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ULTRAVIOLET IMAGING TELESCOPE IMAGES: LIMITS ON RECENT STAR FORMATION IN HOLMBERG IX

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ABSTRACT

Ultraviolet Imaging Telescope near-UV and far-UV images of Holmberg IX show no OB associations. Relative fluxes measured for the galaxy as a whole in the UV and optical B and V bands are consistent with models in which $\sim$0.6–0.7 of the V flux is from an old population of age 10 Gyr, while the remainder is from stars of age 20–200 Myr, which also contribute 0.80 of the near-UV flux and 0.99 of the far-UV flux. Individual stars measured in B and V appear to be evolved stars of mass $\sim 12\ M_\odot$ and age $\sim$20 Myr belonging to the youngest population in the galaxy.

Subject headings: galaxies: individual (Holmberg IX) — ultraviolet: galaxies

1. INTRODUCTION

Holmberg IX (DDO 66, UGC 5336) is a faint dwarf irregular galaxy (dIm V) located east of M81 at $\alpha_{1950} = 9^h53^m28^s$ and $\delta_{1950} = +69°16'53''$. The study of Davidge & Jones (1989) suggests that the galaxy is undergoing episodes of star formation. They estimate an age of $\sim$50 Myr for the end of the most recent episode from the fit of the evolutionary track of a 7 $M_\odot$ star to the upper envelope of the distribution of stars evolving on the asymptotic giant branch (AGB) in their $V-I$ color-magnitude diagram (CMD).

Intermediate-epoch star formation is suggested for other dwarf irregulars as well. Of particular interest is the nearby Pegasus system, whose gas content and absolute magnitude are similar to those of Ho IX. Hoessel & Mould (1982) and Christian & Tully (1983) find this galaxy to be in approximately the same evolutionary state as Ho IX. Our current study including ultraviolet photometry is important for understanding the evolutionary history of this class of galaxies.

Unlike previous papers on Ho IX (e.g., Hopp & Schulte-Ladbeck 1987), which are concerned with determining the distance of the galaxy, we adopt the distance modulus of M81, which has been well established at $\sim$27.6 by CCD photometry of Cepheids (Freedman & Madore 1988). The evolutionary state and stellar population mix of the galaxy are studied with ultraviolet images obtained by UIT during the *Astro-1* mission and with ground-based B- and V-band CCD images. Ultraviolet imagery of galaxies is useful not only as a diagnostic of active star formation, where the emission is dominated by hot massive stars, but also in providing a useful constraint on recent star formation in regions dominated by older stars. This study of Ho IX is unique in that it is the first in which this type of galaxy is imaged in the ultraviolet.

In § 2 we present and describe the ultraviolet and visual images obtained. In § 3 we discuss the magnitudes obtained for Ho IX in the far-UV, near-UV, and B and V bands, and our population modeling procedure. The results are summarized in § 4.

2. UIT AND GROUND-BASED IMAGES

The Ultraviolet Imaging Telescope (UIT) instrument is described by Stecher et al. (1992), who include plots of the wavelength dependence of the sensitivity of the near-UV and far-UV bandpasses used in observing M81. The UV bandpasses are centered at 2490 and 1520 Å, respectively, with widths 1150 and 354 Å. Three exposures were obtained in each bandpass, with exposure times about 25, 128, and 640 s for each camera. The resolution of the images is $\sim 3''$. A description of the data reduction process, including digitization and subsequent processing which applies to all UIT images, is also given by Stecher et al. (1992). The calibration is determined using well-exposed *IUE* spectra of objects imaged by UIT during the *Astro-1* mission, and is accurate to about 10%. The magnitude m_{249} is related to the flux f_{249} by the relation $m_{249} = -2.5 \log f_{249} - 21.10$. A similar relation holds for m_{152} and f_{152}.

Figure 1*a* (Plate L5) is the near-UV 640 s $40' \times 40'$ exposure of M81 with Ho IX to the east. Figure 1*b* is a $3'.3 \times 3'.1$ subimage containing Ho IX from this same image. A comparison of the two galaxies in the near-UV shows that Ho IX does not contain prominent star formation regions like those seen in the spiral arms of M81, which were studied by Hill et al. (1992). One ultraviolet bright region is apparent in the southeast corner of Ho IX, but it is much fainter than the OB associations and H II regions seen in M81.

Hopp & Schulte-Ladbeck (1987) suggest that such regions

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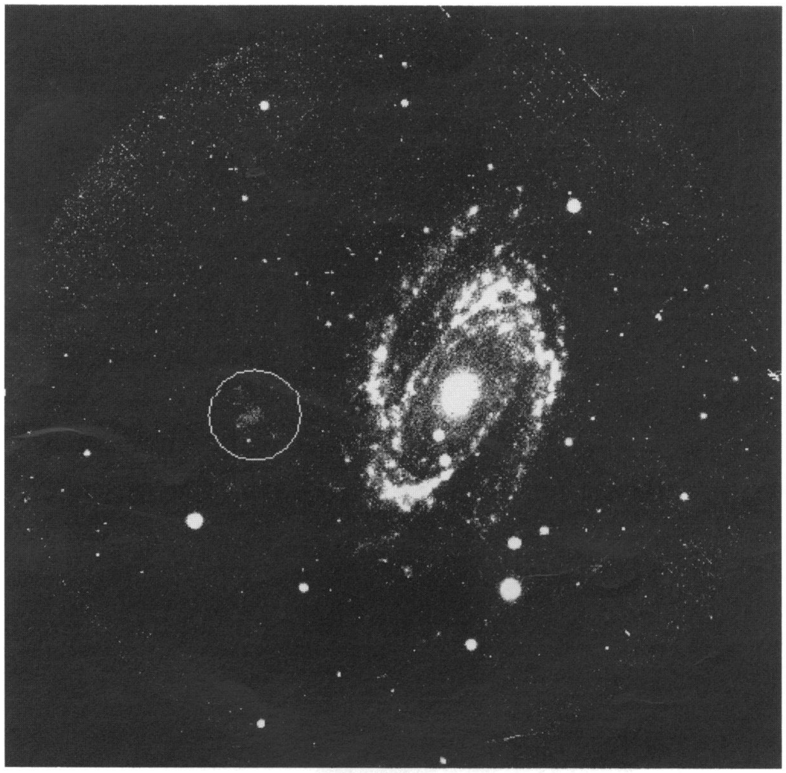

FIG. 1*a*

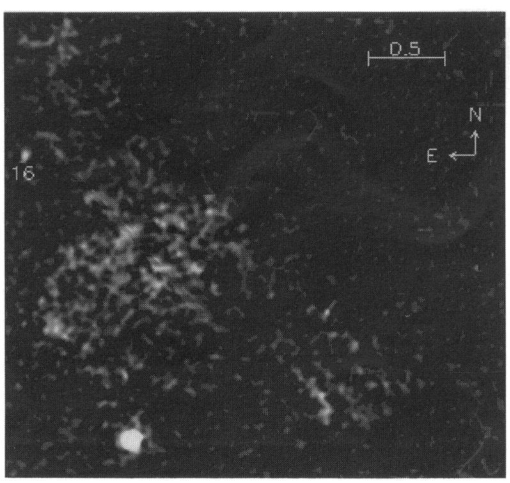

FIG. 1*b*

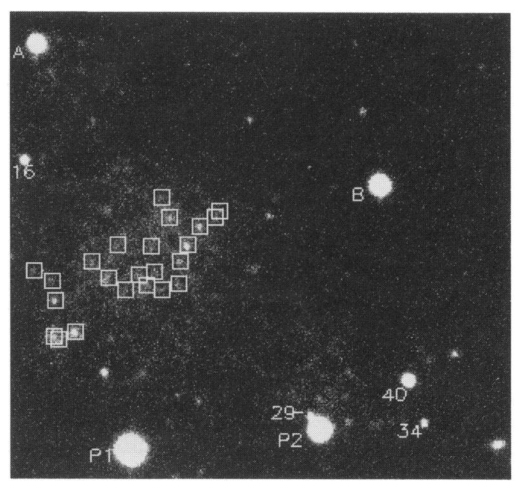

FIG. 1*c*

FIG. 1.—(*a*) 40′ × 40′ near-UV, 2490 Å image of M81, with Ho IX circled. North and east are as indicated in (*b*). (*b*) 3′.3 × 3′.1 section of near-UV 2490 Å image containing Ho IX, registered with (*c*). (*c*) 3′.3 × 3′.1 section of KPNO *V*-image containing Ho IX. Numbers are from Sandage (1984). Stars contained in boxes are found in the CMD of the galaxy.

HILL et al. (see 402, L45)

are OB associations. However, the region's colors, $B-V = 0.29$ and $m_{249} - V = 0.17$, are consistent with those of an A star. The limiting magnitude in the near-UV band of 20.5 rules out the presence of any main-sequence stars of type earlier than B0, since such stars would have $m_{249} \sim 20.3$ at the assumed distance of Ho IX. In making this estimate we assume $E(B-V) = 0.05$ (Hopp & Schulte-Ladbeck), and use the Galactic reddening curve (Savage & Mathis 1979). We use the ultraviolet spectrophotometric library of Fanelli et al. (1992) in estimating the UIT magnitudes as a function of spectral type. Only two individual stars are resolvable on the near-UV image, star 16 on Figure 1*b* and a foreground star (P1), using the designations of Sandage (1984). No individual stars are resolved on the far-UV image in Ho IX.

Wide-field CCD images of M81 including Ho IX were also obtained using the KPNO 0.9 m telescope with the STIS2k (2048 × 2048 pixel) CCD and standard *BVRI* and Hα filter set. Figure 1*c* shows a subimage extracted from the KPNO *V*-image, which matches the scale of the near-UV image in Figure 1*b*.

3. ANALYSIS

The modeling routine developed to date the star formation history of the galaxy requires magnitudes in the far-UV, near-UV, and *B* and *V* bands using identical apertures. An irregular aperture, 3′ (2.88 kpc) in diameter at its greatest width, is used. The shape of the aperture is determined by including as much of the galaxy as possible, while excluding the obvious foreground stars.

Photometry of the brightest stars in the *B* and *V* bands is performed using IDL implementations of DAOPHOT algorithms (Stetson 1987). Magnitude zero points are determined using Sandage (1984) photoelectric standards 9 and 13, which are within our wide-field CCD images, about 7′ from Ho IX. We distinguish between members of Ho IX and foreground stars using the study of the brightest members of M81 by Zickgraf & Humphreys (1991). The magnitude limits for the brightest blue and red members of Ho IX are then $V = 18.8$ and $V = 20.2$, respectively, corresponding to the magnitudes of the brightest blue and red confirmed members of M81. The brightest stars measured by Freedman (1985) have $M_V \sim -8$, corresponding to $V \sim 19.6$.

The field 5 model of Bahcall & Soneira (1981) predicts roughly one to five Galactic foreground stars at magnitudes brighter than these limits. Obvious foreground stars are Sandage's P1 and P2 (Sandage 1984) and the two extremely bright stars to the north (A and B on Fig. 1*c*). The brightest blue member is Sandage No. 16 at $V = 19.16$. Sandage No. 16 is the only star in the galaxy which can be resolved on our UV images. Its colors, $m_{249} - V = 0.05$ and $B-V = 0.45$, together with $M_V = -8.44$, indicate that it is similar in color to, but brighter than, a typical A–F supergiant by a factor ~5. This star has optical magnitudes similar to those of the luminous blue variables seen by Sandage (1984) in M81.

The bright red stars Sandage Nos. 29, 34, and 40 are foreground stars, based on the red star magnitude limit, with $V = 19.75$, 19.72, and 17.69, respectively, but they only contribute 5.2% of the total galaxy flux, well within the error bars. Besides these three, no other stars are included in the aperture which are detected at magnitudes brighter than the limits set for M81 membership. Therefore, the subsequent flux determinations for Ho IX reflect a representative sample of galaxy members.

The 640 s exposure in each camera is used to determine the ultraviolet magnitudes $m_{152} = 14.41 \pm 0.37$ and $m_{249} = 14.67 \pm 0.19$ for Ho IX in the aperture as described above. The ground-based optical magnitudes are $B = 14.69 \pm 0.08$ and $V = 14.21 \pm 0.06$ for the same region. The errors in the fluxes are from uncertainty in the estimation of sky values, plus an estimated 15% linearization, flat-fielding, and calibration error added in quadrature for the ultraviolet fluxes only. These optical magnitudes are slightly fainter than previous magnitude determinations of Ho IX which used larger, circular apertures centered on the galaxy.

The magnitudes are corrected for foreground reddening by using $E(B-V) = 0.05$ (Hopp & Schulte-Ladbeck 1987) and the Galactic reddening curve (Savage & Mathis 1979). The optical fluxes give a bluer $B-V$ color (0.43 after dereddening) than is consistent with the presence of only an old population, since $B-V = 0.71$ for the Buzzoni (1989) model for a population of age 10 Gyr used in the models discussed later. A comparison of the observed colors with the colors of model clusters with ages 0–200 Myr (Fig. 2) demonstrates that, although all three dereddened observed colors, $B-V = 0.43$, $m_{249} - V = 0.23$, and $m_{152} - V = -0.06$, are too blue to be consistent with an old population alone, they are redder than any of these models. The observed magnitudes in the four bands cannot be interpreted as a single stellar population of age 10 Gyr or an age in the range 0–200 Myr.

As noted previously, Davidge & Jones (1989) suggest the presence of populations of age ≥50 Myr from the upper envelope of the distribution of AGB stars in their $V-I$ CMD. We cannot confirm the presence of the stars of age 50 Myr through photometry on our ground images because they are fainter than our detection limit.

However, by combining a model population of stars of ages 50–200 Myr with a 10 Gyr population (Buzzoni 1989), we obtain a fit of the relative fluxes in the four bands to within the estimated error. The spectrum of the older population is obtained from the Buzzoni (1989) models of old stellar populations. A 10 Gyr, $z = 0.001$ model is integrated over our four bandpasses. The slope of the mass function is −2.35, the horizontal-branch type is B, and the mass-loss exponent is 0.3. The spectrum of the younger model population is computed using a synthesis program written by W. Landsman which returns the UV/optical spectrum of a population as a function of age, per unit mass. This program was used to compute the

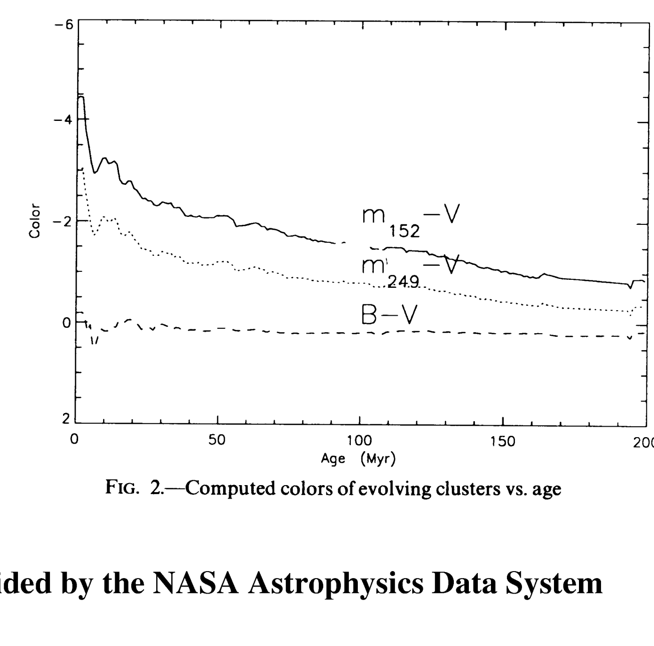

FIG. 2.—Computed colors of evolving clusters vs. age

model colors plotted in Figure 2. It employs the evolutionary models of Schaller et al. (1992) and the atmosphere models of Kurucz (1992).

A model spectrum is computed for an intermediate-age population, represented by a uniform star formation rate for ages 50–200 Myr with $\log(z/z_\odot) = -1.5$ and mass function slope -2.5, using atmospheres and evolution models appropriate for the assumed metallicity. The spectrum is integrated over our bandpasses and combined with the model fluxes representing the older population, both normalized to the V flux. The dashed line in Figure 3 shows the result of weighting the populations so that the older population contributes 0.64 of the V flux. Although the older population contributes 64% of the total galaxy flux in the V band, it contributes only 18% in the near-UV and 1% in the far-UV.

A (V, $B-V$) color-magnitude diagram of 24 of the brightest galaxy members is shown in Figure 4. Boxes mark the stars in the diagram on the V-image (Fig. 1*c*). Only stars from the main body of the galaxy are shown. Davidge & Jones (1989) estimated the age of the most recent epoch of star formation using a 7 $M_\odot$, $z = 0.001$ Bertelli stellar evolution model (Bertelli et al. 1986), represented by a dotted line on the CMD. The line actually marks the lower envelope for the brightest galaxy members. The 12 $M_\odot$ stellar evolution model of Schaller et al. (1992) best fits these stars, as illustrated by the dashed line on the diagram. These stars, of age ~20 Myr, appear to belong to a younger population than the AGB population studied by Davidge & Jones, and should also be accounted for in our population modeling.

The most recent episode of star formation, which includes these stars, can be modeled by the method described above by adding a constant star formation model for the age interval 20–49 Myr, with a lower rate of star formation. A combined model in which the old population contributes 0.705 of the V flux, the 50–200 Myr population contributes 0.235, and the 20–49 Myr population contributes 0.06 also agrees with the observed energy distribution within the estimated errors. Thus,

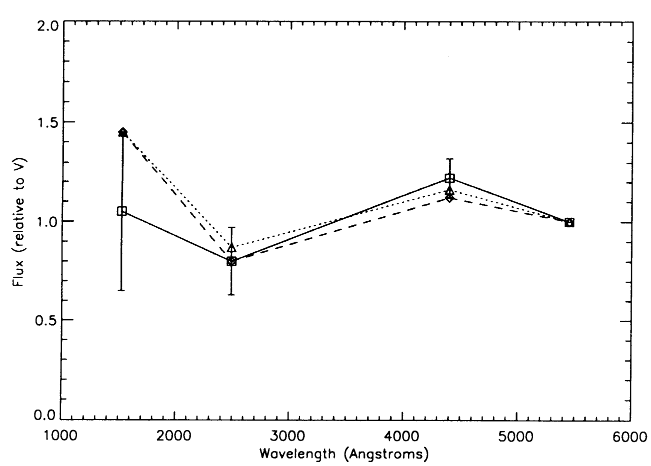

FIG. 3.—Observed fluxes in the far-UV, near-UV, and B and V bands, normalized to the V flux (*solid line*), plotted with the similarly normalized fluxes of two models: combined 10 Gyr and 50–200 Myr populations, where the old population contributes 0.64 of the V flux (*dashed line with diamonds*), and combined 10 Gyr, 50–200 Myr, and 20–49 Myr populations (*dotted line with triangles*), where the old population contributes 0.71 of the V flux, the intermediate population contributes 0.23, and the youngest population contributes 0.06.

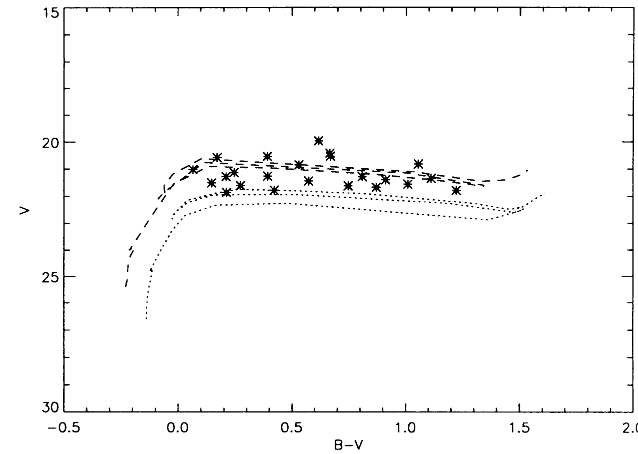

FIG. 4.—$B-V$ CMD of the brightest stars in Ho IX with the 7 $M_\odot$ Bertelli (*solid line*), and the 12 $M_\odot$ Schaller et al. (*dashed line*) stellar evolutionary tracks.

the observed UV and optical fluxes do not lead to a unique model for the stellar populations. The flux ratios for the three-component model are plotted as a dotted line with triangles in Figure 3.

The ultraviolet data confirm the fact that although Ho IX is not presently forming stars, it has undergone episodes of star formation within the last few hundred million years. It is consistent with the decrease in star formation at age 50 Myr suggested by Davidge & Jones (1989), while still accommodating the more recently formed stars which we detect in the optical bands. Hoessel & Mould (1982) find a similar situation in the Pegasus dwarf irregular galaxy from stellar photometry in the Gunn system. Although the age of the most recent star formation activity apparently differs slightly between these two galaxies, both seem to be currently in a quiescent state.

The Pegasus system has a low gas content, and we suspect the same is the case for Ho IX. H I radio maps (Rots & Shane 1975) provide no convincing evidence that Ho IX is located in a concentration of H I. It is in the general vicinity of a condensation in the stream of H I which connects M81 and M82, but there is no apparent H I centered on the galaxy itself (A. H. Rots, private communication).

The lack of current star formation activity could be associated with gas depletion, while the apparent onset of intermediate-epoch star formation ~200 Myr ago could have been stimulated by accretion. The age of the onset of intermediate-epoch star formation is the most uncertain parameter in the models. Hoessel & Mould (1982) suggest that hydrogen depletion has probably occurred in Pegasus because of isolation from possible sources of gas. However, Ho IX is certainly influenced by its proximity to M81. Christian & Tully (1983) compare Pegasus to another dwarf irregular system, LGS 3, located 20° from M31, which is also in an inactive state and appears to contain little H I.

4. SUMMARY

Ultraviolet images obtained during the 1990 *Astro-1* Spacelab mission reveal no regions of active star formation in Ho IX. Colors computed from the UV and optical images suggest that while most of the V flux is from a population formed early on (age ~10 Gyr), about 30% is from stars formed within the last

200 Myr. The younger populations contribute about 80% of the near-UV flux and about 99% of the far-UV flux.

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