are wrong. In fact, we reported by mistake some IRAS fluxes of the Clouds # 126 and # 113 that further checks on the IRAS maps do not confirm. Here is our corrected version of that table.

P. Andreani

TABLE 1. *Infrared and CO Properties of the Clouds*

	Cloud	Coordinates				IRAS			
#	name	α (h)	δ (°)	l (°)	b (°)	12 μ	25 μ	60 μ (MJy/sr)	100 μ
20	L 1642	433	−1420	210.9	−36.5	–	–	.8 ± .2	11.2 ± 2.8
126	ρ-Oph	1616.3	−1948	355.5	−21.1	–	–	20 ± 5	71 ± 8
113	–	1517.1	−2925	337.8	−23.04	–	–	4.6 ± 1.4	26.4 ± 6