THE RED STELLAR CONTENTS OF THREE SELECTED FIELDS OF THE LOCAL GROUP DWARF IRREGULAR GALAXY IC 1613

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RESUMEN

Presentamos la fotometría JK, moderadamente profunda, de tres campos en la galaxia enana IC 1613. El diagrama color-magnitud contiene una mezcla de estrellas supergigantes rojas, estrellas de la rama asintótica (AGB) y gigantes rojas. Las supergigantes rojas son masivas (20–25 $M_\odot$) y jóvenes –con edades entre 8 y 25 Myr. El resultado más importante es la evidencia de una disminución de la densidad de la población de AGB de edad intermedia cerca de las regiones H II. También encontramos una diferencia entre las edades de las estrellas AGB en el cuerpo principal de la galaxia y las de la región alrededor de las regiones H II de la parte noreste en el sentido de que las estrellas del cuerpo principal tienen edades entre 1 y 10 Gyr mientras que las estrellas de la región noreste son más jóvenes que 1 Gyr. Utilizando la relación período-luminosidad derivada por Madore & Freedman (1991) y las magnitudes JK de la Cefeida V20, calculamos el módulo de distancia a IC 1613: $(m - M)_K = 24.37 \pm 0.2$. Finalmente, la nova recientemente descubierta por King, Modjaz, & Li (1999) fue identificada en nuestras imágenes en el campo III. Su presencia y brillo cuestionan su clasificación como nova.

ABSTRACT

We present a moderately-deep JK photometry for three selected areas of the dwarf irregular galaxy IC 1613. The color-magnitude diagrams contain a mixture of red supergiants, asymptotic giant branch stars and the brightest red giant stars. The red supergiants are massive (20–25 $M_\odot$) and young —with ages between 8 and 25 Myr. The most important result is the evidence of the decreasing density of the intermediate age AGB population in the vicinity of the H II regions in the galaxy. We also find age differences between AGB stars in the main body of the galaxy and those near the H II regions in the North-East. The former span a range in ages between 1 and 10 Gyr, while the latter are younger than 1 Gyr. Using the period-luminosity relation derived by Madore & Freedman (1991) and JK magnitudes of the Cepheid variable V20, we calculated $(m - M)_K = 24.37 \pm 0.2$. The recently discovered Nova (King, Modjaz, & Li 1999) was identified in Field III. Its presence in our images and its brightness questioned its classification as a nova.

1. INTRODUCTION

Studies of bright stars in nearby galaxies provide a direct link to their history of star formation. Photometric investigations of red supergiants (RSG) and asymptotic giant branch (AGB) are of particular interest, as these stars probe the evolution during early and intermediate epochs.

Carrying out such studies at near-infrared (NIR) wavelengths have a number of advantages. NIR observations are less sensitive to both the reddening

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towards and within galaxies. They allow us to over-
come the effects of line blanketing, which can af-
fect the spectral energy distributions of moderately
metal-rich giants at optical wavelengths. In addition,
they are the best choice for determining bolomet-
ric corrections and for the analysis of the bolomet-
ric luminosity function of the luminous, cool evolved
stars. Several recent studies of the red stellar con-
tent in nearby spiral and irregular galaxies exploit-
ing these advantages include Davidge (1999: M33),
Davidge (1998: NGC 55, NGC 300, and NGC 7793),
and Cioni et al. (1999: LMC).

Here, we present NIR observations of IC 1613.
IC 1613 is a faint, irregular galaxy within the Lo-
cal Group. Recently, Cole et al. (1999) studied the
history of star formation in the central part of the
galaxy using HST VI photometry. They found a
dominant old stellar population: red giant branch
and red clump stars, and a prominent sequence of
intermediate age AGB stars. Cole et al. (1999) de-
liberately chose their region for study to avoid known
H II regions. In this paper, we present JK photom-
etry of the three selected areas of IC 1613. We chose
our fields to extend the area covered by Cole et al.
(1999) towards the active H II areas. The goal of this
work is to analyze the bright, red stellar content and
to determine the distance of IC 1613.

2. OBSERVATIONS AND DATA REDUCTION

We acquired our data with the "CAMILA" in-
frared camera attached to the 2.1 m telescope of the
Observatorio Astronómico Nacional at San Pedro
Martir, México (Cruz-González, Salas, & Ruiz 1996).
CAMILA is based upon a NICMOS3 (256×256 pix-
els) detector. The scale was 0.85 arcsec/pixel, which
resulted in a field size of about $3.6' \times 3.6'$. A set
of JK frames was taken on October 13 to 15, 1998.
The seeing during these observations was between
$1 - 1.2''$ with stable and very good photometric con-
ditions. Ten UKIRT (Casali & Hawarden 1992) stan-
dard stars were observed during the observations.
All three fields were obtained with equal exposure
times of 960 seconds.

The IRAF data reduction package was used to
carry out the basic image reduction. The final
median-combined J images of the fields are shown
in Figures 1, 2, and 3. The three fields are indicated
on a print of a B plate from STScI Digitized Sky
Survey (Figure 4). Field I is centered on the H II re-
gions in the north-east quadrant of the Galaxy where
the most active ongoing star formation is occurring
(Sandage 1971). Fields II and III were chosen to be
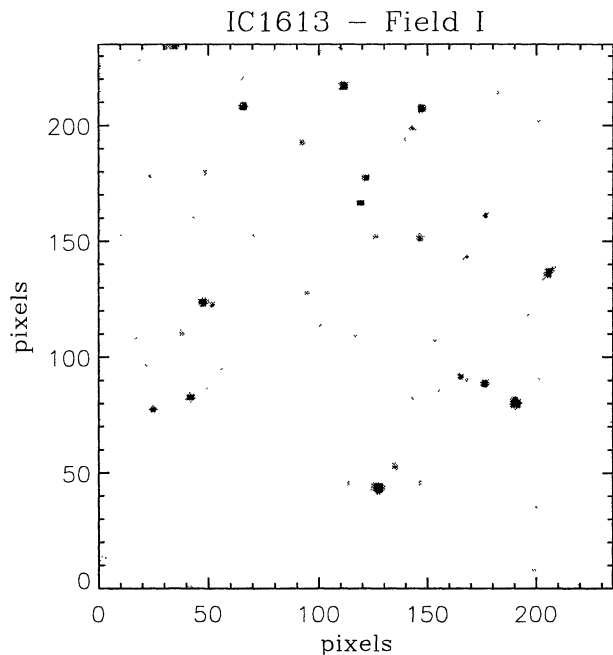within of the main body of IC 1613. There are six

Fig. 1. Final J image of IC 1613 Field I. North is up and East is to the left.

Hodge (1978) associations in Field I: A10, A11, A12,
A13, A14, and A17; Field II include Hodge (1978)
associations A8 and A9, and Field III include A5,
A6, and A7.

The stellar photometry of the median-combined
frames was performed with the point−spread func-
tion (PSF) fitting routine ALLSTAR available in
DAOPHOT (Stetson 1993). The ALLSTAR mag-
nitudes were calibrated against aperture photometry
performed on selected stars which had neighbors sub-
tracted. We then rejected all stars which had values
of $\chi^2 > 2$ and the stars with formal errors from the
PSF fitting greater than 0.25 in all frames. The in-
strumental values were transformed to the standard
J and K system by means of the equations

$$J = -4.447(\pm 0.09) + 1.002(\pm 0.05)\, j - \\ -0.123(\pm 0.03)\,(j - k) - 0.168(\pm 0.06)\, X \;,$$

$$K = -4.724(\pm 0.08) + 0.992(\pm 0.03)\, k - \\ -0.173(\pm 0.05)\,(j - k) - 0.154(\pm 0.03)\, X \;,$$

where j and k are the instrumental magnitudes, X is
the airmass and $(j-k)$ is the color of the object. The
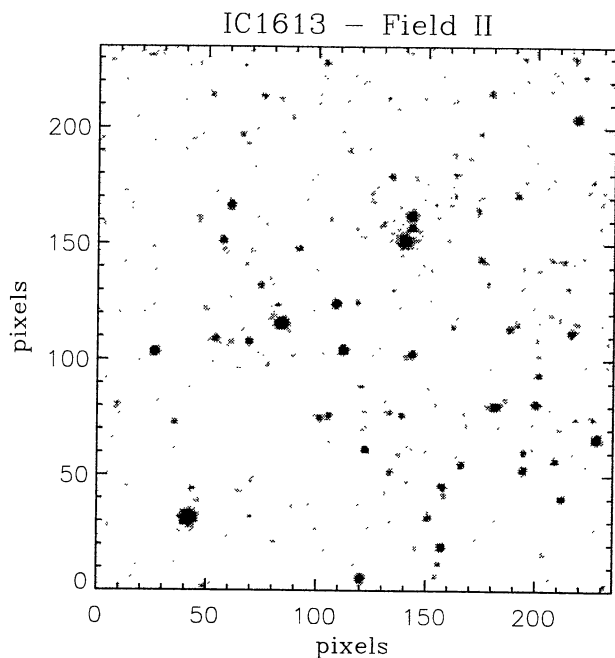errors are the statistical errors in the coefficients.

IC 1613 – Field II

Fig. 2. Final J image of IC 1613 Field II. North is up and East is to the left.
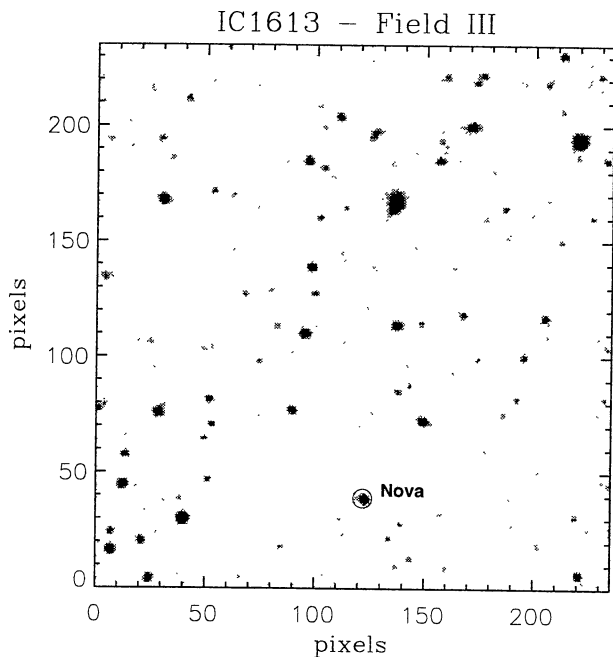
IC 1613 – Field III

Fig. 3. Final J image of IC 1613 Field III. North is up and East is to the left.
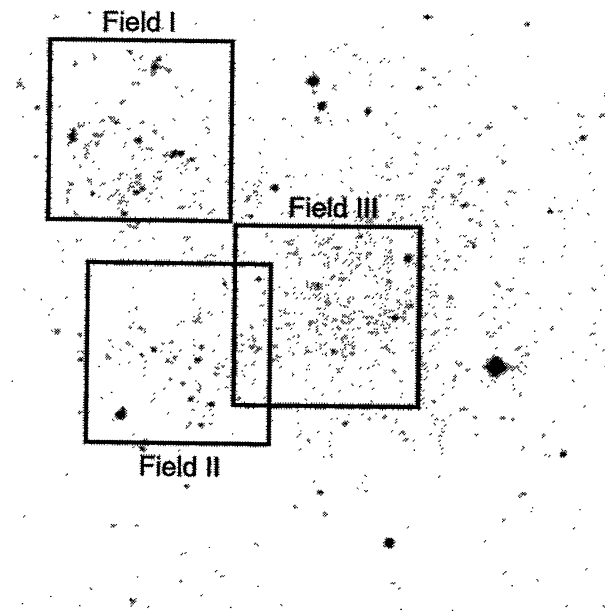

Fig. 4. The Digitized Sky Survey image of IC 1613 (North is up and East is to the left). Our three $3.6' \times 3.6'$ fields are indicated.

The zero-point errors of the transformation are 0.02 in J and 0.05 in K.

The artificial star simulations necessary for the completeness correction are used to determine the measurement errors. The K band "input-output" mean differences between "added" and "recovered" artificial stars as a function of specified magnitude interval for Field I, Field II, and Field III are given in Table 1. In columns 5 and 6, 10 and 11, 15 and 16 are given mean differences between actual and measured magnitudes of synthetic stars recovered in specified interval of one magnitude and the error of the mean difference. The mean differences and errors in J band are within the same intervals. In summary, the median scatter is smaller than 0.1 mag down to 17.5 mag and increases up to 0.2 in the faintest bins.

3. COMPLETENESS AND FIELD STARS CONTAMINATION

The artificial star technique (Aparicio & Gallart 1995) was used to investigate the crowding effects. Following step by step the procedure described in Aparicio & Gallart (1995) we generated the tables in J and K bands with artificial stars, which have realistic magnitudes and colors. Such prepared tables were used to generate the synthetic frames for the three investigated fields. They were processed in

TABLE 1

COMPLETENESS AND MEAN ERRORS FROM ARTIFICIAL STARS IN K BAND

Range	Field I					Field II					Field III				
K	K_{in}	K_{out}	r	ΔM	σ	K_{in}	K_{out}	r	ΔM	σ	K_{in}	K_{out}	r	ΔM	σ
13–14	135	134	0.99	0.02	0.03	126	123	0.98	−0.03	0.04	161	158	0.98	0.02	0.02
14–15	147	145	0.99	0.03	0.02	136	133	0.98	−0.01	0.03	169	170	1.00	−0.02	0.04
15–16	129	128	0.99	0.0	0.05	128	126	0.98	0.05	0.04	146	142	0.97	0.05	0.06
16–17	120	116	0.97	0.08	0.10	113	104	0.92	0.06	0.03	143	131	0.92	0.07	0.05
17–18	98	83	0.85	0.13	0.15	121	97	0.80	0.07	0.11	148	124	0.84	0.08	0.15
18–19	71	38	0.53	0.18	0.21	126	56	0.44	0.18	0.15	153	76	0.50	0.15	0.19

the same way as original frames. The process was repeated many times and in total 700 stars are analyzed for Field I, 750 for Field II and 920 for Field III. In Columns 2, 3, and 4 (respectively 7, 8, and 9, and 12, 13, and 14 for Fields II and III) of the Table 1 are given total number of "input" and "output" stars and the ratio between them in K band. In summary, the analysis of Table 1 show, that the degree of completeness is close to 100 per cent down to 16 mag in K and can seriously affect our analysis for magnitudes fainted than 18 mag. As can be seen there is no significant differences in the completeness factors between the three investigated fields.

The luminosity functions (LF) for the three fields are shown in Figure 5. The decrease in counts at the faint end also indicates that the incompleteness becomes significant when $K = 18.0 - 18.2$.

Field stars should not seriously affect the structure of the color-magnitude diagram because IC 1613 is situated far from the galactic plane ($b = -61°, l = 131°$). The field star densities predicted by the Bahcall & Soneira (1980) model imply that the contamination from our Galaxy is negligible. We applied no correction for contamination by field star.

4. COLOR-MAGNITUDE DIAGRAMS

Figure 6 shows the $(J - K, K)$ color-magnitude diagrams (CMD) of our three fields in IC 1613. Our final list contains 80 stars in Field I, 343 stars in Field II, and 505 stars in Field III.

The CMDs contain a mixture of red supergiants (RSGs), AGB stars, and the brightest red giant stars (RGB). Each field contains one or two stars with $K \approx 13 - 13.5$ and $J - K \approx 1$, which are the very luminous RSGs, and delineate the peak of the RSG luminosity function. Close binaries whose components have similar magnitudes and colors will look like one star of the same color though brighter
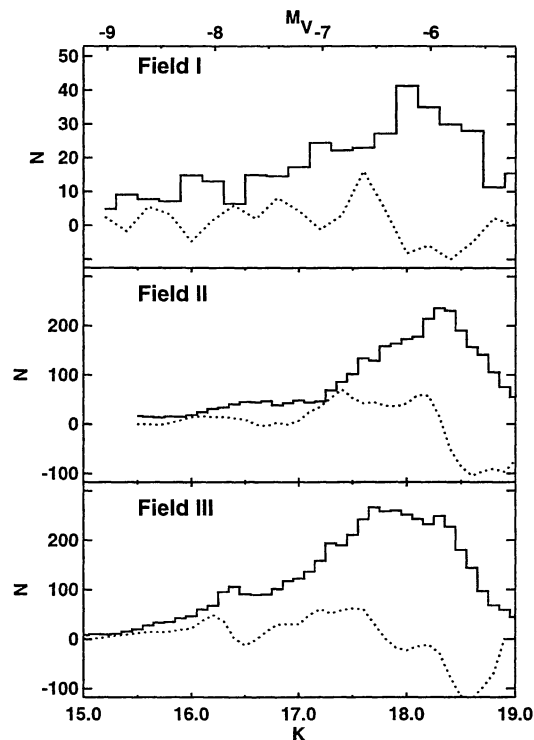

Fig. 5. The differential luminosity function for all stars in Field I, Field II, and Field III. "N" is the number of stars per magnitude interval. The dotted lines are the output from the Sobel edge-detection filters (see § 5 for details).
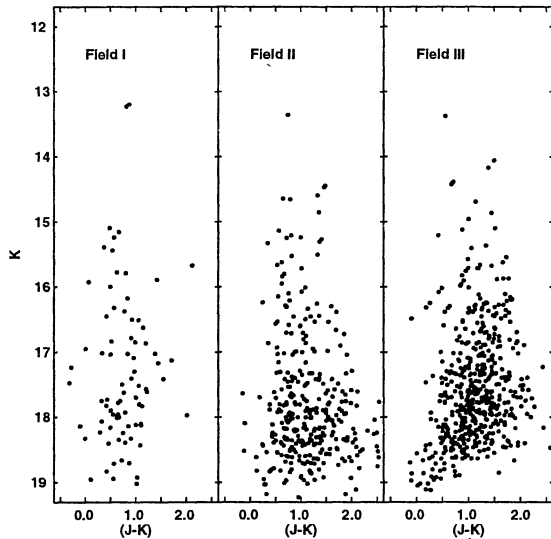
Fig. 6. $(J - K, K)$ color-magnitude diagrams obtained for IC 1613.

in magnitude. The brightest stars were inspected for blending effects on VI frames with much better scale: $0.33''$ pixel^{-1} and seeing of $1''$. The VI frames were obtained on the 2 m Ritchey-Chretien telescope of the Bulgarian National Astronomical Observatory on September 15, 1999 with a Photometrics 1024×1024 camera. No such occurrences were found. The presence of a population of bright RSGs is an indicator of recent star formation in all three fields in IC 1613.

In Field I we can see some deficit of stars redder than $(J - K) \approx 1.0$. The analysis of crowding effects (see Table 1) shows that there is no larger crowding in this field. Since Field I is centered on the H II regions of the Galaxy the higher internal reddening can affect the stars. The "mean" reddening of the area however, determined by Georgiev et al. (1999), is $E(B - V) = 0.06 \pm 0.02$. Assuming $E(B - V) = 0.03 \pm 0.02$ for Fields II and III (Cole et al. 1999) the resulting difference due to reddening is 0.02 for $J - K$ color, the value much smaller than the observing effects. The $(B - V, V)$ photometry by Georgiev et al. (1999) centered on the same area as Field I can provide independent check of the observed number of the red stars in the infrared. The number of stars with $B - V > 0.8$ and V brighter than 21.5 is 92, which is in good agreement with the total number of corrected for completeness stars, obtained in Field I: 95.7. Of course, deeper photometry is necessary to confirm the observed in Field I deficit of stars redder than $J - K = 1.0$.

The stars between $K = 14.5$ and $K = 15.5$ and $0.5 < (J - K) < 1.5$ are also RSGs with lower brightness. When $K > 15.5$ both RSGs and AGBs stars are present, although there is some color separation between them —AGB stars are generally redder than $(J - K) \approx 1.0$. At the faint limit of the CMDs, but still within the completeness limit of the photometry, the brighter red giants can be seen mixed among with the faintest AGB stars.

5. AGE AND LUMINOSITY FUNCTION

To convert our observed color-magnitude diagrams to absolute magnitude and true color, we assumed a foreground reddening, a distance modulus and a metallicity of $E(B - V) = 0.06$ (Georgiev et al. 1999), $(m - M) = 24.20 \pm 0.1$ (Freedman 1988; Saha et al. 1992; Cole et al. 1999), and $Z = 0.004$ (Mateo 1998). The resulting color-magnitude diagrams are shown in Figure 7. The isochrones for $8\,10^6, 2.5\,10^7, 10^9$, and 10^{10} yr, and for $Z = 0.004$ from Padua's library (see Bertelli et al. 1994) are superimposed on the CMDs (Fig. 7).

The isochrones superimposed upon Fig. 7 indicate that the brightest red supergiants in the three fields are very young —about 8 Myr. Georgiev et al. (1999) obtained 5 Myr for brightest red supergiants V32 and V38 in Field I, which is in good agreement. Cole at al. (1999) also found that in the center of IC 1613 the red supergiants are younger than a "few 10^7 yr". Fainter RSGs in IC 1613 have $M_K < -10$ and are matched very well by a 25 Myr isochrone.

Most of the AGB stars in Fields II and III are several Gyr old. In Field I most of them are between the second and third isochrones, and thus are younger than 1 Gyr. As well known (see for example, Aparicio 1999) the colors and life-times of AGB stars depend on the mass loss, bolometric correction and metallicity, which are difficult to parameterize. Without information of main sequence we will consider above determined range of AGB ages as a rough estimates.

To investigate the influence of the various metallicity on the AGB ages we overplot in Figure 8 the isochrones for 10^9 yr and for $Z = 0.0004$, $Z = 0.001$, and $Z = 0.004$. Indeed, the metal poorer and metal richer AGB stars can present, but it is not possible to separate the metallicity from age effects using $(J - K, K)$ color-magnitude only.

To determine the tip of AGB stars we used the K-band LFs. Looking at the differential LFs in Fig. 5 we can see the AGB tips at K between $16.0 - 16.5$ in the three fields. To verify the reality of these edges we convolved the data with a Sobel edge-detection
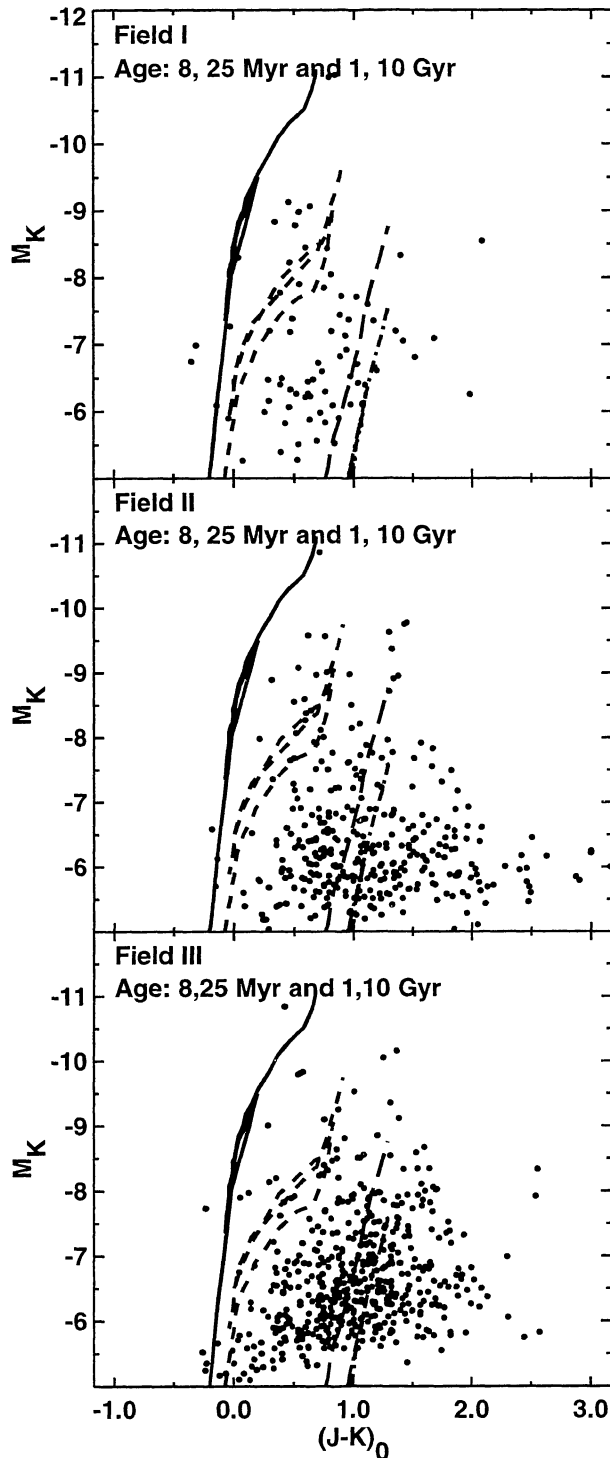
Fig. 7. The $(M_K, (J - K)_0)$ color-magnitude diagrams of IC 1613 with isochrones from Padua's library for $8\,10^6, 2.5\,10^7, 10^9$, and 10^{10} years superimposed (vertical lines).
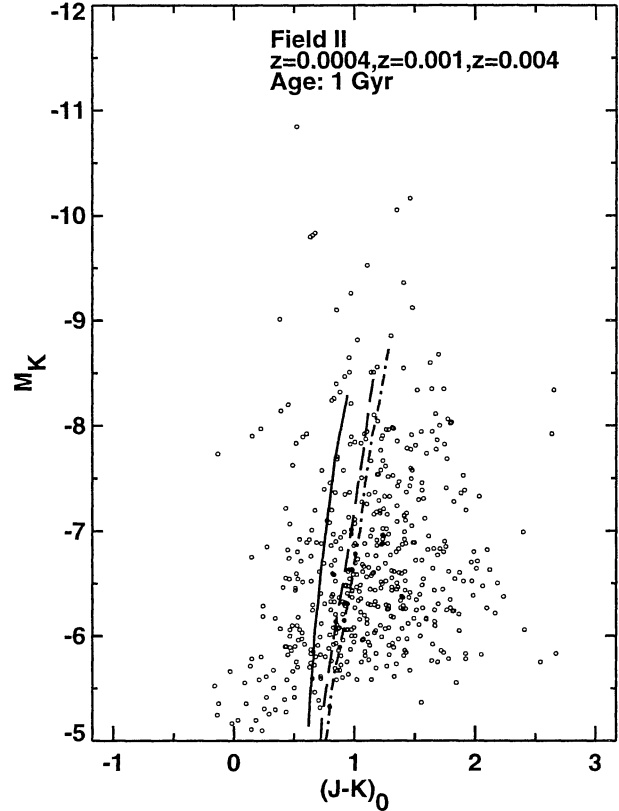
Fig. 8. The $(M_K, (J - K)_0)$ color-magnitude diagrams of IC 1613 with isochrones from Padua's library for 10^9 years superimposed (vertical lines) and $Z = 0.0004, Z = 0.001$ and $Z = 0.004$.

filter with width of the filter 0.2 (Lee, Freedman, & Madore 1993; Sakai, Madore, & Freedman 1996). The filter function outputs are shown as dashed lines in Fig. 5. The limited number of stars in Field I prevents us from drawing any conclusions. For Fields II and III however, there are peaks at $K = 16.15$ and $K = 16.25$, respectively, which mark the tip of AGB. Given the reddening and distance modulus adopted above, this corresponds to approximately $M_K = -8$. This value is in agreement with the tip of the AGB found by interpolating between the isochrones in Fig. 7 for ages of 4–5 Gyr, confirming the reality of the AGB peaks in for Fields II and III.

The derived power-law exponent for the composite (Fields II and III) LF for magnitude interval $15.5 < K < 18$ is 0.51 ± 0.04. Cole et al. (1999) found the slope of V-band luminosity function down to $V = 24.5$ to be 0.48 ± 0.09, which is in acceptable agreement.
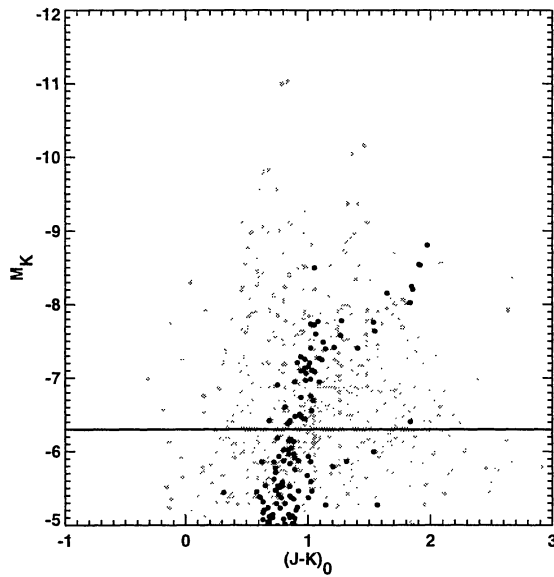
In Figure 9, the stars from all three fields in

Fig. 9. The $(M_K, (J-K)_0)$ color-magnitude diagrams of all three fields of IC 1613 (light circles). JK observations (dark circles) of 12 globular clusters in the Large Magellanic Cloud (Ferraro et al. 1995) are also drawn. The solid horizontal line represents the separation between RGB and AGB stars for the globular clusters.

IC 1613 are shown with overploted JK observations of 12 globular clusters in the Large Magellanic Clouds (Ferraro et al. 1995) (dark circles). The horizontal line is located at the separation threshold between AGB and RGB stars, as given by Ferraro et al. (1995). The globular clusters are a good match to our data, indicating that some long period variables should be located between $-8 < M_K < -9$. Taking into account Ferraro's (1995) separation threshold between AGB and RGB stars, the tip of the RGB should be located around $M_K = -6$. The peaks at $K = 18.15$ of Sobel edge-detection output in LFs of Fields II and III (Fig. 5) provide some support of this determination, but also can be due to incompleteness at fainter magnitudes. Unfortunately, the RGB stars are at the limit of our photometry and deeper photometry is necessary to investigate them in more detail.

6. THEORETICAL HERTZSPRUNG–RUSSELL DIAGRAMS AND VARIABLE STARS

We needed to determine the effective temperatures $(T_{\rm eff})$ and bolometric corrections (BC) in order to locate the stars on the theoretical HRD. We used Costa & Frogel's (1996) method to transform K magnitudes and $(J-K)$ colors into $M_{\rm bol}$ and $T_{\rm eff}$. We first transformed our K magnitudes and $(J-K)$ colors into the CIT system by means of the transformation equations for the set of filters in use at "San Pedro Martir" Observatory (equations 1 and 2 from Ruelas-Mayorga 1997). Then, using the method outlined by Costa & Frogel (1996), we transformed our $(J-K)_{CIT}$ colors to the Johnson system and derived the bolometric correction for the K magnitude, $M_{\rm bol}$ and $T_{\rm eff}$. We used the distance modulus and reddening adopted above (§ 5). The resulting HRDs are shown in Figure 10. The evolutionary tracks from Charbonnel et al. (1993) for $Z = 0.004$ were superimposed on the same plot.

The brightest stars in Field I, V32, and V38, have bolometric magnitudes of $M_{\rm bol} = -8.6$ and masses of 20 $M_\odot$. These values are very different from those found using UBV photometry (Georgiev et al. 1999), which are larger by ≈ 1 mag in $M_{\rm bol}$ and 20 $M_\odot$. The largest sources of uncertainty in transformation to the theoretical plane are the uncertainties in $(J-K)$ colors. Adopting a maximum uncertainty in $(J-K)$ of 0.15 mag, Costa & Frogel's (1996) equations imply a maximum uncertainty of 0.25 mag in $M_{\rm bol}$ and 400 K in $T_{\rm eff}$. Therefore, the differences in temperatures and bolometric magnitudes determined from optical and infrared photometry are much larger that the uncertainties due to the photometry or the transformation to the theoretical plane, and confirm the well-known fact that it is very unreliable to determine bolometric corrections for very red stars from data at optical wavelengths. The effective temperatures derived from our NIR data for V32 and V38 are approximately 4000 K, in good agreement with their M0Ia spectral class (Elias & Frogel 1985).

The brightest star in Field II also has a mass of 20 $M_\odot$, while the brightest star in Field III is more massive at 25 $M_\odot$. The fainter RSGs and brighter AGB stars in the magnitude range $-5.5 < M_{\rm bol} < -7.5$ have masses of 12 to 15 $M_\odot$.

The only variable star in Field II is V20 —a Cepheid with $P = 41\overset{\rm d}{.}953$ and B amplitude $\Delta_B = 1.66$ mag (Sandage 1971). The derived bolometric magnitude from our IR data is $M_{\rm bol} = -5.7$, the effective temperature ≈ 5000 K and 9 $M_\odot$. Two WR/O candidates were also identified in Field II (W2 and W3: Armandroff & Massey 1985; Azzopardi, Lequeux, & Maeder 1988) but they are too faint for reliable measurements.

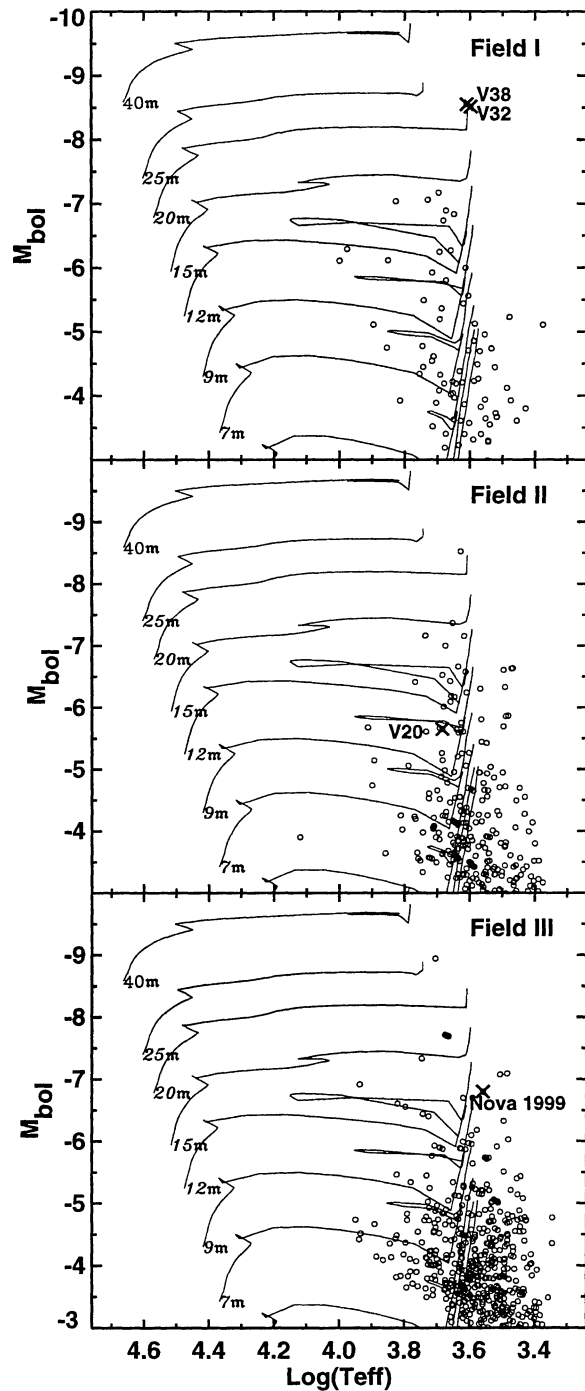We have identified an object at the position of the recently discovered Nova (King, Modjaz, & Li 1999)

Fig. 10. H–R diagram for IC 1613. The evolutionary tracks from Charbonnel et al. (1993) for $Z = 0.004$ are also shown. Known variables are marked with dark crosses and labeled.

in Field III. On the our IR frames, taken in October 15, 1998, Nova 1999 has $(J - K) = 1.14$ and $K = 14.69$. If this is the same object, its presence on our IR frames a year before its discovery bring its classification as a Nova into question. In the subsequent paper, we will discuss the light variations and spectrum of this peculiar object.

7. DISTANCE TO IC 1613

Using the apparent J and K magnitudes of the Cepheid variable V20 and period-luminosity (PL) relation, we can obtain the apparent distance moduli in J and K. Adopting Madore & Freedman's (1991) J and K calibrations of the PL relation, based upon 25 Cepheids in the LMC, and the period found by Sandage (1971), we obtain distance moduli of $(m - M)_J = 24.42 \pm 0.2$ and $(m - M)_K = 24.37 \pm 0.2$. These are in satisfactory agreement with Cole et al.'s (1999) determination of $(m - M)_0 = 24.27 \pm 0.1$.

8. THE BOLOMETRIC LUMINOSITY FUNCTION

The bolometric LFs (not corrected for completeness) for our three fields in IC 1613 are compared in Figure 11. All of the LFs have a discontinuity at $-5.0 < M_{bol} < -5.7$, which characterizes the boundaries between RSG and AGB stars. In Fig. 11, a LF formed from the sum of the stars in the three fields is also shown. We would like to point out the lack of a discontinuity in the LF for the AGB stars in all three fields. The logarithmic LFs are linear for the AGB stars ($-3.0 < M_{bol} < -6.0$), so they can be characterized by a power-law exponent. The derived by least squares fit exponent for the composite LF is 0.43 ± 0.05.

9. SUMMARY

In summary, we find substantial evolved stellar populations in our three fields in IC 1613, including the region of ongoing star formation. The brightest stars are massive ($20 - 25\ M_{\odot}$) red supergiants with K magnitudes between $13 - 13.5$ and $(J - K) \approx 1$. Based upon a comparison with the Padua isochrones (Bertelli et al. 1994), these brightest RSGs are very young, with ages between 8 and 25 Myr.

The main feature of the NIR CMDs is the rich intermediate age AGB population. In the central part of the galaxy (our Fields II and III), the tip of AGB stars can be located at $K = 16.20$. There is an indication of lack of ABG stars in Field I (centered on most active H II region of the galaxy) that are redder than $(J - K)_0 = 1$. All of the AGB stars in Field I are younger than 1 Gyr, whereas those in the
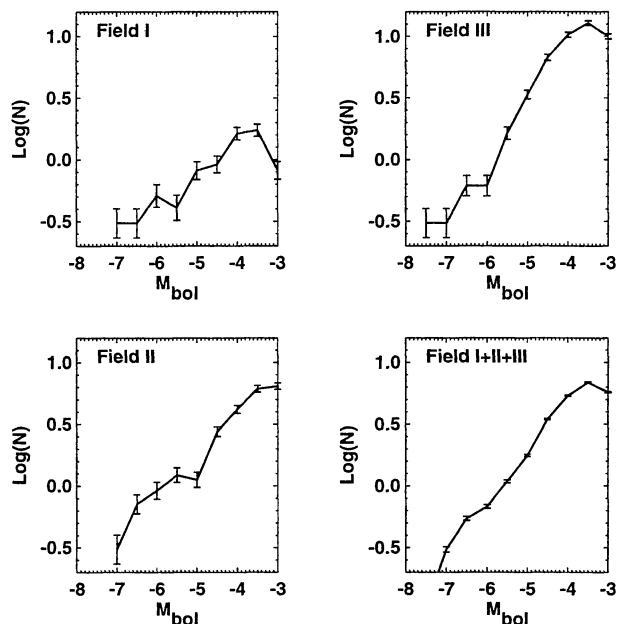
Fig. 11. The bolometric luminosity function for all stars in Field I, Field II, and Field III. "N" is the number of stars per 0.5 mag interval per square arcmin. The error bars represent the uncertainties due to counting statistics.

Fields II and III span ages from 1 to 10 Gyr. Using the PL relation derived by Madore & Freedman (1991) along with our J and K magnitudes for the Cepheid variable V20 we calculate a distance modulus $(m - M)_K = 24.37 \pm 0.2$. In Field III we identify an object at the position of the recently discovered Nova 1999 (King et al. 1999). Its presence in our IR frames one year before discovery indicate that this star is too bright to be a classical Nova.

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