THE U, B, V PHOTOELECTRIC BRIGHTNESS PROFILES OF NGC 362

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Abstract. The photoelectric brightness profiles in U, B, and V colors of the globular cluster NGC 362 are reported down to about 9 magnitudes below the central value, covering a radial distance of about 10 arc min. They were derived from E–W scans, with a large rectangular diaphragm, giving the integrated profile of the cluster in about 6 min. of time. The inverse problem of determining the brightness profiles from integrated luminosities is solved by means of the regularization method. The agreement with the data available in literature (photoelectric brightness measurements in the inner 80 arc sec, bright stars distribution in the range 80–330 arc sec) is generally good. The B–V and U–B radial color distributions are presented. It may seem that there is no color gradient, outside the central region dominated by red giants.

1. Introduction

There are many reasons to determine brightness distributions in globular clusters over a large range of intensities and radii. These data are important for the understanding of the dynamic of globular clusters, since fitting the surface brightness profile may be a useful constraint on dynamical models representing the clusters. A second reason of interest is the suspected existence of radial color gradients in some globular clusters. If they are confirmed, there is the necessity to know where they are come from. Chun and Freeman (1979) have published the color distributions in 24 globular clusters. They found that 8 clusters, one of them being NGC 362, show a radial color gradient, but the reliability of these results is questioned by Da Costa (1979), who believed they are merely due to the sampling method used. NGC 362 is a nearly spherical southern globular cluster, close to the Small Magellanic Cloud. The C–M diagram was first determined and discussed by Menzies (1967a, b) and more recently by Alcaino (1977) and Harris (1982). So far the photometric structure of NGC 362 was derived from V photoelectric measurements by Illingworth and Illingworth (1976, hereafter referred to as II) and from star counts by King *et al.* (1968). One of us (C.C.), while she was holding an Australian National University Exchange Scholarship at the Mount Stromlo and Siding Spring Observatories, in 1978 took UBV observations of NGC 362. The observations consist in photoelectric scans at constant trailing speed using a large rectangular slit instead of the usual circular aperture. This technique enables to obtain in a short observing time the integrated profile of a diffuse object. In addition to linearity, these kind of measures are characterized by both good accuracy, since the sampling error associated with a large area is small; and good resolution, which can be obtained at a required fraction of the slit width by a suitable choice of the sampling time-interval. Under the hypothesis of spherical symmetry, the relation between the continuous brightness distribution $\sigma(r)$

of the cluster and its integrated luminosity $f(x)$ over a slit is expressed by the sum of integral equations of the first kind

$$f(x) = \int_{x-a}^{\sqrt{(x-a)^2+b^2}} r\sigma(r) \arccos((x-a)/r)\,\mathrm{d}r + 2\int_{\sqrt{(x-a)^2+b^2}}^{\sqrt{(x+a)^2+b^2}} r\sigma(r) \arcsin(b/r)\,\mathrm{d}r - 2\int_{x+a}^{\sqrt{(x+a)^2+b^2}} r\sigma(r) \arccos((x+a)/r)\,\mathrm{d}r\,, \tag{1}$$

where $2a$ and $2b$ are the dimensions of the slit, and x is the distance between its centre and the cluster centre. The restoration of $\sigma(r)$ from $f(x)$ is an unstable inverse problem, which can be solved by the Tikhonov's regularization method (see, e.g., Tikhonov and Arsenine, 1976).

2. Data Acquisition and Processing

Figure 1 shows typical U, B, V integrated profiles of NGC 362 obtained at the 24 inch (61 cm) $f/18$ telescope of Siding Spring Observatory. The data acquisition system was a photon counting photometer (2 s integration time), having a slit of 30.5 × 181.5 arc sec dimension, equipped with a 1P21 photomultiplier and a magnetic tape recorder. They consist of 190 points with a resolution h equal to 9.95 arc sec, arising from a continuous scan in R.A. at the speed of 5 arc sec s^{-1}. It is evident that the cluster profile merges in the background well before the end of the observations. While the core of the cluster is unresolved, some secondary peaks due to bright field stars appear in the wings of the observed profiles. These peaks are removed in the data processing by a low band-pass filter. Note the similarity of the details in the profiles. To derive the brightness distributions uncorrected for background, the cluster is assumed to be composed by $N = 60$ concentric annuli with internal radii $n_j = (j - 1)h$ $(j = 1, 2, \ldots, N)$ and constant brightness $\sigma(r_j)$. Let $f(x_k)$ denote the finite set of samples (mean E–W values) of the integrated profile, taken with the center of the slit at the mesh points $x_k = (k - 1)h$ $(k = 1, 2, \ldots, N)$. The relation between $f(x_k)$ and $\sigma(r_j)$ is expressed by the system of linear algebraic equations

$$\sum_{1=j}^{N} K(x_k, r_j)\sigma(r_j) = f(x_k)\,, \tag{2}$$

which discretizes the sum of integral Equations (1), the matrix elements $K(x_k, r_j)$ being the intersections of the jth annulus and the slit. The numerical solution of this

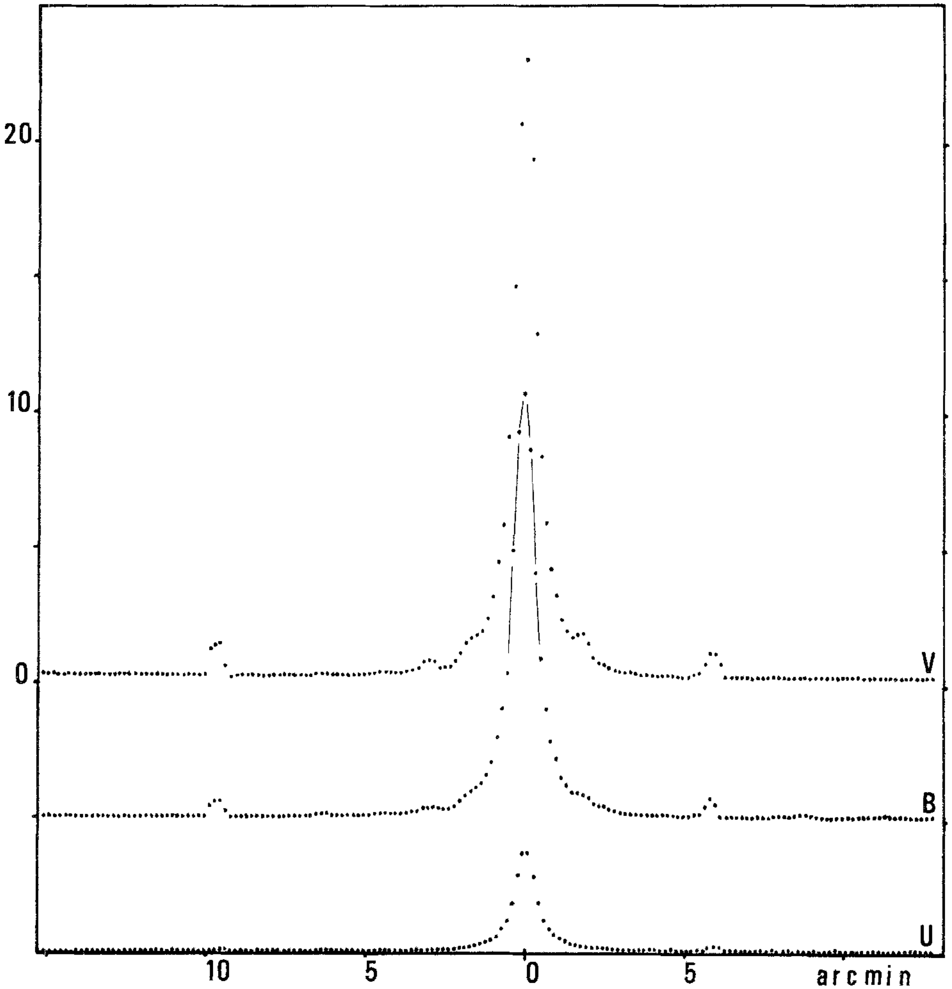

Fig. 1. Plots of the U, B, V integrated scans of NGC 362. X-axis is the distance from the cluster centre in arc min, y-axis is V profile in count sec $\times$ 10^4. Other profiles have zero point suitably shifted.

linear system attainable by any classical method is unstable – i.e., it does not depend in a continuous way on the data input. To avoid this difficulty, the problem is solved by Tikhonov's regularization method. Applications of this method in similar problems of integrated photometry made by different instrumental devices are reported in Bendinelli *et al.* (1977) or Bendinelli *et al.* (1978). The background determination and brightness calibration problems are solved simultaneously by an application of the Newton-Raphson method to the nonlinear system of equations of the form

$$M(r) = K_c - 2.5 \log(L(r) - \pi r^2 K_{bg}) . \qquad (3)$$

These equations relate a set of known integrated magnitudes $M(r)$ to the calculated integrated luminosities

$$L(r) = \int_0^r 2\pi\sigma(r)\,\mathrm{d}r$$

via the calibration constant K_c and the mean value K_{bg} of the background level over the cluster area (including also the SMC stars). Finally, the calibrated profile is given by

$$m(r) = K_c - 2.5 \log[(\sigma(r) - K_{bg})/S] , \tag{4}$$

where S is the value, in square arc sec, of the surface unit assumed in the computations.

TABLE I

Parameters of the calibrated profiles

	V	B	U
K_c	21.05 (0.04)	21.38 (0.04)	19.89 (0.02)
K_{bg}	46.7 (2.8)	31.0 (1.9)	17.9 (0.4)
m_{bg}	21.87 (0.15)	22.64 (0.15)	21.75 (0.06)
s.e.	0.04	0.02	0.02

Note: K_c in mag., K_{bg} in counts s^{-1} surface unit^{-1}, m_{bg} and the error of the fit (s.e.) in mag. arc s^{-2}.

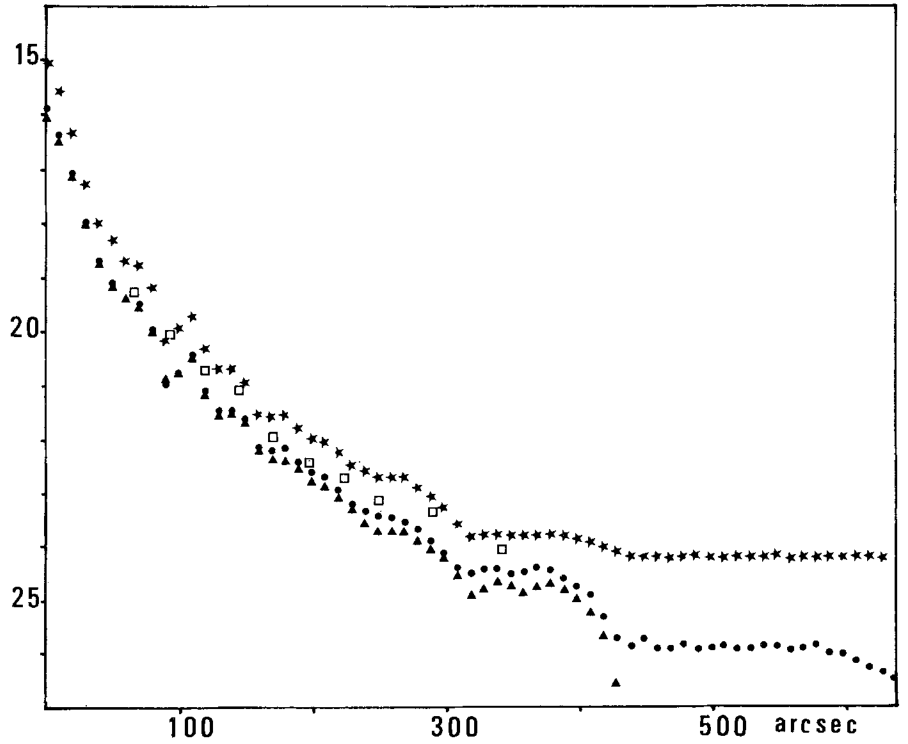

Fig. 2. The calculated U (triangles), B (dots), and V (stars) brightness profiles in mag. arc s^{-2} of NGC 362. The King's bright stars distribution (squares) with an arbitrary vertical shift is also shown.

The integrated magnitudes measured by Il were used to calibrate the V profile. U and B colors do not have any set of observed integrated magnitudes, hence, we have transformed the Il's set using the integrated color index ($B - V = 0^m.76$, $U - B = 0^m.14$, (Harris and Racine, 1979)). The values of the calibration constants K_c and K_{bg} and the sky brightness ($m_{bg} = K_c - 2.5 \log K_{bg}/S$) for each color are reported in Table I, with their formal errors in brackets.

3. Discussion

In Figure 2 the U, B, and V brightness profiles of the cluster are presented, showing no significant differences between them. The profiles are characterized by sudden changes in slope, similar to those found in M3 (Bendinelli *et al.*, 1977). The reliability of these features is confirmed in the range 10–50 arc sec by the agreement between our V profile of the central part of the cluster and those obtained by II using photoelectric scans with small diaphragms and centered apertures. Our central point is lowered by the effect of averaging over a larger integrating area due to sampling step. In the range 80–330 arc sec the behaviour of the star counts made by King *et al.* (1968) on a 7 min. exposure plate overlaps very well our profiles (see Figure 2). In fact no difference in slope between the photometry and the counts would be expected from mass segregation

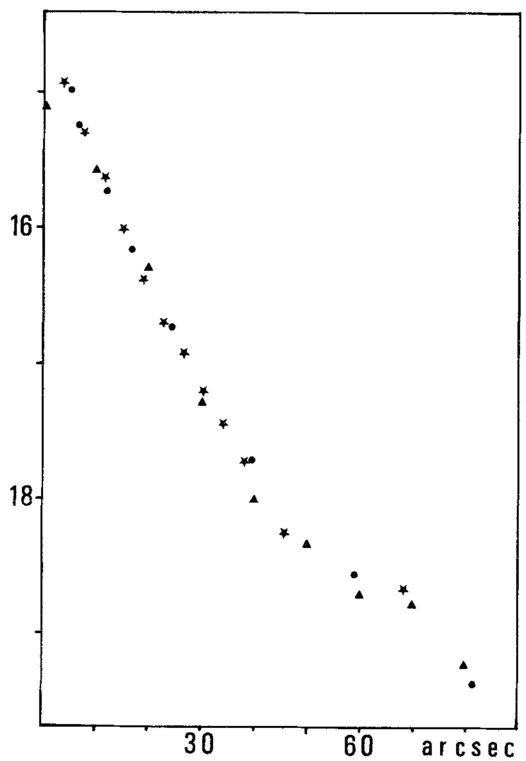

Fig. 3. Comparison between the inner part of the present V (triangles) brightness profile (mag. arc s^{-2}) and previous Il determinations from scans (stars) and apertures (dots).

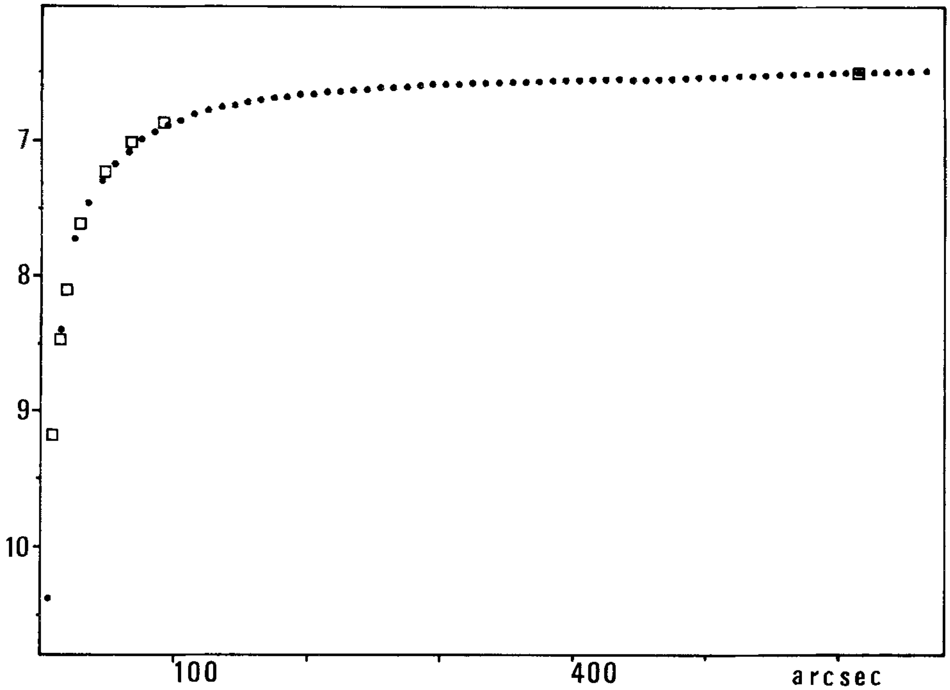

Fig. 4. Integrated V magnitude profile: dots are the present data, squares are II determinations used for calibration.

effects since the limiting magnitude of the 'short' exposure plate ensures that the stars counted are those contributing to most of the measured light. For distances larger than 330 arc sec the slope of the deep counts disagrees from the photometric profile as pointed out by Il. At about 24 mag arc s^{-2} also the calculated brightness profile is very uncertain, because its slope strongly depends on the assumed background level, and spurious humps can appear due to background gradients. The behaviour of the integrated V magnitudes, calculated from the brightness profile, is shown in Figure 4. Reliable information on the colors and their variation in the inner part of the cluster can be directly inferred from the observed integrated profiles, or indirectly from brightness profiles and integrated magnitudes. In the latter case colors can be calculated through successive anuli of effective radius $r_e = [(r_1^2 + r_2^2)/2]$ where r_1 and r_2 are the inner and outer radius, or through centered apertures of outer radius r. In Figures 5 and 6 respectively the four radial distributions so obtained for $B - V$ and $U - B$ colors are presented. The agreement between the plots is very good, as can be seen in the inner region or where the peak values due to individual stars are positioned. There appear to be a slight tendency for the cluster to be redder ($0\overset{m}{.}05$) in $(B - V)$ for $r < 60$ arc sec. In $(U - B)$ too the nucleus is slightly redder ($0\overset{m}{.}1$) than its surroundings. The influence of a few bright stars may explain this color variation. According to Buonanno *et al.* (1981), in the centre of NGC 362 it may be expected 9 red giants in a 9 arc sec radius. As far as the strong gradients found by Chun and Freeman are concerned, the comparison

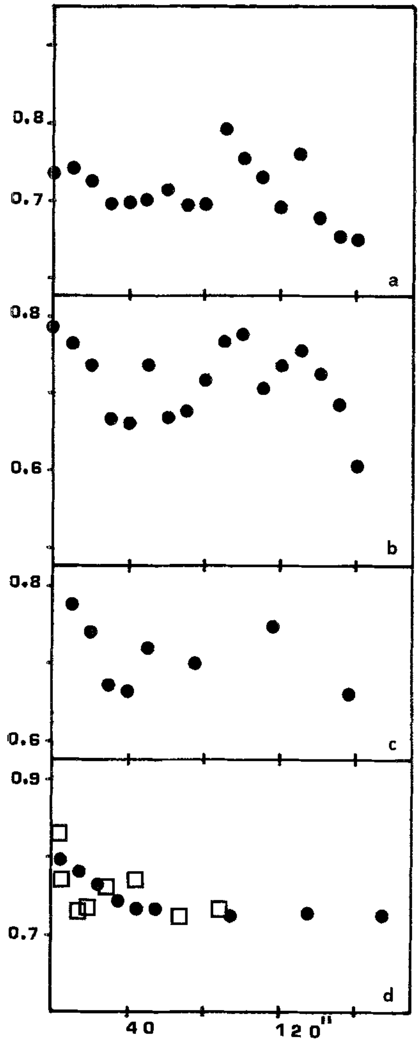

Fig. 5. The color index $B - V$ obtained (see text) from: (a) the integrated profiles, (b) the brightness profiles, (c) anuli, and (d) circles. Superimposed on (d) are the Chun and Freeman measurements shifted by $-0\overset{m}{.}05$ to match our values.

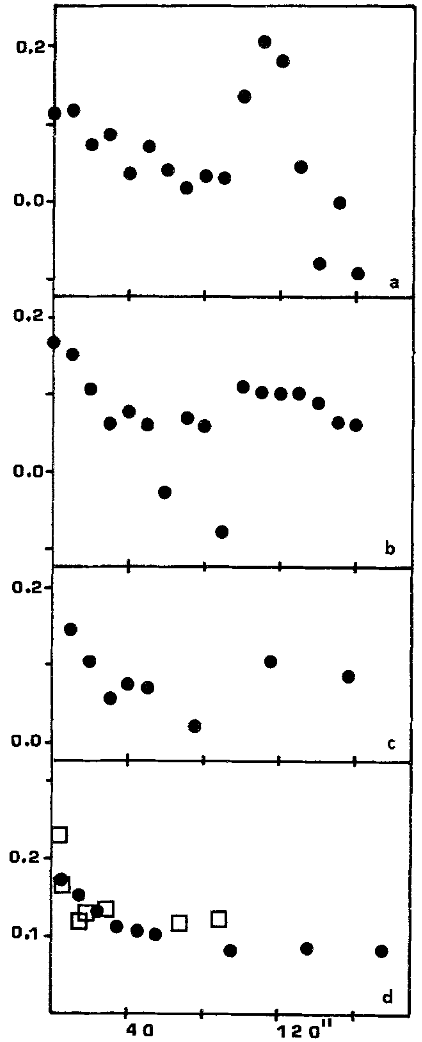

Fig. 6. As in Figure 5 for the $U - B$ color except the (d) case in which original $U - B$ values of Chun and Freeman is reported.

suggests (see Figures 5d and 6d) that their color profile may be thought as a series of oscillations superimposed on an underlying mean profile very similar to that published in this paper. Owing to the circular symmetry assumed and the discretization mesh of 9″.95 the present profile is largely smoothed. This might indicate that the mean profile is due to the intrinsic properties of the cluster while the humps are due to the random occurence of red giants on the position of the aperture. In a future paper we will analyse in more detail the nucleus of this globular cluster using data with higher resolution.

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References

Alcaino, G.: 1977, *Astrophys. J. Suppl.* **29**, 386.
Bendinelli, O., Lorenzutta, S., and Parmeggiani, G.: 1977, *Mem. Soc. Astron. Ital.* **48**, 67.
Bendinelli, O., Parmeggiani, G., Piccioni, A., and Zavatti, F.: 1978, *Mem. Soc. Astron. Ital.* **48**, 713.
Buonanno, R., Castellani, V., Corsi, C. E., and Fusi Pecci, F.: 1981, *Astron. Astrophys.* **101**, 1.
Chun, M. S. and Freeman, K. C.: 1979, *Astrophys. J.* **227**, 93.
Da Costa, G. S.: 1979, in 'Annual Report of the Director of Hale Observatories 1978–1979', p. 734.
Harris, W. E.: 1982, *Astrophys. J. Suppl.* **50**, 573.
Harris, W. E. and Racine, R.: 1979, *Ann. Rev. Astron. Astrophys.* **17**, 241.
King, I. R., Hedemann, E., Hodge, S. M., and White, R. E.: 1968, *Astron. J.* **73**, 456.
Illingworth, G. and Illingworth, W.: 1976, *Astrophys. J. Suppl.* **30**, 227.
Menzies, J.: 1967a, Ph.D. Thesis, Australian National University.
Menzies, J.: 1967b, *Nature* **214**, 689.
Tikhonov, A. N. and Arsenine, V.: 1976, *Méthodes de résolution de problèmes mal posés*, MIR, Moscow.