THE STELLAR POPULATIONS OF NGC 3109: ANOTHER DWARF IRREGULAR GALAXY WITH A POPULATION II STELLAR HALO

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ABSTRACT

We have obtained V- and I-band photometry for about 17,500 stars in the field of the dwarf irregular galaxy NGC 3109, located in the outskirts of the Local Group. The photometry allows us to study the stellar populations present inside and outside the disk of this galaxy. From the VI color-magnitude diagram, we infer metallicities and ages for the stellar populations in the main body and in the halo of NGC 3109. The stars in the disk of this galaxy have a wide variety of ages, including very young stars of age \( \sim 10^7 \) yr. Our main result is to establish the presence of a halo consisting of Population II stars, extending out to about 4.5 (or 1.8 kpc) above and below the plane of this galaxy. For these old stars we derive an age of over \( 10^{10} \) yr and a metallicity of \([\text{Fe/H}] = -1.8 \pm 0.2\). We construct a deep luminosity function, obtaining an accurate distance modulus \((m - M)_0 = 25.62 \pm 0.1\) for this galaxy based on the I-magnitude of the red giant branch tip and adopting \(E(V-I) = 0.05\).

Key words: galaxies: individual (NGC 3109, DDO 236) — galaxies: irregular — galaxies: stellar content — Galaxy: formation — Local Group

1. INTRODUCTION

The results of the MACHO Project indicate that about 50 ± 30% of the dark matter in the Milky Way halo is baryonic and made of faint objects with typical masses around 0.5 ± 0.3 \( M_\odot \) (Alcock et al. 1997). One possibility is that these objects are stellar remnants from old populations, even though their initial mass function may be extreme (Chabrier et al. 1996). If some stars form before galaxies, they would remain collisionless, populating the galactic halos just like elementary cold dark matter (CDM) particles (Miralda-Escudé & Rees 1997; Loeb 1997). If this is indeed the case, it poses the simple question of whether there are old populations of stars to be observed in the halos of other galaxies that, on dynamical grounds, are known to have large amounts of dark matter. To answer this question, it makes sense to target dwarf irregular galaxies for study. These galaxies are known to be dark matter-dominated, having rising rotation curves extending beyond their optical limits (Carignan & Freeman 1988). A typical case is NGC 3109, located in the outskirts of the Local Group (van den Bergh 1994; Mateo 1998). This galaxy is far enough away not to have been affected by interactions with the larger Local Group spirals, yet close enough that it can be resolved into stars.

Some of the parameters of NGC 3109, which has been relatively well studied, are listed in Table 1 (see Mateo 1998 and references therein). We note that NGC 3109 is on the bright end of the family of Local Group dwarf irregulars, almost as luminous as the LMC (Table 1). This galaxy has a system of globular clusters (Demers, Irwin, & Kunkel 1985).

Lee (1993) showed the differences between the color-magnitude diagrams of the NGC 3109 disk and a field located 2' away from it. The outer field seems to be dominated by an old and metal-poor population. Earlier, Sandage (1971) pointed out that direct photographs of all galaxies in the Local Group reveal the presence of a background sheet of red stars, and that the brightest of these stars are at the tip of the red giant branch (RGB) of a globular cluster–like population. Based on these pieces of evidence, and motivated by the discovery of a halo consisting of Population II stars in the dwarf irregular galaxy WLM (Minniti & Zijlstra 1996), we decided to investigate whether a similar halo component is indeed present in NGC 3109. Hereafter we define Population II as the stellar component that is very old (> \( 10^{10} \) yr) and metal-poor (\( Z < 0.002 \), or \( Z < 0.1 Z_\odot \)) (see the reviews by Hodge 1989 and Mateo 1998 for a discussion of star formation histories and Population II stars in the Local Group galaxies).

In this paper we present deep optical photometry covering a large field centered on NGC 3109, which allows a detailed photometric study of individual stars and stellar populations in this galaxy. The observations of NGC 3109, data reduction, and photometry are described in § 2, and the resulting color-magnitude diagrams are given in § 3, along with a discussion about reddening. The spatial distribution of the different stellar populations is discussed in § 4. Section 5 presents the luminosity function (LF) of NGC 3109. Fundamental parameters of NGC 3109, such as metallicity, age, and distance, are determined in § 6. Section 7 discusses other population tracers, namely, star clusters, carbon stars, H ii regions, planetary nebulae, Cepheid variables, and H i observations. The formation and evolution of NGC 3109 are discussed in § 8, and the conclusions of this work are summarized in § 9.

2. DATA

2.1. Observations and Reductions

The observations of NGC 3109 were obtained during the night of 1995 January 7, as part of a long-term monitoring program of variable stars in several galaxies (Zijlstra, Minniti, & Brewer 1996b). We used the red arm (RILD...
may arcsec

NGC 3109 is rich in background galaxies. NGC 3109 field shown in Figure 1. The field to the south of ground frame in the sky is directly to the south of the main ground of this galaxy. These foreground stars from the Galactic halo and disk should appear as a plume of stars in the color-magnitude diagram with mean color $V - I = 0.7$ and a total color range covering about $0.4 \leq V - I \leq 1.5$. The contamination from these stars can be estimated from star counts in a strip along declination of $0.5 \times 8.9$ arcmin$^2$, offset by 10’ from the NGC 3109 major axis. The observed density of red stars in this region is less than 1 star arcmin$^{-2}$ with $I \leq 20$ and 4 stars arcmin$^{-2}$ with $20.5 \leq I \leq 22.5$. From the Galactic model of Ratnatunga & Bahcall (1985), we expect 0.7 foreground halo stars arcmin$^{-2}$ with $V \leq 21$ and $0 \leq V - I \leq 2$ in this low-latitude field.

Since the galaxy-to-star ratio increases rapidly for faint magnitudes, background galaxy contamination also has to be taken into account. Most of the brighter galaxies are resolved and are discarded by our sharpness criterion; only a few fainter and very compact ones may cause confusion. From Tyson (1988) we expect a galaxy density of $10^6$ galaxies deg$^{-2}$ with $I < 21.5$ mag. This would give $\sim 227$ galaxies in our CCD field. Most of these galaxies are resolved and were eliminated on that basis.

3. COLOR-MAGNITUDE DIAGRAMS

Optical color-magnitude diagrams have been the primary tools to study the past history of star formation in dwarf irregular galaxies of the Local Group (e.g., Lee 1993; Lee, Freedman, & Madore 1993; Lee 1995; Tosi 1994; Tolstoy 1995; Marconi et al. 1995; Gallart et al. 1996; Aparicio et al. 1997a; Aparicio, Gallart, & Bertelli 1997b; Dohm-Palmer et al. 1997).

Comparable CCD photometry of smaller areas around NGC 3109 has been published: $BVRI$ photometry by Bresolin, Capaccioli, & Pietro (1993); $BVI$ photometry by Davidge (1993); $VR$ photometry of Greggio et al. (1993); and $VI$ photometry by Lee (1993). The present report, with a larger spatial coverage than these previous studies, gives photometry for a larger number of stars, making it possible for us to study in detail the stellar populations and their spatial distribution across the face of NGC 3109. Star-by-star comparisons with these papers are not possible, but we note that in the overlap regions, these published color-magnitude diagrams are very similar to ours. Infrared photometry of a small field in the central region of this galaxy is presented by Alonso et al. (1998). In addition, photographic photometry also exists in the literature: $BV$ photometry of Sandage & Carlson (1988) and Demers et al. (1985).

Figure 2 shows the $I$ versus $V - I$ and $V$ versus $V - I$ color-magnitude diagrams for a total of 15,000 stars in NGC 3109 that have centroids matched in $V$ and $I$ frames can accommodate a spatially varying point-spread function across the field. This is needed for our frames, which cover a large field. All stars in the $V$ and $I$ frames of NGC 3109 with more than 5 $\sigma$ above the background were located and their magnitudes measured by fitting a Moffat point-spread function. The resulting limiting magnitudes (5 $\sigma$) are $V = 25$ and $I = 24$.

As expected, the completeness is worse in the more crowded disk region of NGC 3109 ($C \sim 75\%$) than in the outer regions ($C \sim 90\%$). However, the present photometry is sufficiently deep that none of our results will depend on the completeness of the sample at the faintest magnitudes.

NGC 3109 is located at a relatively low Galactic latitude ($l = 262.1^\circ, b = -23.1^\circ$), making contamination by foreground stars an issue. The foreground stars from the Galactic halo and disk should appear as a plume of stars in the color-magnitude diagram with mean color $V - I = 0.7$ and a total color range covering about $0.4 \leq V - I \leq 1.5$. The contamination from these stars can be estimated from star counts in a strip along declination of $0.5 \times 8.9$ arcmin$^2$, offset by 10’ from the NGC 3109 major axis. The observed density of red stars in this region is less than 1 star arcmin$^{-2}$ with $I \leq 20$ and 4 stars arcmin$^{-2}$ with $20.5 \leq I \leq 22.5$. From the Galactic model of Ratnatunga & Bahcall (1985), we expect 0.7 foreground halo stars arcmin$^{-2}$ with $V \leq 21$ and $0 \leq V - I \leq 2$ in this low-latitude field.

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to better than 2.0 pixels (0.6) and satisfy stringent criteria of photometric quality ($\sigma \leq 0.5$, $\chi \leq 2$, sharpness $\geq -1$). The sharpness criterion eliminates galaxies, as well as some possible star clusters. The main features of these color-magnitude diagrams are a red tail of asymptotic giant branch (AGB) stars, a blue main sequence with mean color $V-I = -0.2$, and a red supergiant sequence with $I < 20.5$, reaching $I \approx 17.5$. Signs of a population of blue-loop stars are also seen, running in a sequence about 0.3 mag redder parallel to the main sequence. The AGB is very extended and can be traced to $V \approx 25$ and $V-I \approx 3.6$. Because of the low metallicity, this red color AGB may be dominated by carbon stars. Note that Galactic foreground stars have not been removed from this diagram.

The complexity of the stellar content of NGC 3109 is revealed by a consideration of the color-magnitude diagrams of different regions. Greggio et al. (1993) point out that the star formation history differs in different NGC 3109 disk fields. They find a metallicity $0.001 < Z < 0.01$ based on $VR$ photometry and conclude that star formation has been more or less continuous during the past Gyr. Figure 3 shows the $I$ versus $V-I$ color-magnitude diagram of NGC 3109 compared with the theoretical isochrones of Bertelli et al. (1994) for $Z = 0.001$ ($Z = 0.05 Z_\odot$) and $Z = 0.004$ ($Z = 0.2 Z_\odot$). The isochrones with ages log $t(\text{yr}) = 6.6, 7.0, 7.8, 8.0, 8.7, 9.0, 9.7$, and 10.0 have been shifted according to the distance and reddening listed in Table 1. Throughout this work, the isochrones are plotted...
as discrete points to illustrate the varying timescales of evolution. It is clear that stars of different ages are present in Figure 3, as well as different abundances. By comparison with the color-magnitude diagrams of similar galaxies (the LMC Shapley constellation III from Reid, Mould, & Thompson 1987; the SMC from Reid & Mould 1990; and WLM from Minniti & Zijlstra 1997) and with the theoretical isochrones, the stellar disk of NGC 3109 seems to have a mean metallicity between $Z \approx 0.001$ and 0.004.

### 3.1. Reddening

The reddening toward NGC 3109 is thought to be small. Based on the H\textsc{i} column density, Burstein & Heiles (1984) estimate the foreground reddening as $E(B-V) = 0.04$. Schlegel, Finkbeiner, & Davis (1998) obtain a similar value based on the COBE and IRAS maps at 100 $\mu$m. This is equivalent to $E(V-I) = 0.05$ and $A_I = 0.08$ using the reddening ratios $E(V-I) = 1.60E(B-V)$, $A_I = 1.49E(B-V)$ of Rieke & Lebofski (1985). Based on optical photometry, Lee (1993) adopts $E(B-V) = 0.04$ and Sandage & Carlson (1988) adopt $E(B-V) = 0.00$. Davidge estimates a total reddening (internal plus foreground) of $E(B-V) = 0.14$ for a field centered on the disk.

We can estimate the foreground reddening by using the sharp blue cutoff in the stellar distribution of the outer NGC 3109 fields (the outer regions are used to avoid internal disk reddening). This cutoff is interpreted as the locus of the main sequence, which is nearly vertical in the theoretical
color-magnitude diagrams, having an intrinsic color of $(V-I)_0 = -0.20$ (Bertelli et al. 1994). From the observed color we deduce $E(V-I) = 0.03$, consistent with the above value. Given these considerations, we adopt $E(V-I) = 0.05$ and $A_I = 0.08$ for NGC 3109.

We also investigate the presence of differential absorption across the face of NGC 3109. The $V-I$ color of the RGB and the blue main sequence on both sides (east and west) of NGC 3109 differ at the 0.10 mag level in the mean. The obscuration is less severe in the west arm. However, localized regions of higher obscuration are present inside the disk.

4. SPATIAL DISTRIBUTION OF STARS: THE HALO OF NGC 3109

Figure 4 shows the color-magnitude diagrams of an NGC 3109 halo field compared with an inner disk field. The differences are striking, although some effects must be taken into consideration. First, the disk regions are more crowded, with the completeness and photometric errors worse than in the outer regions. Second, we should also expect more differential reddening within the disk than in the halo fields. Third, the proportion of blue to red stars is much larger in the disk field than in the halo fields. However, there is no way in which crowding or reddening can transform the halo color-magnitude diagram (left) to make it look like that of the NGC 3109 disk (right). The population differences are significant. Figure 4 is similar to the color-magnitude diagrams of the central $3.8 \times 3.9$ arcmin$^2$ from Lee (1993), confirming that the population differences between disk and halo extend to a larger area and to both sides of the plane of this galaxy.

Figure 5 shows the same color-magnitude diagrams as Figure 4, with the isochrones of Bertelli et al. (1994) corresponding to a metallicity $Z = 0.001$ and ages $\log t(\text{yr}) = 6.6, 7.0, 7.8, 8.0, 8.7, 9.0, 9.7,$ and $10.0$. It is clear that a wide range of ages is present in the disk field, while the halo field contains only an old population. In order to emphasize this, Figure 6 shows the color-magnitude diagram of the NGC 3109 halo field, zooming in the RGB region, compared with a similar diagram of the halo field in the dwarf irregular galaxy WLM studied by Minniti & Zijlstra (1996, 1997). These diagrams are similar, with the NGC 3109 giant branch being slightly bluer, indicating a slightly more metal-poor population. Also, the FWHM of the NGC 3109 giant branch is similar to that of WLM, in spite of the fact that the giant stars in NGC 3109 are nearly a magnitude fainter than the giant stars in WLM of identical intrinsic luminosity.

The spatial distributions of the blue and red stars are quite different: Figure 7 shows the dependence of $V$ and $V-I$ as function of projected height above the NGC 3109

Fig. 4.—Color-magnitude diagrams of an NGC 3109 halo field (left) compared with an inner disk field (right) (see text)
plane $z$ in pixels. The radial extent of the present observations reaches 3 times as far (11.5') as the outer contours (3.5') of the surface photometry of Jobin & Carignan (1990), which corresponds to a surface brightness $\mu_B = 25.0$ mag arcsec$^{-2}$.

As shown in Figure 7, most of the stars detected in the $V$ frames down to $V = 24.5$ are concentrated in the disk of the galaxy, within $\sim 2.5'$ of the major axis (equivalent to $z = 1$ kpc projected distance from the plane of this galaxy). However, there is a low-density stellar component that extends as far as the edge of our field, out to $\sim 4.5'$ (or $z = 1.8$ kpc from the NGC 3109 plane). Hereafter, $z$ refers to the position measured in pixels along the direction of declination with respect to the plane of NGC 3109. The scale of 0.268 pixel$^{-1}$, 1' is equivalent to 0.4 kpc at the distance of $D = 1.33$ Mpc. This galaxy is reasonably edge-on, with an inclination $i = 80^\circ \pm 2^\circ$ (Jobin & Carignan 1990). Seeing the galaxy edge-on makes the study of the disk population more difficult, because of the absence of depth information: different regions (with various metallicities, star formation histories, and reddenings) overlap along the line of sight. At the same time, however, two advantages are gained from NGC 3109 being nearly edge-on: (1) the separation between a halo and a disk population is simplified, and (2) disk reddening does not affect the halo population.

The radial dependence of $V - I$ is also shown in Figure 7. The red stars with $1.0 < V - I < 1.7$ are less concentrated than the blue stars with $V - I \leq 0.5$, extending as far out as $z = 4.5'$. The appearance of this diagram can be understood in terms of a superposition of an extended old and metal-poor population, plus a younger, more concentrated component, where scatter may be introduced by possible differential reddening and by star crowding in the inner regions.

The H I extends almost as far out as the NGC 3109 halo, to $z = 3.5'$, as shown by the H I maps (Jobin & Carignan 1990). There is evidence of a warp in the disk of this galaxy from these H I maps. We will assume that the extended component belongs to the halo and not to a highly warped disk, because the populations are so different. If the old metal-poor component observed away from the projected plane of NGC 3109 were in the warp, the disk itself would have a strong population gradient.

We cannot measure the flattening of the NGC 3109 halo, because this halo clearly extends outside our fields in the east-west direction. Only an upper limit to the flattening can be derived, $b/a < 0.6$, given by the fact that the total disk extent is at least 11' (Demers et al. 1985). If the halo flattening were the same as the disk seen in projection ($b/a = 0.2$), this halo would have an extension of about 40' in the east-west direction. For a rounder halo, with
Fig. 6.—Color-magnitude diagram (best $X$, large radius) of the NGC 3109 halo field compared with the WLM halo field. Note the tightness of the RGB, with the tip located at $I = 21.7$. The NGC 3109 RGB is slightly bluer than that of WLM, indicating a lower metallicity (see text).

Fig. 7.—Magnitudes and colors of individual stars as function of projected height $z$ above the NGC 3109 disk. This figure shows that the young stars (i.e., the brightest stars in the top panel and the bluest stars in the bottom panel) are concentrated in the disk. A population of old stars (faint and red) is also clearly seen, extending at least out to the edges of the field.
b/a = 0.5, this extension would be about 16'. Note that the halos of the large spirals of the Local Group, the Milky Way, and M31, are also flattened. Larsen & Humphreys (1994) measured an axial ratio of 0.60 ± 0.05 for the Milky Way’s halo and Pritchet & van den Bergh (1994) measured an axial ratio of 0.55 ± 0.05 for the M31 halo. We also estimated that the halo of the dwarf irregular galaxy (dIr) WLM is significantly flattened, with an axial ratio of 0.6 ± 0.1 (Minniti & Zijlstra 1997).

5. THE LUMINOSITY FUNCTIONS

The LF was constructed by counting all of the stars present in the I frames (N = 17,500), regardless of whether they match the V images. The normalized counts of stars are plotted in Figure 8. This LF is dominated by the disk stars, which makes it similar to the LF of the WLM disk (see Minniti & Zijlstra 1997).

The LF for the NGC 3109 halo field is shown in Figure 9. Two distinct features can be seen in the LF: a sharp break at $I_{\text{RGBT}} = 21.7 ± 0.05$, due to the termination of the halo-like RGB, and another break at $I_{\text{AGBT}} = 20.5$, due to the termination of the AGB. Lee (1993) found the RGB break at $I_{\text{RGBT}} = 21.55 ± 0.1$, in reasonable agreement with our measurement. The signature for the RGB termination at $I_{\text{RGBT}} = 21.7 ± 0.05$ is clearer in the halo, and it is seen in the halo LFs as far away as $z = 4'$ from the NGC 3109 plane. This RGB tip allows us to measure an accurate distance to NGC 3109, as discussed in the next section.

We also construct a bolometric LF for the red giant and supergiant stars with $V - I > 0.7$ using

$$M_{\text{bol}} = I_0 + 0.30 + 0.38(V - I)_0 - 0.14(V - I)_0^2 - (m - M)_0$$

(Brewer, Richer, & Crabtree 1995). This bolometric LF is shown in Figure 10. The brightest red supergiants that are likely to be members of NGC 3109 reach $M_{\text{bol}} = -9.5$. Note that the brightest LMC supergiant is WOH G064 (IRAS 4553 – 6825), with $M_{\text{bol}} = -9.3$ (Chiosi & Maeder 1986; Zijlstra et al. 1996). There is also a break (increase in the number of stars) at $M_{\text{bol}} = -6$, corresponding to a numerous ~1 Gyr-old population like that in the LMC. Brighter stars, with $M_{\text{bol}} = -7.5$, can be either AGB stars temporarily experiencing hot bottom burning or supergiants.

6. FUNDAMENTAL PARAMETERS OF NGC 3109

6.1. Metal Abundance for the Halo Population

The metallicity of old and metal-poor populations, such as those found in the halo around NGC 3109, can be derived from the $V - I$ color of their RGB. Da Costa & Armandroff (1990) have shown that for halo globular clusters this parameter is very sensitive to metallicity. We use the recent calibration of the $V - I$ color versus abundances of Lee (1993). This calibration is based on the metallicity dependence of the $V - I$ color of the RGB 0.5 mag below the tip, at $M_I = -3.5$. Figures 3 and 4 show that $V - I = 1.35$ at $M_I = -3.5$ ($I = 22.2$) for the halo of NGC 3109, from which we derive $[\text{Fe/H}] = -1.8 ± 0.2$ using the calibration of Lee (1993). Using a similar approach, Lee (1993) measured $[\text{Fe/H}] = -1.6 ± 0.2$ and Davidge (1993) estimated $[\text{Fe/H}] < -1.6$, which is in excellent agreement with our result.

We use the color spread of the RGB at a fixed magnitude to study the range of metallicities in the stellar population.
of NGC 3109. The mean color of the RGB becomes redder as the metallicity increases. For example, the difference between the isochrones with \([\text{Fe/H}] = -2.0\) and \(-1.0\) is \(\Delta(V-I) = 0.30\) mag at \(M_I = -3.5\). We use the colors of the RGB at 0.5 mag below the RGB tip \((M_I = -3.5)\) because the photometric errors increase with the fainter magnitudes. The spread in the \(V-I\) color at \(I = 22.2\) is \(\Delta V-I = 0.30\), implying a metallicity range of \(\Delta[\text{Fe/H}] \approx 0.3\) dex. The photometric uncertainty at this magnitude level is \(\sigma_{V-I} = 0.05-0.07\), which does not affect this estimate of the metallicity spread.

In summary, the halo of NGC 3109 has \([\text{Fe/H}] = -1.8 \pm 0.2\) and the metallicity range is \(\Delta[\text{Fe/H}] \approx 0.3\) dex. The abundances are comparable to those of the dwarf irregular galaxy WLM (Minniti & Zijlstra 1997).

### 6.2. Distance

Lee et al. (1993) improved the method for obtaining accurate distances for distant galaxies from \(VI\) photometry of their brightest stars. They demonstrated that their method is perhaps as accurate as other primary distance indicators, such as RR Lyrae and Cepheid variables. The method is based on the fact that \(M_I = -4.0\) for the RGB tip of metal-poor stellar populations with \([\text{Fe/H}] < -1.0\).

The halo of NGC 3109 is very metal-poor, as discussed above, where we determined \([\text{Fe/H}] = -1.8 \pm 0.2\). Thus, we can apply the RGB tip to measure the distance of this galaxy. The RGB tip of the NGC 3109 halo is located at \(I = 21.7 \pm 0.05\) (Fig. 7). For \(A_I = 0.08\), the distance modulus to NGC 3109 is \((m-M)_0 = 25.62 \pm 0.1\), which translates to \(D = 1.33\) Mpc. Because we are using the halo stars on NGC 3109, this distance is not affected by internal extinction. The distance measured here is in excellent agreement with the recent determinations of Lee (1993) and Musella, Piotto, & Capaccioli (1997).

### 6.3. Ages

We can obtain a rough age estimate by measuring the magnitude difference between the tip of the RGB and the tip of the AGB, \(\Delta TT\) (Minniti & Zijlstra 1997). From the isochrones of Bertelli et al. (1994), there is a well-defined relationship between \(\Delta TT\) and age at any given metal abundance. The pure halo fields of NGC 3109 are characterized by a single mean abundance, which allows us to apply the method. For a metallicity of \(Z = 0.004\) to \(Z = 0.001\) (and \(Y = 0.23\)), the relationship between \(\Delta TT\) and age computed using the isochrones of Bertelli et al. (1994) gives an absolute age of \(t = 10^{10}\) yr for \(\Delta TT = 0.8-0.9\) mag.

This estimate is independent of reddening and of the distance to NGC 3109, and it agrees with the isochrone fits. However, the method is based on isochrones, which may be affected by systematics (e.g., uncertainties in mass loss, convection, opacities). An alternative way to reliably detect the presence of an old population independent of isochrones is to measure the jump in luminosity at the tip of the RGB. As shown by Renzini (1992), an increase of more than a factor of 4 in this break indicates the existence of old stars. This is indeed the case of NGC 3109, as becomes evident once we subtract the background contamination from the LF plotted in Figure 6.

These approximate age determinations, added to the presence of globular clusters in the NGC 3109 halo, argue in favor of an old age \((10^{10}\) yr) for the NGC 3109 halo. However, confirmation of the old age remains necessary, as would be possible with deep \(Hubble Space Telescope (HST)\) photometry of the horizontal branch.

### 7. OTHER POPULATION TRACERS

#### 7.1. Star Clusters in NGC 3109

The status of globular cluster research in galaxies of the Local Group is summarized by Olszewski (1994). NGC 3109 has 10 globular cluster candidates located outside the disk (Demers et al. 1985), none of which have been confirmed spectroscopically. These clusters are fainter than typical Milky Way globular clusters. Unfortunately, none of these clusters are located in the fields studied here. However, since NGC 3109 is similar to the Magellanic Clouds in many respects, some other clusters may be hiding in the inner crowded regions of this galaxy.

#### 7.2. Carbon Stars

Hodge (1969) found that NGC 3109 contains several H II regions. These H II regions are mostly minor since NGC 3109 is not very active in forming stars. Ten H II regions identified from \([O\text{~iii}]\) \(25007\) images have been studied recently by Richer & McCall (1992). Figure 11 shows the color-magnitude diagrams of the regions surrounding these H II regions. They were made using fields with 100 pixels on a side, or 0.2 arcmin\(^2\). The panels of Figure 11 give a panoramic view of the ages of the stars in the H II region fields. Using the brightest main-sequence (MS) stars, we can set limits on the ages of the youngest stars in these regions. Table 2 lists the positions of the shell centers in our images, the fields covered, the age limits derived from the blue MS stars and red blue-loop stars, and the total numbers of stars plotted in Figure 11. In all cases, there clearly are very young stars present in the fields of the H II regions. We note that there is unresolved background in these regions of the galaxy. We also see different blue edge colors for the MS stars, which is evidence of different amounts of obscuration. The ages measured for these regions are consistent with some more or less continuous star formation in the recent past, as discussed by Greggio et al. (1993).

Richer & McCall (1995) measure a low metallicity, \(12 + \log (\text{O/H}) = 8.06\), equivalent to about \(Z = 0.001\), similar to the SMC and WLM. Within the errors, this abundance is consistent with the stellar abundance derived here, suggesting a moderately low rate of star formation in the past. Since the gas reflects the cumulative process of enrichment through the life of a galaxy, in the absence of infall we are led to conclude that the past star formation activity was not substantial enough to raise this composition significantly. Thus, the metallicities of the disk stars inferred from the color-magnitude diagrams are in agreement with the gas compositions.

Shells and supershells have been found in NGC 3109 from H\(\alpha\) surveys (e.g., Hunter, Hawley, & Gallagher 1993), revealing a complex interstellar medium and active star formation. The panels of Figure 12 show the color-magnitude diagrams of the regions of supershells 3 and 4, and shells 2, 5, 6, 7, 8, 11, and 12. Hunter et al. (1993) pointed out that
not all of these shells are surrounding bright blue stars. We can quantify this statement using the deep $V/I$ photometry. The color-magnitude diagrams shown in Figure 12 cover fields with 100 pixels on a side (0.2 arcmin$^2$) centered in these shells. As with the H II regions, using the brightest MS stars we can set limits on the ages of the youngest stars in these regions. These age limits are also listed in Table 2, along with the central positions of the shells, the field covered, and the total number of stars plotted. We caution that all of the stars in these panels are shown projected along the line of sight and some of them may be foreground or background to the shells, although still within the NGC 3109 disk. Most of these shells surround groups of very young stars. However, it is clear that not all these regions contain very young stars, which would drive the gaseous material away. In particular, the color-magnitude diagrams of shells 6, 11, and 12 are dominated by old stars. Shells 11 and 12 are located above the plane of NGC 3109, explaining the smaller number of stars in their color-magnitude diagrams.

7.4. Planetary Nebulae

Richer & McCall (1992) found seven planetary nebulae (PNs) in NGC 3109 based on [O iii] λ5007 images. They used the luminosity distribution of the nebulae to estimate the distance to the galaxy, concluding that $(m - M)_0 = 25.96$. Even though this distance is greater than the present estimate, Richer & McCall’s quoted error bars of about 0.5 mag make this value consistent with our results as well.

During an NTT observing run in 1996 December, we obtained a 900 s exposure centered on NGC 3109 with the S II narrowband filter (9500 A). Because it is redder than [O iii] λ5007, this filter is well suited to find obscured planetary nebulae. Unfortunately, there is a shift of wavelength sensitivity with position in the detector that is not well mapped, and our search area may be smaller than the actual 9 x 9 arcmin$^2$ observed. In any case, we have not detected any other bright PNs in the central regions of NGC 3109.

7.5. Cepheid Variables

Sandage & Carlson (1988) discovered 29 Cepheids in NGC 3109 and used them to measure the distance of this galaxy. The most recent study by Musella et al. (1997) reports $BVRI$ photometry for 36 candidate Cepheids. They use the LMC Cepheid period-luminosity relation to obtain a relative distance modulus of $\Delta m = -7.10$ mag between the LMC and NGC 3109. This corresponds to
m - \( M_{M3109} \) = 25.67, for \( m - M_{LMC} \) = 18.50. This distance is in excellent agreement with our result. Our ongoing monitoring project (Zijlstra et al. 1996) will detect all the Cepheids in this galaxy down to \( I = 23 \).

7.6. The Gaseous Component: \( \text{H} \text{I} \) Observations

Dwarf irregulars are dominated by dark matter halos, their total \( M/L \) being larger than for normal spiral galaxies (Jobin \& Carignan 1990; Côté 1995). The most recent \( \text{H} \text{I} \) maps of NGC 3109 are given by Jobin \& Carignan (1990), who mapped the whole galaxy at high resolution and sensitivity. The \( \text{H} \text{I} \) emission is detected out to 3.5–4.0 from the NGC 3109 disk, almost as far as the stars in the halo component found here. Jobin \& Carignan (1990) also give a detailed \( \text{H} \text{I} \) rotation curve for NGC 3109 based on these observations. The amplitude of this curve is large for such a small galaxy (\( \sim 50 \text{ km s}^{-1} \)), implying a high \( M/L \). Indeed, NGC 3109 is taken to be a typical dwarf irregular galaxy with a sizable dark matter halo (Navarro, Frenck, \& White 1997).

8. DISCUSSION: FORMATION AND EVOLUTION OF NGC 3109

By analogy with other spirals of the Local Group, we define halo as an old and metal-poor population of stars distributed in a spheroid. Such a population would be kinematically hot, with small rotation and large velocity dispersion. More quantitatively, a halo of Population II stars is defined here as \( \geq 10^{10} \text{ yr old and metal-poor [Fe/H]} \leq -1 \) stars (see the reviews by Hodge 1989 and Mateo 1998).

Mould \& Kristian (1986) established the presence of Population II halos in M33 and M31 based on RGB morphology before there was kinematic information about these halos. Later confirmation that these halos were kinematically hot came, for example, from radial velocities of globular clusters (Schommer et al. 1992; Brodie \& Huchra 1991).

The present observations show that NGC 3109 has an old and metal-poor population of stars that is more extended than the younger, bluer stars located within the disk of the galaxy. While the evidence suggests that this population forms a halo such as the ones seen in Local Group spirals, this conclusion requires confirmation from kinematics, which can show if the population does not participate in the rotation of the disk. Useful targets for radial velocity measurements would be the candidate clusters of Demers et al. (1985) and individual giants in this galaxy.

All well-studied galaxies of the Local Group, regardless of type and luminosity, seem to have Population II stars. This conclusion is based on the presence of globular clusters, RR Lyrae variables, or blue horizontal branches and metal-poor giants (Hodge 1989; Da Costa 1994; Grebel 1998; Mateo 1998). In the case of NGC 3109, the only evidence for the presence of Population II stars was given by the presence of several candidate globular clusters. The present work strengthens the evidence for an old and metal-poor halo in this galaxy. Note that the presence of a halo population around dIr's may be common: Minniti \& Zijlstra (1996, 1997) and Aparicio et al. (1997a) have found such populations in the dIr’s LMC and Antlia, respectively.

As discussed in § 1, the existence of such halos would be very significant for cosmology, since, if the dark matter is baryonic, it may be related to dark matter halos (Alcock et al. 1997). A population of low-mass pregalactic stars would be essentially collisionless (Miralda-Escudé \& Rees 1997; Loeb 1997), populating the diffuse halos of galaxies such as NGC 3109. The degree to which the massive compact objects detected through microlensing are related to the old halos observed in dwarf irregulars like LMC and NGC 3109 is heavily dependent on the initial mass functions (see,
F. 12. $V$ vs. $V-I$ color-magnitude diagrams centered in the shells and supershells of NGC 3109 compared with theoretical isochrones of Bertelli et al. (1994) for $Z = 0.001$. The isochrones with ages $\log t(\text{yr}) = 6.6, 7.0, 7.8, 8.0, 8.7, 9.0, 9.7, \text{ and } 10.0$ have been shifted according to $(m-M)_0 = 25.62$ and $E(V-I) = 0.05$ measured in this work.

...e.g., Chabrier et al. 1996). Unfortunately, these galaxies are too distant to allow observations of their old main sequence. The only information available so far comes from evolved stars, and their initial mass functions remain unconstrained. The old main sequence is within reach for galaxies out to about 1 Mpc, using the Space Telescope Imaging Spectograph on HST (Gregg & Minniti 1997).

The existence of a Population II halo in dwarf irregular galaxies such as NGC 3109 and WLM is also important in the context of galaxy formation. NGC 3109 and WLM give examples of very small mass galaxies that have formed halos of their own. Because they have a small mass, merging of smaller subunits or strong interactions seems less likely than in the Milky Way, for example (particularly in the case of WLM). In our Galaxy, the formation of the halo may have occurred in part by accretion of smaller satellites, as predicted by the CDM clustering model (e.g., White 1996).

These two galaxies formed at the edge of the Local Group but on opposite sides. Indeed, Peebles (1995) finds that NGC 3109, like WLM, has turned around from the Hubble flow and is free-falling toward the Local Group center of mass. The recently discovered Antlia dwarf is the nearest known companion to NGC 3109, at a projected separation $\Delta r = 30 \text{ kpc}$ (Aparicio et al. 1997a). Their relative velocity is $\Delta V = 45 \text{ km s}^{-1}$ (Aparicio et al. 1997a), much smaller than the typical velocity differences of Local Group galaxies ($\Delta V = 400 \text{ km s}^{-1}$), suggesting that these galaxies may be associated. We speculate that at this relative velocity they may have suffered a close encounter within the last Gyr, triggering or sustaining star formation.

9. CONCLUSIONS

We have obtained deep $VI$ photometry of about 17,500 stars in the field of the dwarf irregular galaxy NGC 3109, located at the edge of the Local Group.

We study the structure of NGC 3109, in particular examining the spatial distribution of blue (young) and red (older) stars. The main result of this work is to establish the presence of an extended stellar halo down to very faint levels. The stars populating this halo are clearly different from the stars that make up the NGC 3109 disk: they are old and metal-poor (Fig. 3).

From the $VI$ color-magnitude diagram, we infer metallicities and ages for the stellar populations in the main body and in the halo of NGC 3109. The color-magnitude diagrams also allow us to confirm a low reddening for this galaxy, $E(B-V) = 0.04$.

We give an approximate determination of the age of the...
NGC 3109 halo, independent of the reddening and distance to this galaxy, concluding that it is very old [log (t/yr) ~ 10]. The age measurement depends on the metallicity, which is accurately determined from the color of the RGB and agrees with previous determinations in the main body of the galaxy (Richer & McCall 1995). This halo is also metal-poor, with [Fe/H] = −1.8 ± 0.2, which is characteristic of Population II stars.

We construct deep optical and bolometric LFs, obtaining an accurate distance for this galaxy of (m – M)0 = 25.62 ± 0.10 based on the RGB tip of the metal-poor stellar component. This value is in excellent agreement with recent distance determinations based on Cepheids (Musella et al. 1997).

The real significance of dIrr's as possible elements contributing to the formation of larger galaxies like our own has been overlooked, perhaps under the assumption that, like the LMC, they do not have Population II halos. However, we find that dIrr's can have halos. NGC 3109 represents another such case in addition to WLM (Minniti & Zijlstra 1996), where no spiral arms, nucleus, or bulge is present, but where a disk formed dissipatively within an old and metal-poor halo.

Measuring the kinematics of the NGC 3109 disk and halo components using radial velocities of individual giants is the necessary next step. This would be within the reach of current instrumentation: the ESO Very Large Telescope equipped with the FORS instrument would be ideally suited for getting sufficiently accurate radial velocities of large numbers of individual NGC 3109 giants. These observations would unambiguously determine whether the NGC 3109 halo is kinematically hotter (with smaller rotation and larger velocity dispersion) than the disk, as we would predict based on the present work.

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