Appendix A

Objects in NGC 205 Resolved into Stellar Associations by HST Ultraviolet Imaging[1]

Abstract

We have obtained high resolution UV images with the HST+WFPC2 of the central region of the dwarf elliptical galaxy NGC 205. Our images reveal that many of the hot UV stars previously detected and studied from the ground are actually multiple systems, open clusters and star associations. We have performed photometry of two such clusters and we find our data are consistent with stellar ages of 50 and 100 Myr, respectively. From the number of massive stars in NGC 205 we estimate that the star formation episode in this galaxy has turned $\sim 1,000\,M_\odot$ of gas into stars over the last 100 Myr.

A.1 Introduction

Since the first observations by Hubble (1932) NGC 205, one of the dwarf elliptical companions to M31, has been known to contain a sprinkling of young stars. This is evidenced by ground-based resolved OB associations (Hodge 1973), dust obscuration (Hubble 1932; Hodge 1973; Peletier 1993; Lee 1996) and presence of molecular hydrogen (Young & Lo 1996), as well as several early-type stars with unusually blue $U-B$ colors (e.g., $U-B \leq -1.0$; objects labeled 4, 7 and 12 in the study of Peletier 1993). In our post-COSTAR program to image the hot stars among old stellar populations in Local Group galaxies, we obtained WFPC2 UV images of NGC 205. We find that many of the brightest "stars" in NGC 205 are actually multiple systems, including *bona fide* examples of Orion/Pleiades-type stellar systems.

Indeed, many OB and early-type associations near the Sun have typical sizes of $\sim 2-5$ pc, including the Orion OB association ($\sim 1^\circ$ at 460 pc) and the Pleiades ($\sim 2^\circ$ at 116 pc). At the distance of NGC 205 (830 kpc, Lee 1996) these associations would subtend an angle $\sim 1''$, difficult to resolve from the ground. Another classical example is offered by star-forming regions within the Large Magellanic Cloud (e.g., R136 in 30 Dor, cf. Weigelt et al. 1991), where objects previously thought to consist of a few stars from ground-based observations

[1] Cappellari, M., Bertola, F., Burstein, D., Buson, L. M., Greggio, L. & Renzini, A. 1999, ApJ, 515, L17

resolve themselves into hundreds, if not thousands, of stars at the angular resolutions of HST, i.e., $0\farcs05$.

In this letter we present the pictorial evidence for the existence of these kinds of stellar groupings in NGC 205, which were previously considered to be single stars. The observations are presented in Section 2, while in Section 3 the photometry of individual objects in two ultraviolet bands is presented and the derived color-magnitude diagrams are compared to theoretical isochrones. Our main conclusions are summarized in Section 4.

A.2 Observations

HST/WFPC2 observations of NGC 205 (GO 5430) were taken on 30 September 1994 through the WFPC2 filters F185W (9600 s), F255W (9000 s), F336W (1200 s) and F675W (150 s). These images are calibrated using the standard STScI pipeline with the latest available WFPC2 calibration files, then coadded and cosmic-ray-cleaned using the IRAF/STSDAS task CRREJ. Figure A.1 presents a mosaic of $2\farcs8\times2\farcs8$ regions centered on each of the 10 sources identified as stars on ground-based images by Peletier (1993; using his numbering system), which also are in our WFPC2 frames. Figure A.2 shows a similar mosaic for a larger region $20''$ north of the nucleus rich in UV-bright stars (Hodge 1973; Peletier 1993; Lee 1996), which we term the "Archipelago". The nucleus of NGC 205 is also shown for reference.

Objects 2, 3, 4, 5, 6 and the nucleus ("C") fall in the PC1 CCD of the WFPC2 (pixel size $0\farcs046$). The other objects are in the WF2 CCDs (pixel size $0\farcs100$). As the WF CCDs heavily undersample the $\sim 0\farcs05$ FWHM PSF, we remove the pixellated appearance of the data by bilinear interpolation onto a finer grid with pixel size $0\farcs100/2$.

As is evident, at least half of the brightest "stars" identified by Peletier (1993) are actually multiple systems of UV-bright sources. Objects 1 and 8 are likely open clusters, as indicated by their size ($\sim$ 2 pc, similar to that of the Orion and Pleiades clusters) and numbers of bright, resolved stars. Objects 3 and 4 are multiple systems. Object 11 is likely a background galaxy, judging from its diffuse appearance in the F675W image and its faintness in the UV images. Most of the UV-bright stars in the Archipelago are multiple on scale sizes less than $1''$. The two clusters 1 and 8 shown in Figure A.1, as well as the Archipelago (Figure A.2) are identified in the F336W filter image (Figure A.3).

Previous HST observations have shown that the nucleus of NGC 205 consists of a globular-cluster-sized stellar group (cf. Bertola et al. 1995, Jones et al. 1996). We clearly resolve the nucleus of NGC 205. Its axial ratio is $q = 0.90 \pm 0.05$ (there is some evidence that it is more elongated in the UV). Its position angle is $P.A. = 166^\circ \pm 8^\circ$, consistent within the errors with previous measurements by Bertola et al. (1995) and Jones et al. (1996), as well as with the position angle for the whole galaxy (Nilson 1973). The centroid of the nucleus with respect to the stars is the same in all HST images.

A.3 Photometry

We used the DAOPHOT PSF-fitting package within the IDL Astronomical Library (Landsman 1995) to photometer individual stars in the Clusters 1 and 8 and in the Archipelago. A 4σ detection limit is adopted, equivalent to limiting magnitudes $m_{336} \simeq 22.9$ and $m_{255} \simeq 22.7$. Owing to the lack of good S/N observations of isolated stars in our field, we have fitted a

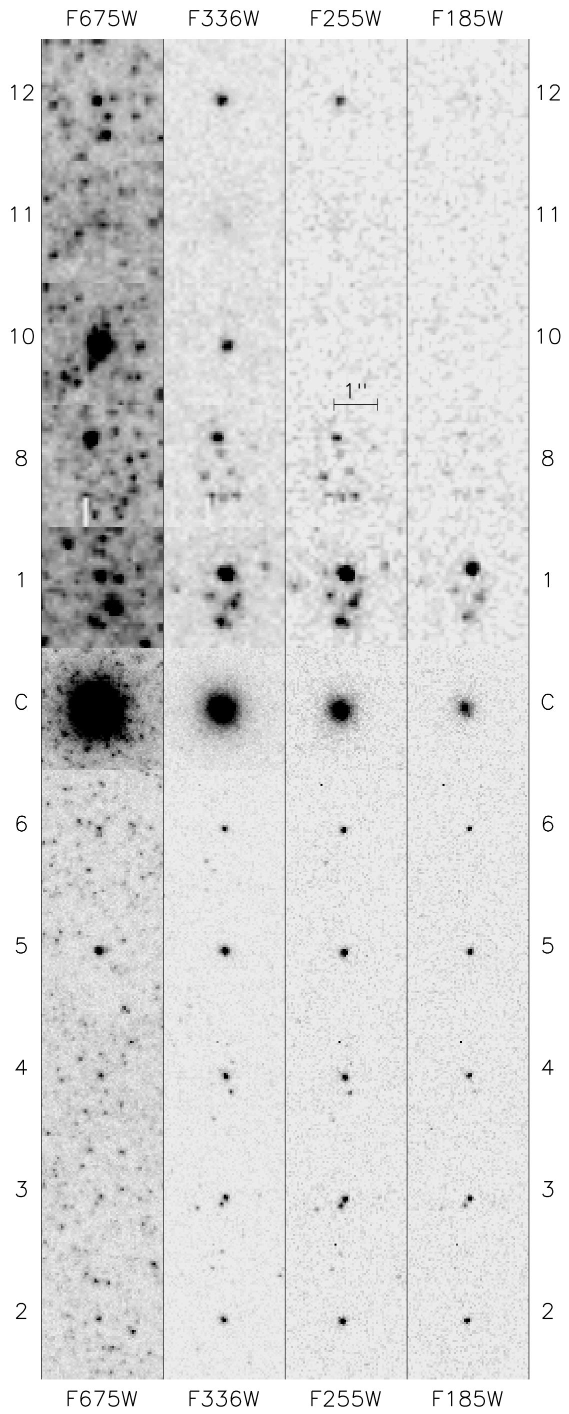

Figure A.1: The WFPC2 F675W, F336W, F255W and F185W $2''\!.8\times2''\!.8$ FOV images (from left to right, respectively) of ten "stars" listed by Peletier (1993) in the central region of NGC 205, and of the galaxy nucleus (labeled as "C"). Objects labeled 2–6 and the nucleus "C" were included in the PC1 CCD which has a pixel size of $0''\!.046$. Frames 1, 8, 10, 11, and 12 are taken from the WF2 CCD which has a pixel size of $0''\!.100$, and have been resampled into a finer grid with pixel size $0''\!.100/2$ by means of bilinear interpolation to smooth the pixellated appearance of the image. Orientation as in Figure A.3.

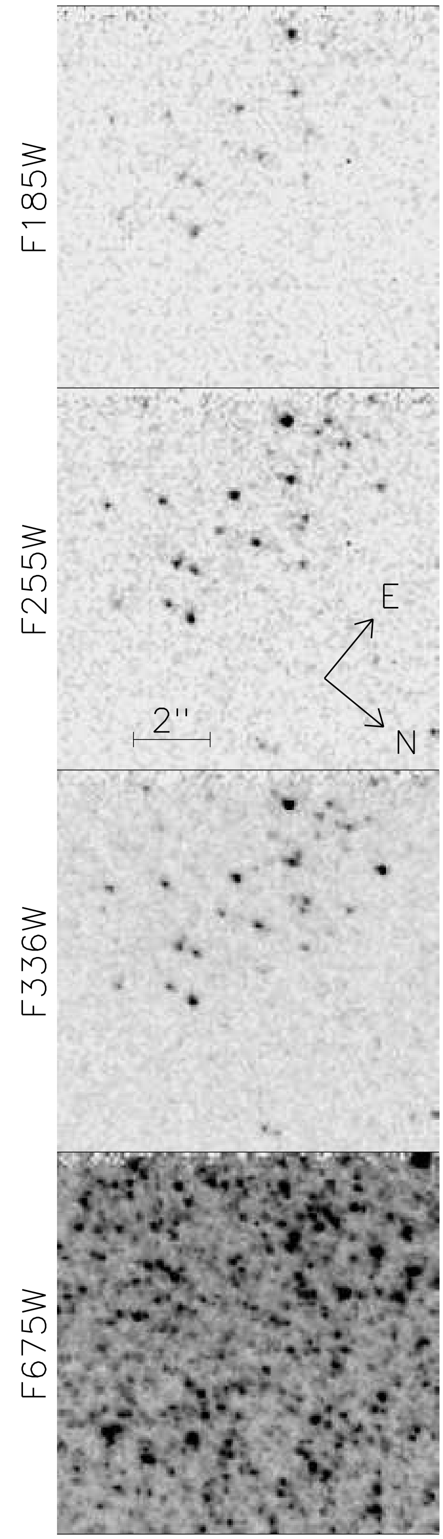

Figure A.2: WFPC2 images (10″×10″ FOV) of the Archipelago region (see text for details) in the F675W, F336W, F255W and F185W bands respectively. The images have been resampled to a smaller pixel size as described in Figure A.1.

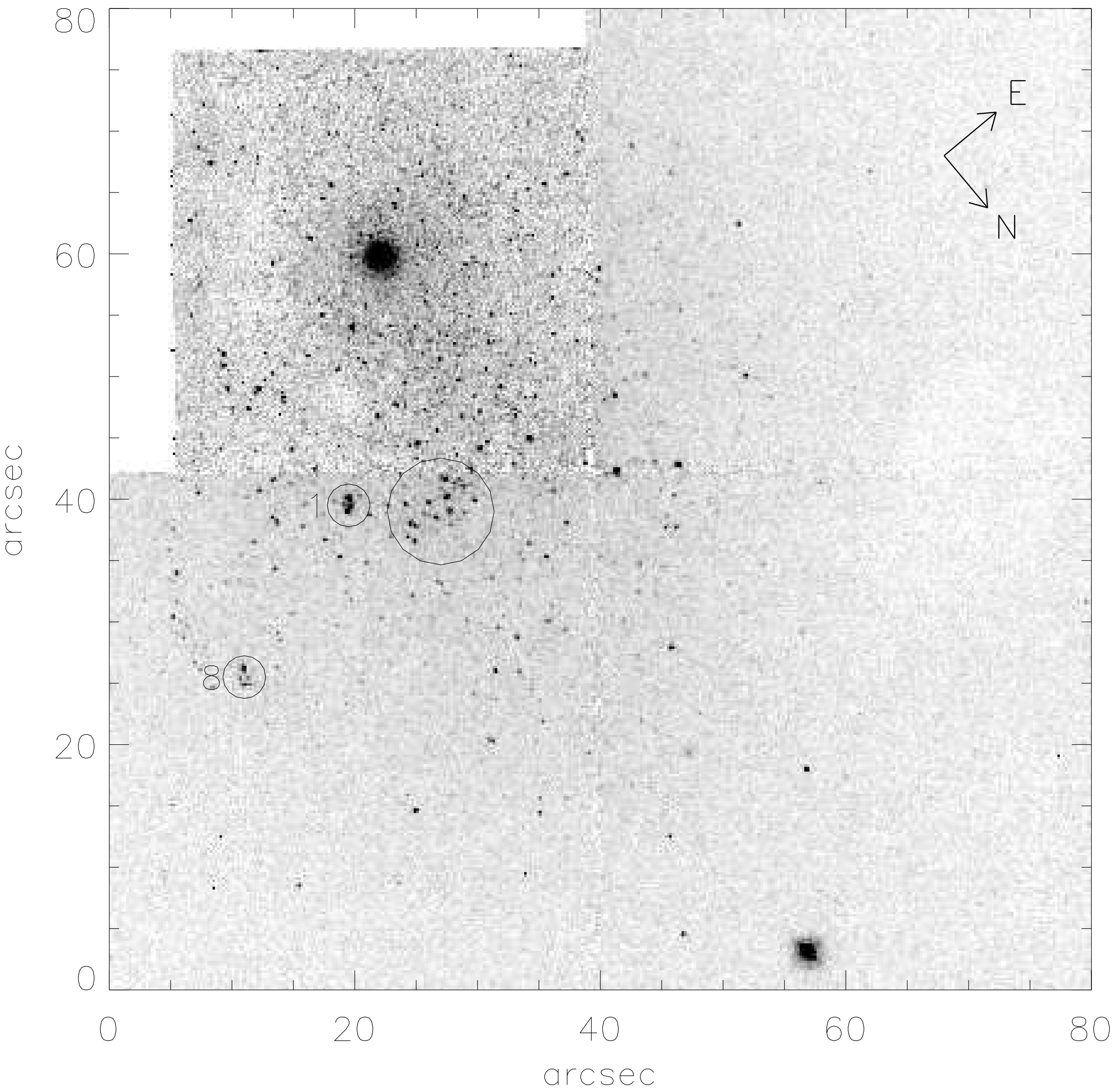

Figure A.3: An $80'' \times 80''$ region taken from the full F336W WFPC2 mosaic. The nucleus of NGC 205 is visible at the center of the smaller PC1 CCD at the upper left corner of the picture. Clusters 1 and 8 are shown inside the small circles. The larger circle marks the area of what we call the "Archipelago" region (see text for details).

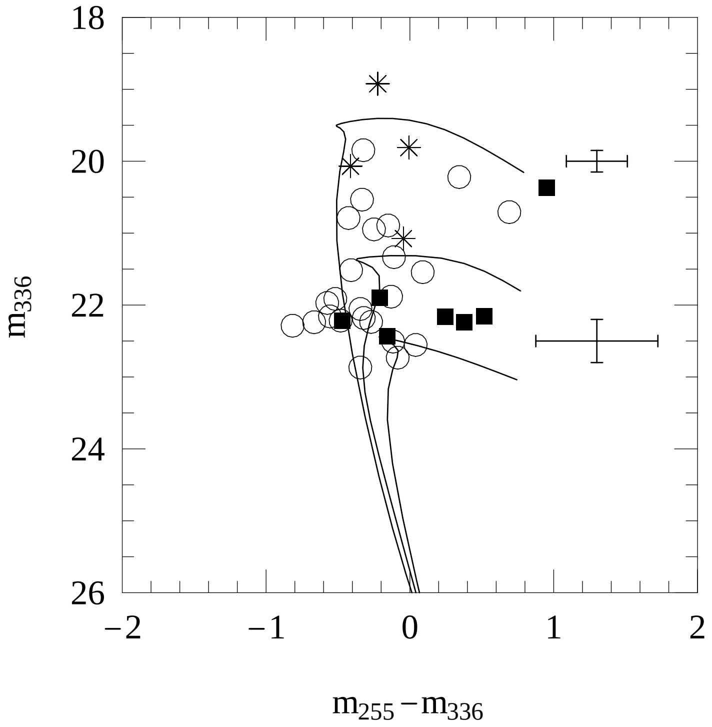

Figure A.4: The color-magnitude diagram (m_{336} vs. $m_{255} - m_{336}$) of Clusters 1 (asterisks) and 8 (filled squares), and of the Archipelago (open circles). Note that only the four brightest stars of Cluster 1 have been included in this diagram, as the photometry of the fainter stars recognizable in Fig. A.1 is affected by large errors. Mean photometric errors are shown by the error bars to the right. Overplotted are the theoretical isocrones from Bertelli et al. (1994) for the metallicity $Z = 0.02$ and ages of 20, 50 and 100 Myr respectively. These isochrones have been tranformed into the STMAG magnitude system, by adopting a true distance modulus of 24.6 mag and a reddening $E(B-V) = 0.18$. The post main-sequence part of the isocrones has been truncated at $T_{\rm eff} = 8,000$ K.

synthetic PSF generated by the Tiny Tim software (Krist 1993), specifically for each different band.

We find 24 UV-bright stars in the Archipelago, 7 in Cluster 8 and 4 in Cluster 1. These data are used to create the color-magnitude diagram of Figure A.4. Adopted magnitudes are in the STMAG system ($m_{ST} = -21.10 - 2.5 \log f_\lambda$, with f_λ in erg cm^{-2} s^{-1} Å^{-1}). The effect of crowding and the severe undersampling of the PSF does not allow a reliable measurement of the other fainter cluster members otherwise visible in both the F336W and the F255W resampled images of Figure A.1 and Figure A.2.

Figure A.4 also shows Bertelli et al. (1994) solar metallicity theoretical isochrones for ages of 20, 50 and 100 Myr, corrected for a total reddening of $E(B-V) = 0.18$ and a foreground-extinction-corrected distance modulus of $m-M = 24.6$ (Lee 1996). The theoretical isochrones are converted to the observational plane using the model atmospheres of Kurucz (1979a,b). The model spectra have first been reddened using the Cardelli et al. (1989) extinction curve (for $A_{\rm V}/E(B-V) = 3.2$). Convolution of the reddened spectra with the most up-to-date instruments+filters sensitivity in the SYNPHOT package within IRAF/STSDAS then yields magnitudes and colors.

Our estimate of $E(B-V)$ has been determined directly from our data. A lower reddening would make the isochrones too blue relative to the observed stars. This value of the reddening is identical to that determined by Han et al. (1997) for the foreground reddening of NGC 147, another companion of M31, but is significantly larger than the value $E(B-V) = 0.035$ given by Burstein & Heiles (1982). For the origin of this discrepancy it is difficult to disentangle between an excess Galactic extinction with respect to the Burstein & Heiles map, and internal absorption to NGC 205 itself.

The combination of low angular resolution, stellar crowding in clusters and relatively shallow limiting magnitude limits the stars in our CM diagram (CMD) to the brighter end of the main sequence (MS), and a few early post-MS stars. Crowding affects our CMD in two ways: an artificial brightening of the MS stars, and an artificial reddening of the measured star relative to the theoretical MS. This latter effect is analogous to what happens in an unresolved double star.

As shown in Figure A.4, the adopted mean reddening, distance modulus, and isochrone metallicity give a reasonable match to the distribution of stars in the CMD. The scatter seen is consistent with observational error. The Archipelago region contains stars with a range of age, with some as young as 20 Myr and masses up to $\sim 11\,M_\odot$ and ones as old as 100 Myr and masses of $\sim 5\,M_\odot$. These objects are expected to spend their core helium burning phase at colors redder than $m_{255} - m_{336} \simeq 2$, i.e., too red with respect to the color of the two reddest stars in the Archipelago. These two stars are likely blends of blue main sequence and red core helium burning stars. The four brightest stars in Cluster 1 are likely main sequence stars as young as the youngest stars in the Archipelago region. In contrast, the stars in Cluster 8 have UV brightness and colors located between the main sequence turn-offs of the 50 and 100 Myr isochrones. While estimates of age (~ 70 Myr) and mass ($6\,M_\odot$) can be made from Figure A.4 for the stars in Cluster 8, uncertainties owing to internal dust and photometric error make these estimates rather uncertain. What is apparent is that the stars in Cluster 8 are older by ~ 50 Myr than those in Cluster 1.

A.4 Discussion

It is not surprising that objects that on poor resolution images appear as single stars turn out to be resolved into many stars with the far superior angular resolution of HST. Warnings on the risks of overlooking this effect of crowding date from the 1950's and 1960's, when Hubble and Sandage (see Sandage & Hubble 1961) noticed the problem for the bright red supergiants in the Local Group. More recent examples include the HST observations of the stellar population of M32 (Grillmair et al. 1996), and the classical case of R136 resolved into myriads of stars (Weigelt et al. 1991). The effect of stellar blends are discussed in general terms by Renzini (1998), with several examples drawn from stellar populations in Local Group galaxies.

Local Group galaxies are currently the only ones for which we can reconstruct their star formation history in a fairly direct and detailed way from the photometry of individual stars. Crowding, however, is a major problem. Our results demonstrate that we have to be wary of interpreting bright "stars" seen with insufficient resolution as individual stars, even in the case of what appear to be bright, young stars in an otherwise diffuse dwarf galaxy. As is apparent from the images presented in this Chapter, it is quite common that the brightest objects are actually not individual stars. This is to emphasize once more that the reconstruction of the star formation history of Local Group galaxies requires superior angular resolution imaging. Blends produce brighter objects, which if interpreted as single stars lead to infer younger ages than the real ones, no matter whether dealing with young main sequence stars, very old red giant branch, or asymptotic giant branch stars.

In the case of NGC 205, young objects are confined to within $\sim 1'$ from the center (Peletier 1993), and are virtually all included in our WFPC2 frames. On these images we can count a total of ~ 35 stars likely to be in the mass range between ~ 5 and $\sim 10\,M_\odot$. Based on their positions in the UV color-magnitude diagram, and assuming a normal IMF, the star formation episode that produced the Archipelago and the young star clusters in NGC 205 has turned $\sim 1,000\,M_\odot$ of gas into stars within the past 100 Myr. Therefore, we are dealing with a quite modest star formation event, of order of $10^{-5}\,M_\odot$/yr when averaged over the last 10^8 years. Even with HST, an event of this kind would become unobservable in a few 10^8 years, and cannot contribute much to the stellar mass of NGC 205. The question as to where this gas came from is not easy to answer. Possibly, as in our Galaxy, high velocity HI clouds may be orbiting M31, and one such cloud might have been captured by the potential well of NGC 205 and squeezed above star formation threshold.

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