GHOSTS IN THE ATTIC: MAPPING THE STELLAR CONTENT OF THE S0 GALAXY NGC 5102*†

T. J. Davidge
Herzberg Institute of Astrophysics, National Research Council of Canada, 5071 West Saanich Road, Victoria, BC V9E 2E7, Canada; tim.davidge@nrc.ca

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ABSTRACT

The spatial distribution of stars in the nearby S0 galaxy NGC 5102 is investigated using images obtained with WIRCam and MegaCam on the Canada–France–Hawaii Telescope. With the exception of gaps between detector elements, the entire galaxy is surveyed in r′ and i′, while the J and Ks data extend out to RGC ≈ 6 kpc, which corresponds to almost 7 disk scale lengths. A modest population of main-sequence stars with M_V ≲ −3.5 and ages ≈70 Myr are detected throughout the disk, with the majority located in the southern half of the galaxy. The stellar disk in the northern half of the galaxy is warped, following structure that is also seen in H_1. Objects with photometric properties that are consistent with those of bright asymptotic giant branch (AGB) stars are seen throughout the disk, and the ratio of C stars to bright M giants is consistent with an overall increase in the star formation rate within the past 1 Gyr. Star-forming activity during the interval 0.1–2 Gyr was more centrally concentrated than during the past ≈100 Myr. The structure of the disk changes near RGC ≈ 5 kpc (5.5 disk scale lengths), in the sense that the radial surface density profile defined by red supergiants (RSGs) and bright AGB stars levels off at larger radii. RSGs and bright AGB stars are traced out to a radius of 14 kpc (15.6 scale lengths) along the southern portion of the major axis, while a tentative detection is also made of bright AGB stars at a projected distance of ≈16 kpc along the southeast minor axis. A large clump of AGB stars that subtends ≈1 arcmin is identified to the west of the galaxy center. It is argued that this is the remnant of a companion galaxy that triggered past episodes of elevated star-forming activity.

Key words: galaxies: elliptical and lenticular, cD – galaxies: evolution – galaxies: individual (NGC 5102) – galaxies: stellar content

Online-only material: color figure

1. INTRODUCTION

The stellar contents of nearby galaxies constitute a fossil record that can be used to gain insight into the processes that shape galaxy evolution and define basic global properties, such as morphology. There are five galaxy groups within ≈4 Mpc (classically referred to as the Local, Sculptor, M81, Centaurus, and Maffei Groups), which in turn contain subsystems centered on the largest members (e.g., Karachentsev 2005). The brightest members of the nearest groups show a diverse range of properties, although a common feature shared by the most massive members of the Local, M81, and Centaurus groups is that they show signs of having experienced cosmologically recent interactions. This commonality underlines the important role that local environment and galaxy-galaxy interactions play in the evolution of even relatively commonplace galaxies.

Located at a distance of only 3.2 Mpc, the S0 galaxy NGC 5102 is a key laboratory for probing the evolution of gas-poor disks. There is only modest star-forming activity in NGC 5102 today, and this is restricted to the southeast quadrant of the disk, where H_1 regions are found (van den Bergh 1976; McMillan et al. 1994). Davidge (2008a) found small numbers of red supergiants (RSGs) and blue main-sequence (MS) stars in a field along the northwest minor axis, and estimated that the integrated star formation rate (SFR) during the past 10 million years was 0.02 M_☉ yr⁻¹. The moderately deep color–magnitude diagram (CMD) of the northern disk of NGC 5102 discussed by Karachentsev et al. (2002) shows that while there is a spray of blue objects, there is neither a well-defined bright MS nor an RSG sequence in this part of NGC 5102, again consistent with a low recent SFR.

There are indications that the specific SFR in NGC 5102 within the past few hundred Myr was much higher than it is today, at least in some parts of the galaxy. The deep Balmer absorption lines (Gallagher et al. 1975; Rocca-Volmerange & Guiderdoni 1987) and blue colors (van den Bergh 1976; Pritchet 1979; Bica 1988; Kraft et al. 2005) that are seen in the central regions of NGC 5102 are perhaps the most overt signatures that at least 10% (e.g., Serra & Trager 2007) of the central stellar mass formed during intermediate epochs. Applying spectral synthesis techniques to the ultraviolet–visible spectrum of the center of NGC 5102, Kraft et al. (2005) conclude that at least 50% of the central stellar mass in NGC 5102 formed within the past 3 Gyr.

There is also evidence of recent episodes of large-scale star formation in other parts of the galaxy. van den Bergh (1976) detected filamentary Hα emission, which McMillan et al. (1994) subsequently found to be part of a complex web of emission features, the dominant structure of which is a supershell. The size and expansion velocity of the supershell suggest an age of ≈10 Myr. Finally, the numbers of bright asymptotic giant branch (AGB) stars in the western portion of NGC 5102 suggests that ≈20% of the total stellar mass in this field may have formed during the past Gyr; assuming that the stellar content of this area is representative of the galaxy as a whole then the galaxy-wide...
SFR was at least 1.4 $M_\odot$ yr$^{-1}$ throughout much of the past Gyr (Davidge 2008a).

Elevated levels of star-forming activity are usually associated with interactions, and so it is puzzling that NGC 5102 has no obvious close companions. The distance and radial velocity of NGC 5102 are consistent with it being a companion of Cen A (Karachentsev et al. 2002), although it is located near the outer periphery of the Cen A satellite system. Indeed, NGC 5102 is relatively isolated when compared with other galaxies associated with Cen A and M83 (e.g., Figure 1 of Karachentsev et al. 2002).

While sampling relatively faint objects, the photometric observations discussed by Karachentsev et al. (2002) and Davidge (2008a) cover only a small fraction of NGC 5102, missing the areas near the H II regions where the richest concentrations of young stars should lurk. These data are also restricted to visible and red wavelengths, and so are biased against stars that may have their photometric properties affected by line blanketing, have very low effective temperatures, and/or are highly obscured. These observational deficiencies, coupled with the evidence that there was much more extensive star formation throughout NGC 5102 within the past $\approx$ Gyr, provide a clear motivation for conducting a detailed census of the bright stellar content throughout the galaxy.

In the present study, observations obtained with the MegaCam and WIRCam imagers on the 3.6 m Canada–France–Hawaii Telescope (CFHT) are used to survey the stellar content in and around NGC 5102. The data obtained with these instruments are complementary. The brightest NGC 5102 stars in the MegaCam observations are young MS stars and RSGs, while those in the WIRCam observations are highly evolved oxygen-rich and carbon-rich AGB stars. Observations of highly evolved cool stars at infrared wavelengths benefit from the enhanced contrast with respect to the comparatively blue body of unresolved stars in a galaxy, while observations of bright MS stars at visible wavelengths exploit the low number density of blue background galaxies in the magnitude range of interest, making bright MS stars potentially important probes of structure in areas of low stellar mass density (e.g., Davidge 2008b).

The paper is structured as follows. The observations and data reduction procedures are described in Section 2, while the CMDs obtained from these data are discussed in Section 3. The statistics of M giants and C stars in the WIRCam data are used to investigate the recent star-forming history of NGC 5102 in Section 4. The spatial distribution of stars spanning a range of ages and evolutionary states are examined in Section 5, while a summary and discussion of the results follows in Section 6.

2. OBSERVATIONS AND REDUCTIONS

2.1. MegaCam

NGC 5102 was observed with MegaCam (Boulade et al. 2003) during the night of 2008 January 16. The detector in MegaCam is a mosaic of 36 CCDs that covers a $1 \times 1$ deg$^2$ field with 0.185 arcsec pixel$^{-1}$. There is a 13 arcsec gap between most CCDs, and two 70 arcsec gaps that separate CCD banks. The nucleus of NGC 5102, where individual stars cannot be resolved, was centered on the detector mosaic, and thus fell in a gap between detectors.

Four 300 s exposures were recorded each in $r'$ and $i'$, and the raw images were reduced with the ELIXER pipeline. The ELIXER processing consisted of bias subtraction, the division by a flat-field frame, the subtraction of a fringe frame from the $i'$ images, and the insertion into the image header of photometric calibration information based on standard star observations that were made during the MegaCam run. To create final images, the ELIXER-processed data in each filter were aligned, median-combined, and trimmed to the area common to all frames. Stars in the final images have FWHM $\approx$ 1 arcsec.

2.2. WIRCam

NGC 5102 was observed with WIRCam (Puget et al. 2004) on the night of 2008 February 17. The detector in WIRCam is a mosaic of four $2048 \times 2048$ HgCdTe arrays, which together image $20 \times 20$ arcmin$^2$ with 0.3 arcsec pixel$^{-1}$. Gaps between the arrays have a width of $\approx$ 45 arcsec.

Twenty 45 s exposures were recorded in $J$, and eighty 20 s exposures were recorded in $K_s$. The disk of NGC 5102 extends over many arcmin$^2$, and this complicates efforts to construct the calibration frames that are needed to remove interference fringes and thermal emission signatures. While the calibration frames could be constructed from observations of a separate background field, time constraints ruled out this approach, and so it was decided to sacrifice the angular coverage of the final processed image to enable the construction of the required calibration frames. Images were recorded with NGC 5102 centered on each array of the mosaic in turn; this corresponds to a 10 arcmin offset between pointings. A four-point square dither pattern with 3 arcsec amplitude was also implemented at each offset position to further facilitate the suppression of stars, cosmic rays, and isolated bad pixels.

The raw WIRCam images were processed with the I1WI pipeline, which performed dark subtraction and the division by flat-field frames. Calibration images to remove interference fringes and thermal signatures were constructed by median-combining the unregistered flat-fielded images in each filter, and the results were subtracted from the flat-fielded data. The processed images were then aligned, median-combined, and trimmed to the region having a common exposure time. The region with the full exposure time covers a $10 \times 10$ arcmin area, and this is sufficient to sample much of the NGC 5102 disk. Stars in the final images have FWHM $\approx$ 0.9 arcsec.

3. THE CMDs

3.1. Photometric Measurements

The photometric measurements were made with the point-spread function (PSF) fitting program ALLSTAR (Stetson & Harris 1988), using source lists, PSFs, and preliminary brightnesses obtained from DAOPHOT (Stetson 1987) tasks. Between 50 and 100 stars were used to construct each PSF. The PSFs were constructed iteratively, with contaminating objects subtracted using progressively improved PSFs.

ALLSTAR computes an uncertainty, $\epsilon$, for each object that is based on the quality of the PSF fit, but does not account for systematic errors due to crowding or the tendency for the faintest stars to be located on positive noise fluctuations. $\epsilon$ was used to cull objects with large measurement errors from the photometric catalogs. Objects with $\epsilon \geq 0.3$, which tend to be near the faint limit of the data, were rejected. In addition, a plot of $\epsilon$ versus magnitude reveals a well-defined relation, and outlying objects from the dominant trend were deleted. Objects that depart from the dominant trend tend to be either obvious blends in the crowded central regions of NGC 5102, galaxies, or residual cosmetic defects.
Artificial star experiments were used to estimate completeness. The artificial stars were assigned $r' - i'$ and $J - K$ colors that follow the ridgeline of the AGB sequence in NGC 5102. The brightnesses of the artificial stars were measured using the same procedures employed for actual stars, including rejection based on $\epsilon$ (see above). As with actual stars, an artificial star was considered to be recovered only if it was detected in two filters, and so could be placed on either the $(i', r' - i')$ or $(K, J - K)$ CMDs.

The completeness fraction varies with position in NGC 5102. The 50% completeness fraction for stars with $R_{GC}$ between 3 and 4 kpc occurs near $i' = 24$, and is 0.5 mag fainter for the outer regions of NGC 5102. For comparison, the 50% completeness fraction occurs at $K \approx 20.5$ throughout most of the WIRCam image. Unlike the $i'$ data, the completeness fraction in $K$ is not as sensitive to location within the galaxy because of the comparatively high contrast between the brightest resolved stars in $K$ and the main body of unresolved stars. The artificial star experiments also indicate that many of the stars fainter than the 50% completeness limit in $i'$ and $K$ are probably blends.

3.2. $(i', r' - i')$ CMDs

The $(i', r' - i')$ CMDs of stars in various radial intervals are shown in Figure 1. The distance intervals given in each panel are galactocentric radii, $R_{GC}$, that assume a distance modulus of 27.5 and a disk inclination of 64.4 degrees (Davidge 2008a). The exponential disk scale length for NGC 5102 measured from 2MASS Large Galaxy Catalog (Jarrett et al. 2003) images is 0.9 kpc, and this is in excellent agreement with the scale length measured by Freeman (1970). While the CMDs do not go as deep as those presented by Karachentsev et al. (2002) and Davidge (2008a), they extend out to many disk scale lengths and sample stars over the entire galaxy.

Stars evolving on the AGB form a diffuse cloud of objects with $i' > 22$ and $r' - i'$ between 0.2 and 1.2 in the CMDs of objects with $R_{GC} < 7$ kpc. It becomes difficult to identify a concentration of AGB stars in the CMDs at larger $R_{GC}$ due to contamination from field stars and background galaxies. Still, a modest population of AGB stars is present at larger $R_{GC}$ (Section 5).

Davidge (2008a) detected blue MS stars and RSGs along the western arm of the NGC 5102 minor axis, and objects with $r' - i' < 0$ and $i' < 24$ are seen in the $R_{GC} < 5$ kpc CMDs. The blue objects tend to have intrinsic brightnesses that are consistent with them being stars, rather than star clusters. The apparent absence of bright, compact, blue clusters is worth noting, as one might expect these to be present if, as suggested by Davidge (2008a), NGC 5102 experienced a burst of star formation during the recent past. Very few objects are detected with $r' - i' < 0$ and $i' > 24$ at large $R_{GC}$. This is a consequence of the drop in the number of bright MS stars in NGC 5102 at these radii, coupled with the modest number of background galaxies with this color at these magnitudes (e.g., Davidge 2008b).

There is substantial contamination from background galaxies in the portion of the $(i', r' - i')$ CMD that contains RSGs, with the result that faint, unresolved galaxies introduce a significant source of uncertainty when probing the stellar content and
structure of the low surface brightness outer regions of NGC 5102. An RSG plume, which is a conspicuous feature in the CMDs of spiral galaxy disks (e.g., Davidge 2006, 2007), is not seen in the NGC 5102 CMDs. Still, the spatial distribution of objects with brightnesses and colors that are consistent with RSGs indicate that a modest population of these objects is present throughout the galaxy (Section 5). That bright MS stars and RSGs are found over a range of $R_{GC}$ indicates that there has been star formation throughout the NGC 5102 disk during the past few tens of Myr, although the small number of these objects indicates that the overall SFR during this time has been modest.

3.3. $(K, J - K)$ CMDs

The $(K, J - K)$ CMDs are shown in Figure 2. The WIRCam data sample the brightest AGB stars in NGC 5102, which have $K > 19$ and $J - K \approx 1.1$. The density of stars on the infrared CMDs is lower than on the visible/red CMDs because evolution at infrared wavelengths is spread over a larger range of magnitudes, and only the most evolved AGB stars are detected in the WIRCam images (Section 3.4). Many of the brightest stars in the central 1 kpc are recovered in the WIRCam data because of the comparatively (at least with respect to visible wavelengths) high contrast between these objects and the underlying body of fainter stars. The diminished density of stars on the infrared CMD notwithstanding, an obvious concentration of AGB stars can be traced out to $R_{GC} \approx 4$ kpc in Figure 2.

The CMDs of sources with $R_{GC} > 4$ kpc are dominated by objects that do not belong to NGC 5102. The plume of objects with $K < 18$ and $J - K \approx 0.7$ consists of foreground Galactic disk stars, while the more diffuse sequence with $K > 16$ and $J - K \approx 1.6$ is made up of background galaxies. The WIRCam observations of NGC 5102 are spatially complete out to $R_{GC} \approx 6$ kpc, and the decrease in the number density of objects in the CMDs with $R_{GC} > 6$ kpc reflects the progressively smaller areas on the sky that are sampled as one moves to larger $R_{GC}$.

3.4. Comparisons with Isochrones

Isochrones from Girardi et al. (2002, 2004) are compared with the CMDs of objects with $R_{GC}$ between 2 and 3 kpc in Figure 3. Davidge (2008a) found that the majority of RGB stars in the disk of NGC 5102 have $[M/H]$ between $-0.9$ and $-0.1$, and so only models with $Z \geq 0.019$ and $Z \geq 0.004$ are considered here. While Kraft et al. (2005) deduce a super-solar metallicity using spectral synthesis techniques, this is based on observations of the central regions of NGC 5102, and not the disk (Davidge 2008a).

The red stars sampled with these data are intrinsically bright and are highly evolved. Therefore, some aspects of the physics used to construct the portions of the isochrones that deal with the advanced stages of AGB evolution are worth noting. The isochrones used here include evolution during the thermally pulsing AGB (TP-AGB) phase. This evolution is tracked using
the models discussed in the appendix of Marigo & Girardi (2001), which include prescriptions for hot-bottom burning and the third dredge-up. There are uncertainties in key aspects of the model physics, such as the equation of state, the rates of mass loss among highly evolved stars, and the handling of convection and convective boundaries. Girardi et al. (2000) discuss the loss among highly evolved stars, and the handling of convection model physics, such as the equation of state, the rates of mass loss, and some of the assumptions for the portions of isochrones used here that cover evolution prior to the TP-AGB. The isochrones were transformed onto the observational plane by assuming oxygen-rich photospheres, and so do not match the properties of C stars. Finally, an observational complication of using highly evolved AGB stars as chronometers is that a large fraction are long period variables (LPVs). With photometric observations alone, it is evident from Figure 3 that stars may be located in the $(i', r' - i')$ CMD that Demers & Battinelli (2005) found to contain C stars. The Large Magellanic Cloud (LMC) CMD from Nikolaev & Weinberg (2000) contains a distinct C star plume is indicated in the lower panel. The blue stars on the $(i', r' - i')$ CMD, which are likely evolving on the MS, have log($t_{\text{yr}})\lesssim7.5$, depending on the assumed metallicity. The WIRCam CMD contains stars with log($t_{\text{yr}})\gtrsim9.0$.

![Figure 3](image_url)

**Figure 3.** Isochrones from Girardi et al. (2002, top panel) and Girardi et al. (2004, lower panel) are compared with the CMDs of stars with $R_{\text{GC}}$ between 2 and 3 kpc. Isochrones with log($t_{\text{yr}}) = 7.5, 8.0, 8.5, 9.0, 9.5,$ and $10.0$ are shown, although the last three sequences are too faint to appear on the $(i', r' - i')$ CMD. The region of the M31 $(i', r' - i')$ CMD that Demers & Battinelli (2005) found to contain C stars is indicated in the upper panels, while the region of the LMC $(K, J - K)$ CMD from Nikolaev & Weinberg (2000) that contains a distinct C star plume is indicated in the lower panel. The blue stars on the $(i', r' - i')$ CMD, which are likely evolving on the MS, have log($t_{\text{yr}})\lesssim7.5$, depending on the assumed metallicity. The WIRCam CMD contains stars with log($t_{\text{yr}})\gtrsim9.0$.

The MS turnoff is consistent with log($t_{\text{yr}})\lesssim7.5$, indicating that star formation occurred during the past few tens of Myr at intermediate radii in NGC 5102. As for more evolved stars, the age–metallicity degeneracy confounds efforts to determine ages for these objects from photometric data alone, and the ages estimated for AGB stars from the $Z = 0.004$ models are $0.2–0.3$ dex older than those from the $Z = 0.019$ models.

C stars are important probes of stellar content because they have conspicuous photometric properties, and contribute significantly to the light output from simple stellar systems with ages between roughly 1 Gyr (Persson et al. 1983) and 3 Gyr (Cole & Weinberg 2002; Feast et al. 2006). Demers & Battinelli (2005) investigated the C star content in the outer regions of M31, with the majority of the candidate C stars identified on the basis of their $g' r' i'$ spectral energy distributions. The area of the $(i', r' - i')$ CMD that Demers & Battinelli (2005) found to contain C stars is indicated in the upper panels of Figure 3. The area containing oxygen-rich and carbon-rich AGB stars overlaps on the $(i', r' - i')$ CMD, and so C stars cannot be identified from the $(i', r' - i')$ CMD alone. It is evident from Figure 3 that some C stars may be located in the $(i', r' - i')$ CMDs with log($t_{\text{yr}})\lesssim9.0$. Still, there are stars near the red edge of the isochrones with $M_K\gtrsim-8$ that may have ages approaching 10 Gyr, although at least some of these are probably warm C stars (see below).

The red envelope of the isochrones in Figure 3 occurs near $J - K = 1.25$ ($Z = 0.004$) and $J - K = 1.3$ ($Z = 0.019$), due to the assumption of oxygen-dominated photospheres. In fact, there are objects in the $(K, J - K)$ CMDs with $J - K\gtrsim1.3$, and some of these are probably C stars. The Large Magellanic Cloud (LMC) $(K, J - K)$ CMD constructed by Nikolaev & Weinberg (2000) from Two Micron All Sky Survey data contains a prominent C star sequence, and the region of the LMC CMD
that contains C stars is indicated in the lower row of Figure 3. Of course, some of the red objects in the NGC 5102 CMDs are undoubtedly compact background galaxies, the majority of which will have $J − K > 1.0$. Still, in Section 5 it is shown that the spatial distribution of the objects with $J − K ≥ 1.3$ cluster around the main body of NGC 5102, as expected if a large fraction are C stars.

### 4. M GIANTS AND C STARS AS PROBES OF THE RECENT STAR-FORMING HISTORY OF NGC 5102

#### 4.1. A Constant SFR Model

The numbers of C stars and bright M giants in NGC 5102 can be used to gain insight into its evolution during the past few Gyr. For a given star-forming history, the ratio of C stars to M giants on the TP-AGB can be calculated using the fuel consumption theorem (Renzini & Buzzoni 1986), and these predictions can be compared with the observed ratio. For the current work, a model in which the SFR in the disk of NGC 5102 has been constant with time, since forming 10 Gyr in the past, is considered. There is evidence that the SFR in NGC 5102 has departed significantly from the time-averaged mean SFR during the past $≈ 1$ Gyr (Daveide 2008a; Kraft et al. 2005), but the goal of the present effort is not to reproduce the observed statistics in NGC 5102. Rather, a constant SFR model simply provides a convenient benchmark for gauging the relative behavior of the SFR with respect to time when comparisons are made with observations.

The relative contributions that stars evolving on the TP-AGB make to the total luminosity of a stellar system were computed using evolutionary fluxes and fuel consumption values from Maraston (2005). The fuel consumption fractions for C stars with $Z_{⊙}/2$ from Figure 12 of Maraston (2005), which was calibrated from C star counts in Magellanic Cloud star clusters, were also adopted. This has an important implication for C star statistics, since these fuel consumption values imply that all TP-AGB stars with ages between $\log(t_{\text{yr}}) = 9.0$ and 9.3 are C stars (i.e., 100% of the fuel consumed during TP-AGB evolution is done so while the star has a C-rich atmosphere).

Isochrones with ages $\log(t_{\text{yr}}) = 10$ pass through the $(K, J − K)$ CMD (Section 3.4), and the numbers of old AGB stars in the data can be estimated using the fuel consumption theorem. Due to the progressive decline of the evolutionary flux with increasing age, coupled with the decline in the amount of fuel consumed by stars with $M \leq 2.5 M_{⊙}$ during TP-AGB evolution, then TP-AGB stars with ages in excess of 2 Gyr contribute only modestly ($< 10\%$) to the total number of oxygen-rich TP-AGB stars in the constant SFR model given. The evidence for elevated levels of star formation during intermediate epochs then it is likely that the majority of bright AGB stars in the WIRCam data formed within the past $≈ 2$ Gyr.

Using the assumptions described above then the total number of C stars and luminous M giants can be estimated if the total stellar mass of the NGC 5102 disk is known. The total brightness of NGC 5102 is $K = 6.9$ (Jarrett et al. 2003), so that $M_{K} = −20.6$. Assuming that the luminosity-weighted age of NGC 5102 falls between 0.5 and 3 Gyr, which is the range of dates that Davidide (2008a) and Kraft et al. (2005) suggest correspond to significant recent star formation activity, then $M/L_{K} ≈ 0.2−0.5$ (Mouchine & Lançon 2003), and so the total stellar mass of NGC 5102 is $0.7−1.8 \times 10^{10} M_{⊙}$. The surface brightness profile of Jarrett et al. (2003) suggests that roughly two-thirds of the $K$ light originates from the central portion of the galaxy that deviates from an exponential light profile, and so the disk mass is $2.5−6.2 \times 10^{10} M_{⊙}$. Adopting the upper and lower luminosity limits for TP-AGB evolution from Mouchine & Lançon (2002) and a Salpeter initial mass function for the MS component, then the constant SFR model predicts $1800−4400$ M giants experiencing TP-AGB evolution, and $4300−10,800$ C stars.

Given galaxy-to-galaxy variations in star-forming history and metallicity, one might not expect that the number of C stars predicted from the constant SFR model would agree with what is seen in other galaxies. It is thus interesting that the number of C stars predicted from the model, in which 10% of the total stellar mass formed between 1 and 2 Gyr in the past, is roughly consistent with C star counts in other galaxies after adjusting for differences in mass. For example, the LMC, which has a total stellar mass $≈ 10^{9} M_{⊙}$, contains $10^{4}$ C stars (Nikolaev & Weinberg 2000), so $≈ 2500−6200$ C stars would be predicted in a galaxy with the same star-forming history as the LMC, but a mass comparable to the disk of NGC 5102. Demers et al. (2003) find 413 C stars in NGC 3109, and the number of C stars predicted for a galaxy with the same $M_{K}$ as NGC 5102 from these data is $≈ 7400$. Finally, the number of C stars predicted from the Letarte et al. (2002) survey of NGC 6822 after scaling to the mass of NGC 5102 is $≈ 10^{4}$.

#### 4.2. Comparing the Predictions with Observations

C stars and M giants that are evolving on the TP-AGB can be identified based on their location on the $(K, J − K)$ CMD. For C stars, the number of objects throughout the disk of NGC 5102 in the region indicated in Figure 3 has been counted. The blue edge of the C star sequence in Figure 3 is $J − K = 1.5$. However, there is some uncertainty in defining the blue edge of the C star sequence, and so counts were also made for objects with a blue edge at $J − K = 1.3$ and having the same $K$ magnitude boundaries as the C star region in Figure 3. The final C star count is the mean of the counts with the two $J − K$ cutoffs.

As for the region of the $(K, J − K)$ CMD that contains M giants on the TP-AGB, the Girardi et al. (2002) isochrones indicate that the onset of the TP-AGB phase of evolution occurs near $M_{K} ≈ −7.0 \pm 0.5$ for intermediate-age stars, while the AGB-tip peaks at $M_{K} = -9.5$. The isochrones also predict that M giants on the AGB have $J−K$ between 0.9 and 1.3. Thus, the number of sources with $M_{K}$ between $−7 \pm 0.5$ and $−9.5$ and between $J−K = 0.9$ and 1.3 have been counted; the mean of the counts with the lower $M_{K}$ set at $−7.5$, $−7.0$, and $−6.5$ is adopted as the number of TP-AGB M giants in NGC 5102.

Applying the methodology described above, and correcting for contamination from background galaxies using observations of a control field along the minor axis of NGC 5102 (the number of contaminating objects is modest when compared with stars in NGC 5102) then there are $1260 \pm 410$ M giants and $550 \pm 180$ C stars in the disk of NGC 5102. The uncertainties are dominated by the dispersion in counts arising from the different photometric selection criteria described in the previous paragraphs.

The number of M giants agree with the range predicted in Section 4.1, and broadening the color boundaries for M giants on the CMD by $± 0.1$ mag increases the number of these stars by 10%–20%, further improving the agreement with the constant SFR predictions. In contrast, the number of C stars is significantly lower than predicted by the constant SFR model. Highly evolved AGB stars may be obscured by circumstellar dust, and this might decrease the numbers of C stars. However, it can be anticipated that this will be a factor only for the stars
that are nearing the end of their TP-AGB evolution, and it is unlikely that correcting for such stars will boost the numbers of C stars substantially. Taken at their face value, the numbers of M giants and C stars in the \((K, J - K)\) CMD suggest that \(\approx 10\%\) of the total stellar mass in the disk formed within the past 1 Gyr, but that \(<20\%\) of the total stellar mass formed within the past 2 Gyr. The mean SFR in NGC 5102 during the past 1 Gyr is then \(\approx 1 M_{\odot} \text{ yr}^{-1}\), whereas Davidge (2008b) estimated an SFR of at least \(1.4 M_{\odot} \text{ yr}^{-1}\) based on the modeling of the bolometric luminosity function of AGB stars along the minor axis of NGC 5102. Given the (substantial) uncertainties in computing the mass of NGC 5102 from photometric data, the estimated SFRs are not significantly different.

While there are considerable uncertainties in the computation of the numbers of M giants and C stars, such as determining the mass of the NGC 5102 disk, the ratio of C stars to M giants (C/M) should yield a more robust means of probing recent star formation. The counts from the CMDs indicate that C/M = 0.4 ± 0.2, which is significantly smaller than the ratio predicted from the constant SFR model, which is C/M = 2.4. The measured C/M ratio is consistent with a recent marked increase in the SFR of NGC 5102 during the past \(\approx 1\) Gyr, which produced a high number of bright M giants when compared with the C stars that formed 1–2 Gyr in the past. However, the reader is cautioned that a lower than expected C/M ratio could result from other factors. For example, a C/M ratio that is lower than the model prediction could occur if the dominant population in NGC 5102 is either younger than \(\approx 0.2\) Gyr or older than \(\approx 2–3\) Gyr. Such ages for the dominant population are in conflict with the large number of intrinsically bright AGB stars that are seen throughout the disk of NGC 5102 (e.g., Davidge 2008a), and the evidence of elevated SFRs in other parts of the galaxy a few tenths of a Gyr in the past (e.g., Kraft et al. 2005).

The C/M ratio also depends on metallicity. As discussed by Maraston (2005), the fraction of fuel that is consumed during TP-AGB evolution while a star has a C-rich atmosphere scales with metallicity, as a metal-rich star must dredge up more C in order to bind O in CO than a metal-poor star. Kraft et al. (2005) conclude that the central regions of NGC 5102 have a super-solar metallicity, and so a C star survey of this part of the galaxy should find a C/M ratio that is lower than in a comparatively metal-poor environment that had the same recent star-forming history. This being said, it is unlikely that metallicity plays a major role in the low C/M ratio in the disk of NGC 5102. The metallicity measured by Kraft et al. (2005) is based on the central regions of the galaxy, and the colors of the RGB sequence in the disk measured by Davidge (2008a) are indicative of a sub-solar metallicity. In fact, the peak metallicity among RGB stars is [M/H] \(\approx -0.6\) (Davidge 2008a), which is lower than the metallicity used to compute the numbers of C stars and M giants in Section 4.1. The adoption of a lower metallicity in the calculations will result in a higher predicted C/M ratio, increasing the difference with respect to the observed ratio.

5. THE SPATIAL DISTRIBUTION OF STARS

5.1. Mapping the Spatial Distributions of Stellar Types in NGC 5102

Stars with ages from \(\approx 10\) Myr to at least a few Gyr are detected in the MegaCam and WIRCam images, and these data can be used to investigate the spatial distribution of star-forming activity with respect to time in NGC 5102. A caveat is that the ability to resolve stars that formed over a given age range drops as progressively older stars are considered, and isolating sites in a galaxy that formed stars over narrow age ranges becomes problematic. Stars of different ages and evolutionary stages were identified based on their locations in CMDs, as indicated in Figure 4. The bright MS stars and RSGs that formed during the past few hundred Myr are identified from the MegaCam data, while AGB stars that formed within the past few Gyr are identified from the WIRCam data. The region of the MegaCam CMD that contains RSGs has been divided into three groups, the brightest of which contains stars with ages \(<30\) Myr, whereas the faintest samples stars with ages in excess of 100 Myr.

The various stellar types have distinctly different spatial distributions, and this is demonstrated in Figure 5. While there are only a modest number of objects in each group, it can be seen that MS stars and BRSGs occur in largest numbers in the southwestern half of the disk, which is the area of the galaxy that also contains \(\text{H} \alpha\) regions. In contrast, the IRSGs and FRSG/BAGBs, where “BAGB” refers to “Bright AGB” stars, are more evenly distributed across NGC 5102. The uniform distribution of these stars is likely a consequence of their ages. With ages that exceed many tens of Myr, these stars have probably obtained random velocities through interactions with molecular clouds that have allowed them to diffuse away from their places of birth, thereby blurring any structure in their original distribution.

The AGB stars with oxygen-rich (OAGB stars) and carbon-rich (CAGB stars) atmospheres that were identified from the WIRCam images define a more compact distribution than the MegaCam-based samples. Given that these stars have ages of a few hundred Myr to a few Gyr, then this suggests that star formation at this epoch was more centrally concentrated than during the past few hundred Myr. It is thus interesting that, in contrast to the spatial distribution of objects identified from the MegaCam data, the OAGB stars are not uniformly distributed. An arm of OAGB sources extends to the northeast of the galaxy along the major axis, and this same feature is seen among CAGB stars. A corresponding feature is not seen to the southwest of the galaxy.

There is a clear concentration of OAGB stars to the west of the galaxy center. Although the small numbers of CAGB stars makes the identification of an obvious concentration amongst these stars more difficult, the distribution of CAGB stars is clearly asymmetric along the east–west axis, in the sense that CAGB stars extend \(\approx 2\) kpc to the west of the galaxy center, but only \(\approx 1\) kpc to the east. A corresponding structure is not evident in the FRSG/BAGB counts as most of the area containing the OAGB concentration falls in a gap between CCDs.

The concentration of AGB stars coincides roughly with the center of a loop of [O II] emission discovered by McMillan et al. (1994), for which they estimated an age of \(\sim 10\) Myr based on its size and expansion velocity. This might suggest that the AGB concentration was also a site of very recent star formation. However, while Davidge (2008) found MS stars to the west of the galaxy center, these tend to be fainter, and hence older, than the MS stars in the southern portions of NGC 5102. In fact, the distribution of stars in Figure 5 indicates that the area near the AGB cluster does not contain an anomalous number of bright MS stars, with the caveat that the center of the AGB cluster falls in a gap between CCDs. The absence of \(\text{H} \alpha\) regions in this part of NGC 5102, based on the entries in Table 4 of McMillan et al. (1994), further argues that it is not a site of star formation at the present day.
Figure 4. Photometric boundaries of the stellar groups that are used to investigate the distribution of stars in NGC 5102. The CMDs are those of sources with $R_{GC}$ between 2 and 3 kpc. Isochrones with $Z = 0.004$ from Girardi et al. (2002, 2004) are shown, and these have ages $\log(t_{\odot}) = 7.5, 8.0, 8.5, 9.0, 9.5$, and 10.0. The last three sequences are too faint to appear on the $(i', r' - i')$ CMD. Three groups of RSGs are identified on the $(i', r' - i')$ CMD: bright RSGs (BRSGs), consisting of stars with ages $\leq 30$ Myr, intermediate brightness RSGs (IRSGs), consisting of stars with ages between 30 and 100 Myr, and faint RSGs and bright AGB stars (FRSG/BAGBs), consisting of stars older than 100 Myr. AGB stars with oxygen (OAGB) and carbon (CAGB) dominated atmospheres are identified on the $(K, J - K)$ CMD. The bright and faint end of the CAGB box is based on the location of C stars on the LMC CMD discussed by Nikolaev & Weinberg (2000).

Figure 5. Spatial distributions of the stellar types defined in Figure 4. The center of NGC 5102 is marked with a cross, and each panel is $10 \times 10$ arcmin in size, with north at the top, and east to the left. MS and BRSG stars occur in largest numbers in the southwestern half of the disk, while the IRSG and FRSG/BAGB stars are more uniformly distributed. The dearth of stars near the center of NGC 5102 in the FRSG/BAGB distribution is the result of crowding and gaps between CCDs. A concentration of OAGB stars is seen immediately to the west of the galaxy center, while the spatial extent of CAGB stars along the east–west axis is asymmetric, with CAGB stars extending to larger distances to the west than to the east of the center of NGC 5102. In the text, it is argued that the concentration of OAGB stars is a companion galaxy that is projected against the disk of NGC 5102.
The stellar content of the AGB concentration to the right of the galaxy nucleus in Figure 5 appears to differ from that of the NGC 5102 disk, and this is demonstrated in Figure 6. The $K(J-K)$ CMDs of 1.6 arcmin$^2$ regions that are centered 50 arcsec to the east and west of the nucleus of NGC 5102; the AGB Cluster field is centered on the concentration of AGB stars that is seen in Figure 5. Lower panel: $J-K$ color distributions of stars with $K$ between 19 and 20 in both fields, where $n_{J-K}$ is the number of stars per 0.2 mag $J-K$ bin, normalized to the total number of stars with $J-K$ between 0.0 and 2.5. The number of stars that were used to construct each distribution are indicated. While both distributions peak near $J-K = 1.1$, the AGB Cluster distribution appears to be skewed by $\approx$0.2 mag to bluer $J-K$ colors. A Kolmogorov–Smirnov test indicates that the two distributions differ at the 91% significance level. A 0.2 mag difference in $J-K$ corresponds to a difference in ages of at least 0.5 dex among stellar systems with the same metallicity.

The stellar content of the AGB concentration to the right of the galaxy nucleus in Figure 5 appears to differ from that of the NGC 5102 disk, and this is demonstrated in Figure 6. The $K(J-K)$ CMDs of 1.6 arcmin$^2$ regions that are centered 50 arcsec to the west (“AGB Cluster”) and east (“Disk East”) of the galaxy nucleus are compared in the upper row of Figure 6. There are almost twice as many stars in the AGB Cluster area, and so the CMD of this feature is more richly populated than that of the eastern disk. The CMD of the Disk East field also appears to be broader than that of the AGB Cluster region. Indeed, the Disk East field contains six stars with $J-K > 2$, whereas there is only one such star in the AGB Cluster CMD. The more compact CMD morphology of the AGB Cluster is consistent with this area being dominated by stars that have a narrower range in age and metallicity than occurs in the main body of the disk.

The $J-K$ color distributions of stars with $K$ between 19 and 20 (i.e., with $M_K$ between $-7.5$ and $-8.5$) in the Disk East and AGB Cluster fields are compared in the lower row of Figure 6. Both distributions peak near $J-K = 1.1$. However, the color distribution of the AGB Cluster appears to be skewed by $\approx$0.2 mag to smaller $J-K$ colors than that of the Disk East field. A Kolmogorov–Smirnov test indicates that the color distributions differ at the 91% significance level, and so the evidence for a difference in stellar content should be considered to be suggestive, rather than conclusive. Deeper photometric studies will provide greater statistical robustness when comparing the stellar content of the AGB Cluster with that of the rest of the disk. This being said, if the stars in both fields have similar metallicities, then a 0.2 mag difference in $J-K$ is consistent with a younger mean age for the AGB Cluster field, amounting to $\Delta \log(t_{\text{year}}) \geq 0.5$ dex, based on the isochrones shown in Figure 3.

5.2. The Distribution of Stars Along the Major Axis

The distribution of stars in the outermost regions of the NGC 5102 disk may provide clues into its past history. Because the disk of NGC 5102 is viewed at a moderately high angle, the projected intrinsic width of the disk complicates efforts to study the distribution of stars, especially at small $R_{\text{GC}}$ along the minor axis. To reduce the possible impact of disk thickness on structural studies, in the following analysis star counts are restricted to a strip along the major axis with a projected width $\pm 1$ kpc.

The numbers of MS, BRSG, and IRSG sources are too small to allow their radial profiles to be investigated. However, FRSG/BAGB, OAGB, and CAGB stars are present in moderately large numbers, allowing limited conclusions to be drawn about their radial distributions. The number of sources in these groups are shown as a function of $R_{\text{GC}}$ in Figure 7. The counts have been corrected statistically for contamination from background galaxies and foreground stars by subtracting number counts measured in control fields. The CMDs in Figure 1 indicate that incompleteness is an issue in the FRSG/BAGB star counts for $R_{\text{GC}} < 3$ kpc, and so little weight should be assigned to the FRSG/BAGB counts near the center of NGC 5102.

It is evident from Figure 7 that the OAGB and FRSG/BAGB stars have very different radial distributions, in that the former are more centrally concentrated than the latter. This difference is perhaps not surprising given that there is not a one-to-one correspondence between the stars that fall in the FRSG/BAGB...
portion of the \((i', r' - i')\) CMD and those located in the OAGB portion of the \((K, J - K)\) CMD, and that stars with different age distributions are found in each of these boxes. As noted in Section 5.1, the more compact spatial distribution of OAGB stars suggests that star formation \(\approx 1\) Gyr ago was more centrally concentrated than during the past \(\approx 0.1\) Gyr.

The number density of FRSG/BAGB stars in Figure 7 flattens when \(R_{GC} > 5\) kpc, although (1) there are substantial errors in the measurements at large \(R_{GC}\) due to the small numbers of objects, (2) even a modest variation in the number of background galaxies will have a major impact on the behavior of the FRSG/BAGB profile at large \(R_{GC}\), and (3) the distribution of stars at large radii is asymmetric in both the WIRCam (Section 5.1) and MegaCam (Section 5.3) data sets. The radial profile of CAGB stars, which have systematically different photometric properties than the majority of FRSG/BAGB objects, also show evidence of flattening near \(R_{GC} \approx 5\) kpc, although the WIRCam data are limited in their spatial coverage on the sky and so star counts cannot be extended past this radius. Still, the number density of OAGB stars drops off near \(R_{GC} \approx 4.5\) kpc, and the OAGB and CAGB profiles in Figure 7 suggest that the ratio of C stars to M giants increases with \(R_{GC}\) in NGC 5102, as is seen in other disk galaxies (e.g., Demers & Battinelli 2005).

The FRSG/BAGB and CAGB profiles in Figure 7 suggest that the distribution of stars in the disk of NGC 5102 does not follow a simple exponential profile. Erwin et al. (2005) investigate the light profiles of barred early-type galaxies, and find that at least 25% of their sample have “anti-truncated” light profiles. The light profiles of these galaxies at large radii follow an exponential profile that is shallower than at small radii. Similar light profiles are seen among unbarred disk galaxies, with the highest frequency of occurrence among galaxies with early morphological types (Pohlen & Trujillo 2006).

Two possible mechanisms for generating an anti-truncated light profile are considered here, with the goal of yielding possible insights into the past history of NGC 5102. Anti-truncated light profiles may be the consequence of mass redistribution in disks during interactions. Younger et al. (2007) argue that the angular momentum of gas that is funneled to smaller radii is transferred to disk stars, causing the latter to move outwards. To the extent that the disks of “normal” spiral galaxies likely have formed stars over a wide range of ages prior to any interactions, then most of the stars that move outwards in a spiral galaxy will have ages in excess of a Gyr. If the outer disk of NGC 5102 was populated in this way then it should have a luminosity-weighted age that is older than that of the inner disk, which at some point (or points) in the past experienced an elevated SFR due to the interaction.

The model described by Younger et al. (2007) is not without its problems. The distribution of stars in the outer disk of the interacting galaxy M81 does not support the predicted stellar content trends, in that the outer disk of M81 appears to be younger than the inner disk. This might indicate that some fraction of the gas in M81 was the beneficiary of angular momentum redistribution, or that gas was accreted from M82 (Davidge 2009). In addition, secular processes, such as viscosity-induced redistribution of angular momentum, are expected to act on the order of a few disk crossing times, and these will blur any age signatures that may have been imprinted at the time of formation of the outer disk.

An anti-truncated light profile may also result from the accretion of material with an angular momentum distribution that is different from that of the original disk, and this provides a natural explanation for warped outer disks (van der Kruit 2007). If this mechanism is/ was at play in NGC 5102, then the oldest stars in the outer disk will be younger than those in the main body of the disk. A difference in age between the inner and outer disk of NGC 5102 might be measurable using integrated light or the brightest resolved stars if the outer disk was assembled from material that was accreted only during the past 1–2 Gyr. If the outer disk was accreted earlier then very deep imaging will be required to detect an age difference between the inner and outer disk. Secular processes will also blur differences in stellar content with time.

We close this section by noting that an extended disk might also result from starburst activity, although it is not clear if an anti-truncated light profile would result. Dalla Vecchia & Schaye (2008) model galaxy outflows, and find that the gas dispelled by winds initially escapes the disk plane along the minor axis. Material builds up along the minor axis as gas loss proceeds, with some gas falling back into the disk plane. The resulting increase in density forces gas to escape along the major axis, and the disk boundary moves outwards as ejected gas moves to larger radii. A prediction of this model is that the mass-weighted age of the region near the outer boundary of the disk after the starburst subsides will be younger than at larger radii, with the oldest stars in this part of the galaxy having an age that corresponds to the onset of material being ejected along the major axis. In the case of NGC 5102, this means that the outer disk will be populated by stars with ages \(< 1\) Gyr. There should then be an extended distribution of OAGB stars, which is not seen.

### 5.3. The Stellar Distribution at Large Radii

Regions of a galaxy that have very low stellar density and span large spatial scales can be identified from star counts if the number density of photometrically selected objects exceeds a threshold defined by the number of foreground stars and background galaxies. Davidge (2008b) searched for young stellar groupings in the M81–M82 debris field, and found three objects that have surface brightnesses of 27–28 mag arcsec\(^{-2}\) in \(V\). This procedure has been applied to the MS and FRSG/BAGB objects in the MegaCam data. Source counts were made in 700 \(\times\) 700 pixel bins, which corresponds to 130 \(\times\) 130 arcsec, or 2.1 \(\times\) 2.1 kpc at the distance of NGC 5102. This binning produces a moderately large number of objects per resolution element, while also sampling the spatial scales over which significant changes in galaxy structure might be expected. The results are not critically sensitive to bin size, and the basic conclusions drawn below do not change if 500 \(\times\) 500 pixel or 1000 \(\times\) 1000 pixel binning factors are employed.

Aside from the central few arcmin of NGC 5102, statistically significant overdensities were not found in the numbers of MS objects over the 1 deg\(^2\) MegaCam field. This is interesting given the low level of contamination from background galaxies with blue colors (Davidge 2008b). This null detection suggests that NGC 5102 is not accompanied by kpc-sized companions that contain stars that formed within the past few tens of Myr.

The situation is very different when the spatial distribution of FRSG/BAGB objects is considered. A gray scale image illustrating the distribution of FRSG/BAGBs is shown in the top panel of Figure 8. The star counts in the northwest portion of the image are affected by bright stars, which suppress the detection of faint sources over arcmin or larger scales. The brightest of the stars in the MegaCam image is the \(V = 2.8\) star HD 112892 (\(i\) Cen), which is at the center of the large dark spot.
The bright stellar content of the nearby ($D \approx 3.2$ Mpc) S0 galaxy NGC 5102 has been surveyed with the WIRCam and MegaCam imagers on the CFHT. With the exception of the

6. DISCUSSION AND SUMMARY
crowded central regions of the galaxy, the MegaCam data cover all of NGC 5102, while the WIRCam data are spatially complete out to $R_{GC} \approx 6$ kpc. This is the first published study of the stellar content of NGC 5102 at near-infrared wavelengths, and the data have been used to probe the spatial distribution of stars, with particular emphasis on the outer regions of the galaxy. Structural information of this nature will provide insights into the past evolution of NGC 5102, and may identify the trigger of the elevated star-forming activity that occurred within the past 1 Gyr.

There is a large body of literature that deals with the properties of gas-poor disks, and most of the papers focus on the higher mass kindred of NGC 5102. Given that the current paper deals with only a single galaxy, no attempt is made to present a comprehensive review of the literature on S0 galaxies. Rather, we simply note here that it is broadly accepted that the progenitors of S0 galaxies are spiral galaxies that have experienced gas depletion. There is an environmental dependence (e.g., van Dokkum et al. 1998). An active nucleus may also drive gas from the field into an area with a dense intergalactic medium (e.g., Butcher & Oemler 1984), and the mechanism causing gas removal has been the subject of much debate, focusing on galaxy–galaxy interactions (e.g., Lavery & Henry 1988), or infall from the field into an area with a dense intergalactic medium (e.g., van Dokkum et al. 1998). An active nucleus may also drive gas from a galaxy (e.g., Silk 2005; Silk & Norman 2009), although this is expected to be restricted to disk systems that have massive spheroids. Of course, it is possible that not all S0s were subjected to the same gas-removal mechanism.

Low surface brightness structures such as those found here in the vicinity of NGC 5102 may prove challenging to detect in more distant S0 galaxies, and so NGC 5102 may play an important role for investigating the formation and evolution of gas-depleted disks. This being said, the reader is reminded that some characteristics of NGC 5102 are not typical of S0 galaxies. These include its intrinsic faintness ($M_R \approx -17.7$; Karachentsev et al. 2002), the blue central colors and deep Balmer absorption lines (Gallagher et al. 1975), the modest total dust mass (van Woerden et al. 1993), the low number of X-ray binaries, and the low globular cluster specific frequency (Kraft et al. 2005). In regards to the modest intrinsic brightness and blue central colors of NGC 5102, Bedregal et al. (2008) investigate the spectroscopic properties of Fornax cluster S0 galaxies that span a range of masses, and find a trend between luminosity-weighted central age and galaxy mass, in the sense that lower mass S0s have younger central ages. The blue central colors of NGC 5102 may thus be tied to its modest mass.

6.1. Tracing Star Formation in NGC 5102: The Recent Past and the Immediate Future

There is only a modest number of resolved bright MS stars and RSGs throughout the disk of NGC 5102, demonstrating the low SFR during the past $\approx 30$ Myr. The majority of young stars are in the southern half of the galaxy, which is where the only H ii regions are located. This is also where the H ii density is highest and there are H ii clumps; for comparison, H ii in the northern part of the NGC 5102 disk is more uniformly distributed, with a lower mean density (van Woerden et al. 1993). The H ii distribution strongly suggests that—barring some external influence—the part of the disk that is presently south of the galaxy center will continue to be the dominant area of star formation for timescales of at least a few disk crossing times.

RSGs and AGB stars span a much wider range of ages than the brightest MS stars, and these objects are more uniformly distributed throughout the disk of NGC 5102 than bright MS stars. This indicates that star formation within the past $\approx 0.1–0.2$ Gyr was not restricted to selected locations in the disk. Indeed, the number densities of FRSG/BAGB stars at intermediate radii along the northern and southern arms of the major axis are similar, indicating that the northern and southern parts of the galaxy had similar time-averaged SFRs $\approx 0.1–0.2$ Gyr in the past.

6.2. The Outer Disk of NGC 5102

The number counts of objects that are classified as FRSG/BAGB stars suggest that the light profile of the NGC 5102 disk does not follow a single power law, but breaks to a shallower profile near $R_{GC} \approx 5–6$ kpc (5.5–6.7 disk scale lengths). The error bars in the FRSG/BAGB counts are significant at large radii, and background galaxies that—at an angular resolution of roughly an arcsec—are unresolved introduce a considerable source of uncertainty. Still, the majority of early-type disk galaxies have light profiles that become shallower at large radii (Pohlen & Trujillo 2006). The spatial distribution of OAGB stars, selected from the WIRCam data, is more compact than that of the FRSG/BAGB stars. Given that the OAGB stars tend to be older than those in the FRSG/BAGB sample, then this suggests that the outer disk of NGC 5102 has a younger mean age than the inner disk. This is similar to what is seen in M81, where the structural properties of the outer disk have almost certainly been affected by interactions with M82 (Davidge 2009).

Stars along the major axis of NGC 5102, which presumably belong to the disk, can be traced out to $R_{GC} \approx 14$ kpc, or $\approx 15.5$ disk scale lengths, in the southern half of the galaxy. This indicates that the disk may extend to a greater distance than was estimated by Davidge (2008a), who used RGB star counts along the minor axis to trace the disk out to a deprojected radius of $\approx 10$ kpc. Clumpiness in the outer disk of NGC 5102 may explain why the disk radius estimated made by Davidge (2008a) along the minor axis differs from that found here. The distribution of FRSG/BAGB stars in Figure 8 indicates that there is structure in the outer disk of NGC 5102, with a marked concentration of objects along the southwest semimajor axis. The disk of NGC 5102 is also markedly warped at large radii in the northern portion of the galaxy. This is evident in the H i map of van Woerden et al. (1993), where the H i distribution veers to the northwest of the northern arm of the major axis as extrapolated from smaller $R_{GC}$. OAGB stars follow the H i warp. A cluster of background galaxies could masquerade as the southern extension of the NGC 5102 disk, although such a cluster would have to be positioned fortuitously along the major axis of NGC 5102.

Deep images with angular resolutions of the order 0.1 arcsec or better will provide the data needed to confirm the nature of the objects that define the low surface brightness structures along the major axis of NGC 5102. If, as suggested here, the structures are made up of stars that belong to the disk of NGC 5102, as opposed to background galaxies, then the projected density of extended objects in these structures will be comparable to that in other parts of the area around NGC 5102. On the other hand, if high angular resolution observations detect an excess population of galaxies then the FRSG/BAGB counts will need to be revisited.

6.3. The Nature of the AGB Concentration Near the Center of NGC 5102: Star Cluster or Satellite?

The kpc-sized concentration of AGB stars immediately to the west of the galaxy center is the most prominent structure...
found in the vicinity of NGC 5102, and the nature of this feature is of considerable importance for understanding the recent evolution of NGC 5102. The relatively blue $J-K$ colors of the majority of AGB stars in this area (Section 5) suggest that this was probably an area of localized star formation in the not-too-distant past. The physical coincidence with a probable superbubble (McMillan et al. 1994) suggests that star formation may have continued in this stellar concentration up to within the past few tens of Myr, and H$\text{I}$ is concentrated in this area (van Woerden et al. 1993). Deeper images should reveal a population of intermediate-age MS stars in the AGB concentration with a spatial density that is roughly twice that on the eastern side of the disk. The age measured from the MS turnoff of this stellar concentration will provide a means of timing starburst activity in NGC 5102.

Two possible origins for the AGB concentration are considered here. One is that the AGB concentration is a large cluster in the disk of NGC 5102. An awkward aspect of this interpretation is that much of the most recent star-forming activity during intermediate epochs in NGC 5102 would have been concentrated in a single region of the disk that is offset from the center of the galaxy. This is not typical for starburst systems, where star formation tends to be centered on the nucleus (e.g., Kewley et al. 2006, and references therein). Still, if the star cluster interpretation is correct then it cannot be older than $\approx$1 Gyr. The crossing time of the NGC 5102 disk is on the order of a few hundred Myr, and coherent structures might be expected to dissipate after a few crossing times, due to kinematic heating by interactions with large gas clouds and other star clusters. The difference in colors between the brightest M giants in the disk to the east of the galaxy center and the AGB concentration (Figure 6) is qualitatively consistent with a relatively “young” age for the AGB concentration, although it is difficult to assign a reliable absolute age without MS turnoff information.

The second interpretation is that the stellar concentration is a satellite galaxy seen in projection against (or behind) the disk. Kraft et al. (2005) hypothesize that a gas-rich dwarf galaxy triggered the large episode of star formation in NGC 5102 during intermediate epochs. A long-recognized difficulty with this hypothesis is that NGC 5102 is in an isolated environment. Using distances measured by Karachentsev et al. (2007), the nearest known neighbor of NGC 5102 is the barred spiral galaxy ESO383-G087, which is at a distance of $0.3-0.4$ Mpc. The satellite interpretation of the AGB concentration is thus attractive as it provides a trigger for the burst of star formation in NGC 5102.

Comparatively easy tests of the satellite hypothesis are that (1) a satellite would have left a trail of material as it was disrupted, and this trail might still be visible, and (2) NGC 5102 should show signs of having experienced a recent interaction. While unambiguous stellar streams have not been detected near NGC 5102, there are two possible tidal remnants. The grouping of stars along the minor axis could be the remnant of an interaction involving a satellite with an orbit that was perpendicular to the disk plane. The integrated brightness of the three minor axis pixels in Figure 8 that breach the 2$\sigma$ threshold is $V \approx 15.3$, such that $M_V \approx -12.2$, which is $\approx$1% of the integrated brightness of NGC 5102. Mori & Rich (2008) model interactions in which satellites with masses that are no more than a few percent of the total mass of M31 pass through the central regions of M31. While caution should of course be exercised when extending these results to NGC 5102, some broad conclusions are worth noting. The satellite is significantly disrupted, and its stars are distributed throughout the extraplanar environment, forming distinct streams and shells during the first $\approx$1 Gyr. The disk of M31 is not affected significantly as long as the satellite has a mass that is less than $\approx$1% of that of the galaxy. A few Gyr after the first interaction the extraplanar region is dominated by a diffuse component, with little evidence of streams and shells.

The clumpy structures found in the outer disk of NGC 5102 are reminiscent of the extended outer disk of M31 (Ibata et al. 2005). Based on its disk-like stellar content, Faria et al. (2007) argue that the M31 “cluster” G1, which falls along the major axis of M31, might actually be a fragment of the M31 disk that was pulled from the disk during a past interaction. Richardson et al. (2008) find that the stellar content throughout the outer disk of M31 is highly uniform, and argue that the extended disk may be the consequence of the heating and disruption of the thin disk of M31 by a satellite. An extended disk formed in this manner may stay in place for many Gyr given the long mixing times in the outer regions of galaxies (e.g., Johnston et al. 1996). It is further worth noting that the ring-like H$\text{I}$ distribution in NGC 5102 is reminiscent of the distribution of gas and dust in M31, which simulations suggest may be the result of a smaller companion (presumably M32) passing through the disk (e.g., Block et al. 2006). The warping of the NGC 5102 disk, which is seen in both the H$\text{I}$ and stellar distributions, may also be the consequence of a tidal encounter.

There are other tests of the satellite hypothesis, but they will prove challenging to implement. A satellite galaxy would probably contain a substantial old population, with a metallicity that may be distinct from that of NGC 5102. However, such a population would prove difficult to detect given that the proposed satellite is viewed against/through the crowded inner regions of NGC 5102. Another test is that the radial velocities of stars in the cluster and the disk may differ. An obvious difficulty is that an investigation of the velocities of even the most luminous stars will require larger telescopes than those currently available. This being said, the AGB concentration is coincident with a localized peak in the H$\text{I}$ distribution that is not kinematically distinct in H$\text{I}$ channel maps (van Woerden et al. 1993). A large velocity difference between NGC 5102 and the supposed satellite may not be present today, as dynamical friction will act to harmonize the kinematic properties of stars in the satellite with those in NGC 5102, although this may require very long timescales depending on the orbital geometry and relative system masses (e.g., Colpi et al. 1999).

### 6.4. Star Formation in an Outflow from NGC 5102?

In Section 6.3, the collection of stars at a projected galactocentric distance of $\approx 18$ kpc on the southeast minor axis of NGC 5102 was discussed in the context of it being a possible tidal remnant. In this section, we consider another possible origin for this structure. Galaxies with elevated SFRs may experience outflows, and this can have an impact on their surroundings. The outflow from M82 may trigger star formation in its extraplanar regions (e.g., Davidge 2008c, 2008d), as the wind interacts with circumgalactic clouds that presumably were tugged from M82 and/or M81 as they interacted, or condensed from material that was ejected from M82 by winds. The features identified as the “Cap” (Devine & Bally 1999) and M82 South (Davidge 2008d) are perhaps the most obvious signatures of the interplay between the M82 outflow and surrounding material.

The interstellar medium of NGC 5102 shows only marginal evidence for an outflow at the present day (Schwartz et al. 2006),
although Kraft et al. (2005) find diffuse X-ray emission in the central 1 kpc of NGC 5102, which they attribute to a superbubble that is powered by supernovae associated with the most recent burst of star-forming activity. However, the SFR in NGC 5102 during intermediate epochs was probably sufficient to power a galaxy wind (Section 7.3 of Davidge 2008a). Could the diffuse stellar component along the southeast minor axis of NGC 5102 have formed in such an outflow?

An outflow origin for these stars provides a natural explanation for their location along the minor axis of NGC 5102. However, such structures will probably not be long-lived, and will probably be disrupted over a few orbital timescales around NGC 5102 (i.e., within \( \approx 1 \) Gyr). There would also have to be a large diffuse gas component surrounding NGC 5102, and no evidence for this has been found. Finally, with \( M_V \approx -12.3 \) (Section 6.3), the minor axis structure would be much larger than the largest outflow cluster in M82 (Davidge 2008d). Thus, while an outflow origin for these stars cannot be ruled out, this possibility appears to be unlikely.

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