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NGC 362: MORE ARGUMENTS FOR DUST IN GLOBULAR CLUSTERS

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ABSTRACT

Following the detection of dust clouds in several globular clusters (Forte and Méndez), we present new U CCD data of the southern globular cluster NGC 362. Image processing shows the existence of dark patches distributed asymmetrically around the center of the cluster. Three different types of arguments are used to identify these patches as dark clouds within the cluster, namely (*a*) color mapping; (*b*) improved resolution images using modified unsharp masking technique; (*c*) behavior of the apparent extinction with wavelength. Finally, a total dust mass of $\sim 0.1\ M_\odot$ is estimated for the cloud complex.

Subject headings: clusters: globular — interstellar: grains

I. INTRODUCTION

The existence of dark lanes in globular clusters has been suspected since the observations of Lord Rosse (1861; see Kanagy and Wyatt 1978). However, their identification as interstellar matter associated with these clusters remained as a controversial subject along the years (Roberts 1988, and references therein). While the theory of stellar evolution predicts the existence of a few hundred solar masses of dust and gas within a globular cluster (at least between two passages across the galactic plane), both optical and radio surveys have set a low upper limit of gas (ionized or neutral) present within these systems (see Smith, Hesser, and Shawl 1976, or Knapp, Rose, and Kerr 1973).

While the literature shows a good number of visual detections of star-free regions in globular clusters, the results concerning the absence of gas have probably argued against their identification as dust clouds associated to the clusters. However, Roberts (1960) has shown that the probability of these patches being produced by foreground clouds, or statistical fluctuations in the projected number of stars within the cluster, is quite small. On the other hand, Forte and Méndez (1988, hereafter FM), in a recent $BVRI_{\rm KC}$ CCD survey have shown that out of 21 cloud candidates in 10 globular clusters, 18 have an apparent extinction curve which can be explained by the combination of scattering effects and geometric position of the cloud within the cluster. NGC 362, the subject of this paper, remained as one of the dubious cases since no evident wavelength dependence was present in the $BVRI_{\rm KC}$ domain. In order to further discuss this object, our original observations were extended into the ultraviolet expecting that, if the dark patches were real dust clouds, scattering effects, which become more noticeable toward shorter wavelengths, could be detected.

The method presented in FM is based upon the estimation of the mode of the pixel brightness distribution inside annular regions with different radii. This mode brightness represents the contribution arising in the *faint unresolved* stellar population, which defines a smooth continuum against which clouds can be detected in absorption (see Fig. 1 [Plate 2]). The method is constrained both for small and large radii (due to stellar crowding effects and low signal-to-noise ratio, respectively). However, alternative methods could be devised in order to detect the presence of dust in the neighborhood of the cluster nucleus. While color mapping would be helpful in detecting the existence of selective absorption produced by this dust, a resolution enhancement technique may be attempted in order to detect small-scale variations in the apparent distribution of stars due to the obscuring effects of these cloud candidates.

II. OBSERVATIONS AND DATA HANDLING

All the observations were secured using the 0.9 m telescope at CTIO, in combination with the RCA chip No. 4 (for $BVRI_{\rm KC}$), and the TI Chip No. 1 (for U). The scale for both chips at the Cassegrain focus of the telescope was 0.5 arcsecs per pixel. The frames were obtained between 1985 August 5 and 9 and 1987 September 12 and 15 with typical exposure times of 180 s for the blue band, and 50 s in the I filter. In the case of the ultraviolet we preferred taking several frames with moderate exposure times (300 s), in order to avoid cosmic-ray effects on the CCD. At least two frames in each color were taken (four in the case of the U band) and were added when appropriate. Also, off-center frames were obtained and were used in estimating the level of sky brightness (see FM).

A frame using an interference filter centered at 6606 Å was obtained on the first run. The instrumental and standard systems were linked by observing standard stars taken from Vigneau and Azzopardi (1982).

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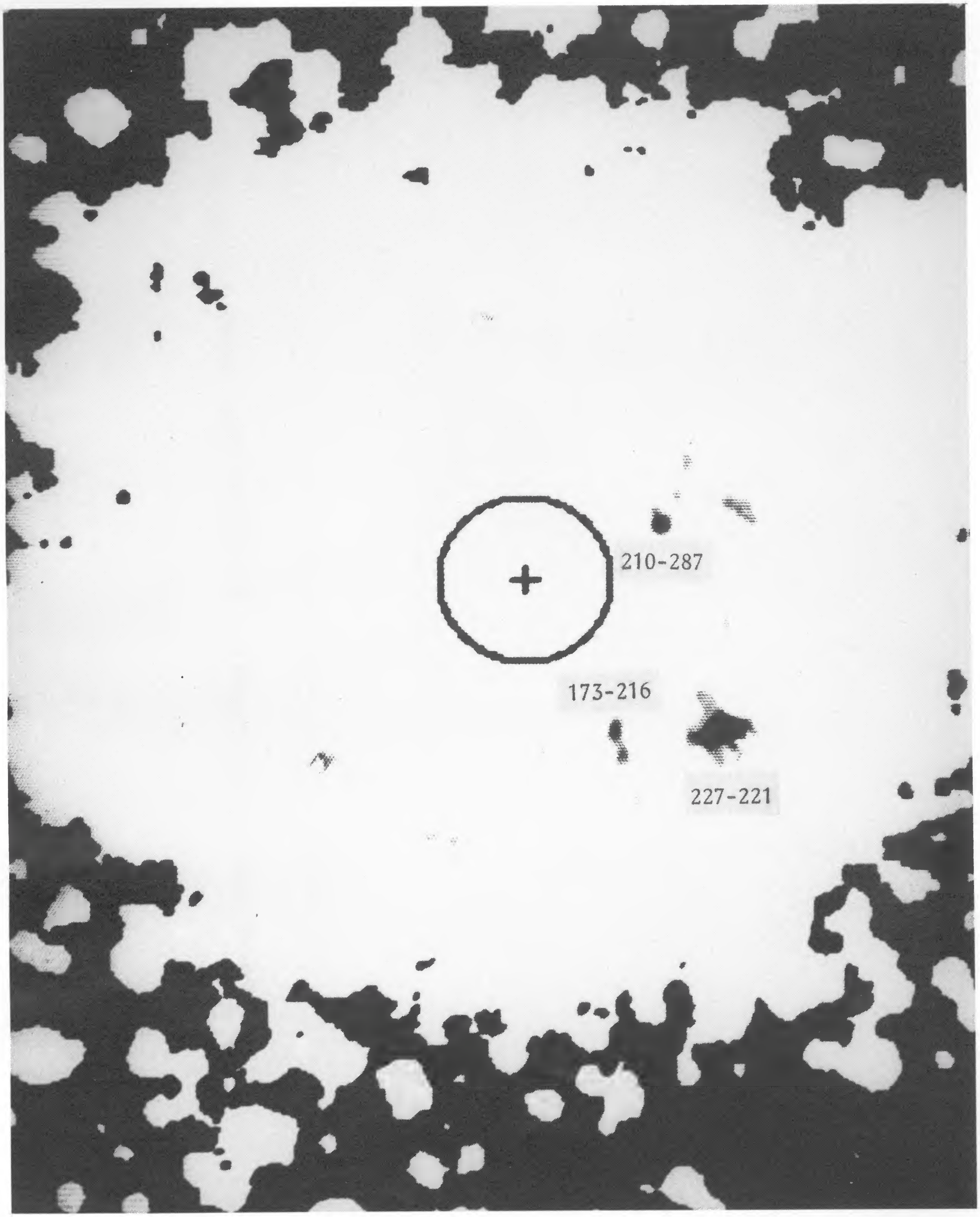

FIG. 1.—Cloud candidates in NGC 362. This composite image was obtained by subtracting and then dividing the original visual frame of NGC 362 by the best-fitting King profile (see FM). The cross indicates the photometric center of the cluster while the circle has 13″ in radius (1 core radius). The positions of the cloud candidates are indicated as listed in Table 1. Cloud 158-159 is not shown because it falls below the surface brightness threshold given in FM. North is left and east is up.

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Flat-fielding, bias correction, and dark subtraction was done at the mountain using the CFCCD package. Subsequent analysis was performed by using the CTIO–IRAF facilities, the Quasi-Interactive Image Processing System of La Plata Observatory, and some routines (center and sky level determination, mode analysis, etc.) specifically written for this work.

III. RESULTS

a) Color Mapping

Figure 2 (Plate 3) shows a $B-I$ color index map obtained by superposing the observed B and I frames by means of the shifting routines available in the IRAF package (shifting errors in the order of ± 0.1 pixel), and subtracting the corresponding sky values. These two colors were selected as they define an adequate wavelength-base in order to detect the existence of selective absorption across the cluster nucleus. Interestingly, this composite plate shows that the color distribution inside the core radius is not uniform around the center (indicated by the cross), and that there is a blue patch toward the north (left of the plate). This asymmetry in the color distribution suggests that the cloud complex present to the south of the cluster center (and outside the core radius) extends into the nuclear region.

b) Resolution Enhancement

In order to improve the resolution of our images in the neighborhood of the nucleus of the cluster, we attempted a variation of the unsharp masking technique (see Malin 1981). In our case we used a red broad-band frame and the one obtained using the narrow-band filter centered at 6606 Å. Both images have slightly different point spread functions and, at the same time, as a consequence of the difference in the effective wavelengths they define a short wavelength-base color index.

After subtracting the corresponding sky levels, both images were sampled in concentric annulii in order to determine the scaling factors which brings them to the same signal level (this factor takes into account the differences between exposure times and filter widths). Then the 6606 Å frame was subtracted from the broad R image. The result is shown in Figure 3 (Plate 4), where stars with intermediate colors ($0.25 < V-I < 1.50$) appear as white dots surrounded by black rings, enhancing the position of the peak of the stellar profile, redder stars ($V-I > 1.50$) appear as black disks, and bluer stars ($V-I < 0.25$) as white ones.

The most obvious feature of this image is that the blue patch observed toward the north of the photometric center of the cluster is resolved into many individual stars (the photometric center being the one that gives the best center of symmetry to the overall cluster profile, as determined through a mirror autocorrelation map, Djorgovski 1988). Star counts show that there is an excess of 60% of stellar images inside the northern part of a 10″ semicircle centered on the cluster nucleus, when compared with the counterpart counts to the south. This fluctuation may be associated with the existence of obscuring clouds, which might extend up into the nuclear region.

c) Apparent Extinctions

The apparent extinctions for the $UBVRI_{\mathrm{KC}}$ bands listed in Table 1 were obtained by measuring the different frames through a square window, 3 pixels wide, as explained in FM. The inclusion of the new U band data confirms the general trend found there, that is, the extinction increases from the near-infrared toward the visual, and then decreases again to the blue and ultraviolet. This behavior may be explained as the consequence of two combined effects, i.e., the geometric position of the cloud within the cluster, and the scattering of the cluster light by the cloud.

These two effects can be modeled as follows.

If L and l represent the surface brightness contributed by the cluster at a given line of sight, and by the stars located between a cloud at that line of sight and the observer, respectively, then the apparent extinction may be written as

$$\Delta m_\lambda = -2.5 \log \left[\frac{l + (L - l) \exp(-\tau_\lambda)}{L} + S_\lambda \right]$$

(see FM), where τ_λ is the optical depth of the cloud at wavelength λ, and S_λ represents a measure of the light contributed by dust scattering.

In Figure 4 we present the apparent extinctions of the different clouds in NGC 362 versus λ^{-1} (including a new cloud candidate not mentioned in FM), and the corresponding model fittings, characterized by l, the measure of the cloud position inside the cluster, A_v, its intrinsic visual absorption, and S_v, a scattering parameter at visual wavelength. For the model fitting we have adopted the standard extinction law for τ_λ (Schultz and Wiemer 1975), and the scattering was assumed to follow a wavelength dependence close to λ^{-4}. This behavior is comparable to that of the bluest reflection nebulae observed by Witt and Schild (1986). The inclusion of the ultraviolet observations strongly enhances the (mild) wavelength dependence detected in FM, something that is also true for the rest of the clouds within the different globular clusters presented there (see Méndez and Forte 1988).

The analysis of model fitting showed that the errors quoted in Table 1 for Δm_λ are in accordance with variations in the order of 15% for l and S_v, and 50% for A_v. We also want to point out the fact that the photometric properties of this interstellar matter (Population II in origin) might differ from those typical for the galactic plane dust.

TABLE 1

OBSERVED DATA ON DUST CLOUDS IN NGC 362

Cloud	D^{a}	A_U	A_B	A_V	A_R	A_I
158/159	4″90	0.13 (9)	0.54 (3)	0.54 (4)	0.51 (5)	0.36 (5)
173 216	3.00	0.11 (9)	0.32 (3)	0.31 (5)	0.30 (8)	0.29 (9)
210/287	4.00	0.48 (7)	0.52 (3)	0.51 (5)	0.49 (4)	0.52 (3)
227/221	12.00	0.42 (9)	0.59 (3)	0.54 (2)	0.56 (4)	0.53 (2)

NOTE.—Quoted errors are in hundredths of magnitude.

[a] Cloud diameters in arc seconds. In the case of elongated clouds, an average diameter is given.

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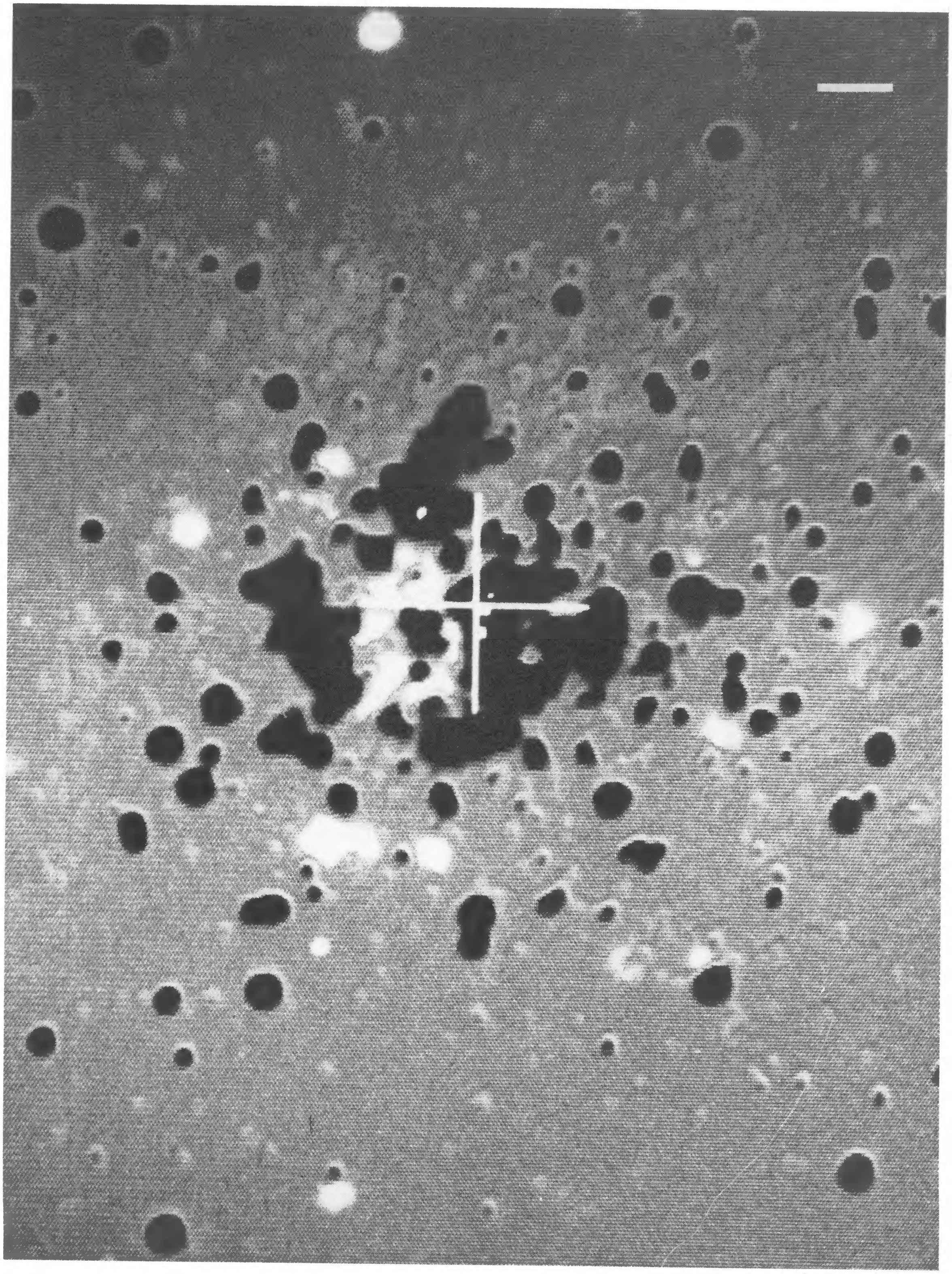

FIG. 2.—$B-I$ color index map of NGC 362. A blue patch appears some 10″ to the north of the cluster center. The position of this patch is opposite to that of the cloud candidates depicted in Fig. 1. The horizontal bar (*upper right*) is 10″ long.

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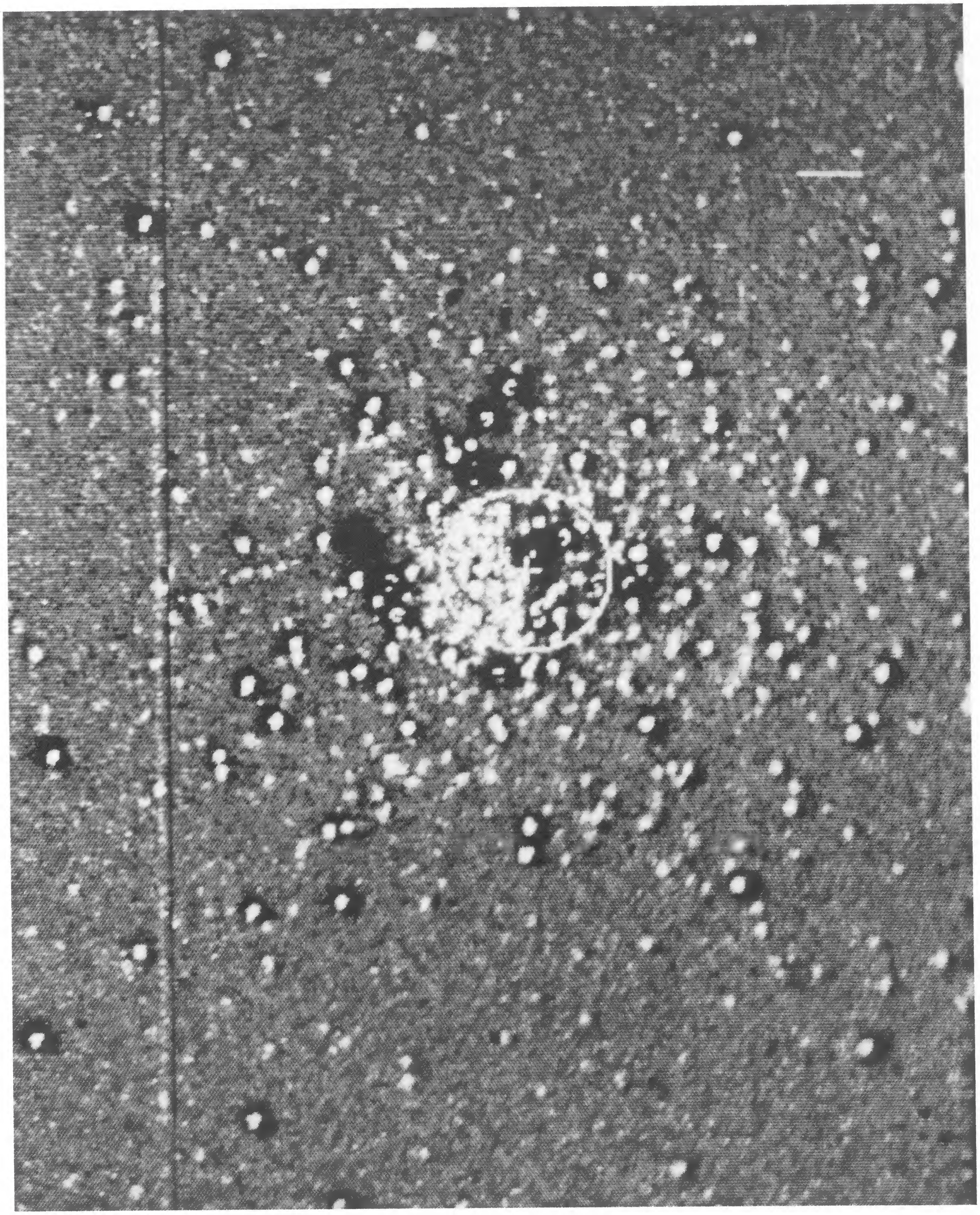

FIG. 3.—Composite image of NGC 362 using a frame obtained with an interference filter centered at 6606 Å, and another one in the *R* band, both having a slightly different seeing (see text). A clump of resolved stars can be seen in the position of the blue patch in Fig. 2. The scale is the same as in Fig. 2.

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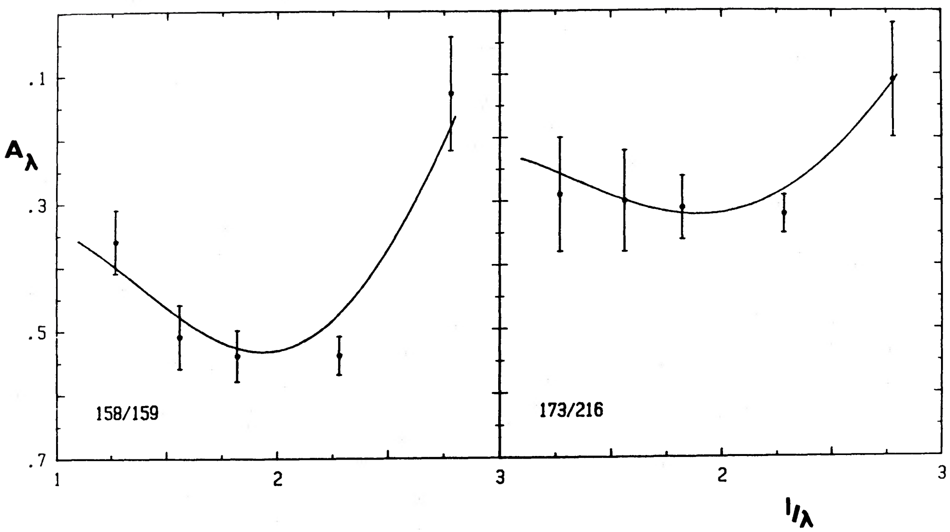

FIG. 4*a*   FIG. 4*b*

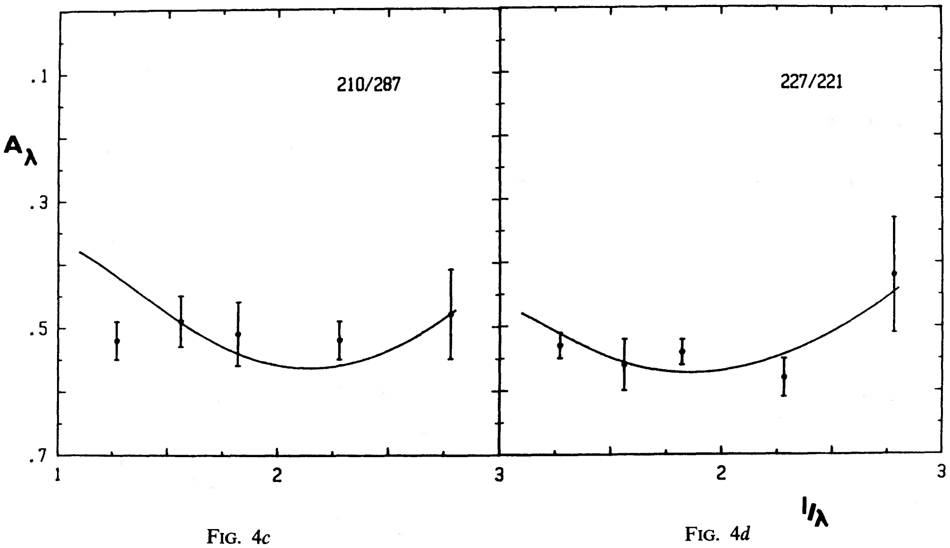

FIG. 4*c*   FIG. 4*d*

FIG. 4.—(*a*) Apparent extinction as a function of inverse wavelength for cloud candidate 158-159. The solid curve represents the model fitting using the parameters as listed in Table 2. (*b*) Same as (*a*), for the cloud candidate 173-216. (*c*) Same as (*a*) for the cloud candidate 210-287. (*d*) Same as (*a*) for the cloud candidate 227-221.

Following Kanagy and Wyatt (1978), the mass of each cloud may be computed as

$$M_d = 0.13 r^2 \tau \quad \text{(solar masses)}\ ,$$

r being the average radius of the cloud in parsecs, and τ its optical depth. Using the absorption and diameter values given in Table 2 we obtain masses which ranges from $1 \times 10^{-3}\ M_\odot$ in the case of 173/216, up to $3.8 \times 10^{-2}\ M_\odot$ in the case of 227/221 (see footnote of Table 1 for cloud denomination). Thus, allowing for a completeness factor of 2 accounting for our detectability restrictions, the total dust mass in NGC 362 would be close to $\sim 0.1\ M_\odot$. However, this value should be taken cautiously, as it relies on a number of uncertain assumptions (e.g., the geometry of the cloud, or the chemical composition, albedo, or size of the dust grains).

From this value, and assuming a gas-to-dust ratio of ~ 150 (Knapp 1985), some 15 $M_\odot$ of gas would have to be expected in this case (this value must be considered as a lower limit to the gas contents, as the gas-to-dust ratio used was derived using Population I stars). This number is nearly one order of magnitude bigger than what is actually reported in the literature (e.g., Smith, Hesser, and Shawl 1976), thus suggesting the possible existence of a cleansing mechanism much more effective acting on the gas than on the dust.

However, all these masses still remains well below (at least an order of magnitude) what is predicted by the theory of stellar evolution.

IV. CONCLUSIONS

Our CCD data support the existence of dust clouds within the southern globular cluster NGC 362. Simple numerical tests show that these clouds cannot be attributed to statistical fluctuations in the projected number of stars (Roberts 1960). Their nature is also supported by the analysis of the apparent extinc-

TABLE 2

Derived Parameters of Dust Clouds in NGC 362

Cloud	D^a (pc)	A_v	l	S_v	$M_d{}^b$
158/159	0.24	1.00	0.20	0.08	1.72×10^{-3}
173 216	0.15	1.30	0.55	0.05	9.96×10^{-4}
210/287	0.20	2.00	0.50	0.02	2.39×10^{-3}
227/221	0.59	3.55	0.55	0.02	3.82×10^{-2}

[a] Linear approximate diameters, assuming a distance of 10.2 kpc.

[b] Mass of the dust cloud in solar masses.

tion curves as a function of wavelength. The observations may be fitted by using simple models accounting for scattering processes in a cloud well inside the cluster. These models depend on three parameters, namely:

1. the intrinsic visual absorption, which in the case of NGC 362 clouds averages $A_v = 2.5$ mag;
2. the geometrical depth of the cloud within the cluster, l, which in all cases is less than 0.6. Clouds beyond the cluster nucleus would be more difficult to detect as they produce smaller photometric effects;
3. the scattering in the visual band, S_v, which ranges from 2% to 10% of the unextinguished light of the cluster at the cloud position.

The distribution of the dust appears to be not uniform around the cluster center, and seems shifted toward the south.

The presence of dust is also supported by the color mapping and by the results of the "unsharp masking" technique, which shows a clump of resolved stars whose position is offset from the photometric center of the cluster, opposite to the position of the cloud candidates.

The total dust mass detected in this cluster ($\sim 0.1\ M_\odot$) further emphasizes the intriguing question regarding the apparent low levels of monatomic gas present in these systems. Although this reasoning rests on the assumption that the gas-to-dust ratio is independent of the chemical composition of the interstellar matter, the possible existence of a cleansing mechanism being more effective on the gas than on the dust should be investigated.

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