IR PHOTOMETRY OF M33

10

The Local Group: Comparative and Global Properties

The Third ESO/CTIO Workshop, La Sereña, January 1994

Dante Minniti, E.S.O., Karl-Schwarzschild-Str. 2, D-85748 Garching, Germany
Edward Olszewski, Steward Observatory, Univ. of Arizona, Tucson AZ 85721, USA
Marcia Rieke, Steward Observatory, Univ. of Arizona, Tucson AZ 85721, USA

Abstract

We present JHK photometry for stars in a 12.5×2.5 arcmin field that includes the bulge and inner disk of the Local Group spiral M33. Color–color and color-magnitude diagrams for different regions of this galaxy are constructed, including the M33 bulge, arm and interarm regions, and giant stellar associations. We compare the color-magnitude diagram of the M33 bulge with those of other galaxies of the Local Group (MW, M31, M32, and LMC). The bulk of the M33 bulge population is similar to those of the bulges of MW, M31, and to M32. It is confirmed that there has been a recent episode of star formation in the inner regions of M33. We also discuss the distribution of the blue and red supergiants within 2 arcmin of the M33 nucleus.

1 The Bulge in M33

M33 is the smallest of the three spirals in the Local Group, and its study is of particular interest to link the Magellanic Clouds with the two other spirals M31 and Milky Way (MW). Optical studies revealed a complicated inner region in M33, with spiral structure and star formation extending all the way to the center (Bothun 1992, Kent 1987, Zaritzky, Elston & Hill 1989). Indeed, it was not clear whether there was a bulge in M33 (e.g. Van den Bergh 1991), until Minniti, Olszewski & Rieke (1993, hereafter MOR) detected and resolved the M33 bulge at 1.6 μm. This work presents the results of further JHK imaging of the bulge and disk M33.

Most relevant data for M33 has been recently reviewed by Van den Bergh (1991). From his paper we adopt a distance modulus of $(m - M)_0 = 24.5 \pm 0.2$, a Galactic foreground reddening of $E_{B-V} = 0.07$, equivalent to $A_H = 0.04$ magnitudes, and an average total reddening (internal + foreground) $E_{B-V} = 0.30$, equivalent to an average absorption of $A_H = 0.17$. At the distance of M33, 5 arcmin $\approx$ 1 kpc.

The stellar component of the M33 bulge is best studied in the near–IR bands for various reasons. Firstly, the emission from old red giants peaks beyond 1μm. This determines that the giant branches in the IR color-magnitude diagrams (CMDs) are almost vertical. Therefore, the contrast with the underlying, more numerous fainter stars is much higher at J (1.2 μm), H (1.6 μm), and K (2.2 μm) than in optical passbands, allowing better photometry and reduced confusion. Specifically, the magnitude difference between the brightest giants and the turn–off region for a 13 Gyr–old population with [Fe/H] = −0.7 (like the globular cluster 47 Tuc) is $\Delta_{TO}^{RGT} = 7.5$ magnitudes in K, and only 4.5 magnitudes in V.

Second, bolometric luminosities are readily obtained from near–IR observations, unlike in the optical. This allows a more direct comparison with theoretical models. For example, the bolometric correction in H for the stars of interest here is $BC_H = 2.6 \pm 0.2$, independent of color (Bessell & Wood 1984). Comparison with the bolometric corrections given by Frogel & Whitford (1987) shows a good agreement with this result.

Third, populations of widely different metallicities are equally represented. This is not true in the optical, where the more metal–rich populations would be absent in magnitude limited samples (Bica et al. 1991). This last point is particularly important when studying the bulges of nearby galaxies, where

Dec 1994

existing VI photometry completely misses the metal–rich giants (Bica et al. 1991), which are supposed to be their dominant components.

Is There a Bulge in M33? As it was pointed out by Schommer et al. (1991), their discovery of bona–fide globulars in M33 (more than about 20) means that this galaxy has an very high specific frequency of globular clusters, because at that time the luminosity or even existence of the bulge was in question. This high specific frequency of globulars resembles that of giant ellipticals, rather than spiral galaxies.

Another important point about the existence of a bulge in M33 was raised by Kormendy & McClure (1993), who studied the structure and dynamics of the M33 nucleus. At the time they assumed there was no bulge in M33. They then asked what was special about the nucleus for the material to be concentrated there; in the absence of a bulge, the potential well is not deep. They concluded that there is no supermassive black hole in M33 and that this galaxy never contained a quasar. They advance that the difference between this galaxy and the others that could have had quasars (M32, M31, MW) is that M33 has no bulge. MOR find a bulge in M33, and so the difference between these galaxies disappears. However, it is interesting to keep part of the argument: it could well be that galaxies with nuclei have spheroidal stellar populations (bulges or halos). For example, the presence of a halo in the LMC is uncertain (Freeman et al. 1983), although there is no bulge, and no nucleus. It would be profitable to study other nearby late type galaxies to test this hypothesis.

Determining the existence and stellar content of the M33 bulge is also important in the context of galaxy formation. If there is a causal connection between the formation of bulges and halos, both should be present. For example, Carney et al. (1989), Wyse & Gilmore (1992) and Minniti (1994) argue that the Galactic bulge formed from gas left over after the halo formation. As discussed below, it is fair to say that M33 has a halo like the MW and M31. In this paper we argue that M33 also has a bulge with similar stellar content as those of the MW and M31.

Is the central component detected and resolved by MOR the bulge or the halo of M33? This question could be asked after we have precisely defined what we understand by bulge or halo. It is not clear that we even know in the Milky Way if they are distinct components. Minniti (1994) argued that the MW halo is metal–poor, slowly rotating, and has a large velocity dispersion, even in the inner regions. In contrast, the MW bulge is more metal–rich, rotates more rapidly, and has a velocity dispersion declining with distance from the Galactic center. Future observations will decide if this is also the case for M33. It is difficult to discriminate between bulge and halo in M33 without detailed information on the kinematics and metal abundances.

However, there is good evidence for a halo in M33. The stars found in a field at 7 kpc from the center of M33 resemble those of the MW halo (Mould & Kristian 1986). This is supported by the discovery of RR Lyraes (Pritchet 1988), and by a population of kinematically hot metal–poor globular clusters (Schommer et al. 1991). The stars in the inner regions of M33 appear to be different from those of the MW halo (section 5.6), reaching maximum 2.2 μm emission typical of a bulge population, much brighter than the brightest metal–poor halo giants (e.g. Frogel, Persson & Cohen 1983). However, we cannot discard the presence of an old, halo–like population in the central regions of M33 on the basis of the present observations. These stars would contribute to the unresolved stellar background, as argued by MOR.

2 Observations and Data Reduction

Given that M33 has an inclination angle of 56° (e.g. Zaritsky, Elston & Hill 1989), to characterize the bulge stellar populations, one also has to observe a large part of the disk, to allow proper disk subtraction. Therefore, we chose to map a field extended along the major axis of M33.

The IR observations were taken on the nights of 1991 December 23 (H filter), 1992 January 19 (J filter, observations discarded due to cirrus), 1993 September 4, 5 and 6 (JHK' filters), and 1993 November 1 and 2 (JHK' filters) at the Steward Observatory 90" telescope equipped with the 256×256 Nicmos 3 camera. The median seeing value was about 1.5 arcsec in K. We used the medium pixel scale of the camera (0.6 arcsec pixel^{-1}), without sampling problems. The total field of view of a single frame was then 2.5×2.5 arcmin. The observations were made with airmass less than 2.

All frames were bias and dark–current subtracted, and flat fielded with a median filtered image of the neighboring 15 frames. Typical exposure times per frame were 20 seconds in J, 30 seconds in H, and 20 seconds in K'. There was substantial overlap between adjacent frames within a map (60%), which allowed precise shifting to create the final mosaics. These mosaics are oriented in the N–S direction, and cover a substantial part of M33: 12.5×2.5 arcmin for the J and K filters, and 20.5×2.5 arcmin for the H filter. The same ragion was observed several times in all the filters, to obtain deeper photometry. After registering and co–adding all the frames, the total integration time in the central regions of M33 amounts to 13 minutes in J, H, and K'.

Several standards of the list published by Elias et al. (1981) were observed each night, and the extinction values and transformations to the standard system derived independently for each night. However, in the end these transformations were not very different, and we chose to combine all the frames, since the telescope configuration was similar for all the runs. To do that, we adopted the transformation to the standard system of the nights of 1993 November 8 and 9, which had the best photometric conditions. The K' observations were transformed to K. The rms of the observations with respect to the standard values turn out to be 0.028 mag for J, 0.035 mag for H, and 0.020 mag for K.

The photometry of the final mosaics was performed with DAOPHOT, following the precepts outlined by Stetson (1987). Two passes of DAOPHOT sufficed to detect and measure all the stars we could see down to the faintest magnitudes (H $\sim$ 19). The mean photometric errors are $\sigma_K = 0.03$ and 0.16, $\sigma_{J-K} = 0.04$ and 0.21, $\sigma_{H-K} = 0.05$ and 0.25, for K = 14 and 17, respectively.

At least two different epochs were observed per filter. We plan further observations to obtain a complete sample of long period variables in the inner regions of M33, where previous optical searches are limited by confusion.

To complement the IR photometry, we acquired optical observations at the Steward Observatory 90" telescope with the CCD camera using the 2048×2048 Loral detector on the night of 1993 July 17. We obtained several exposures of the central 5×5 arcmin of M33 with the Cousins R filter, which combined give a total integration time 18 minutes. The airmass of the observations ranges from 1.14 to 1.23. These observations were reduced to the standard system using frames of M92 obtained shortly thereafter.

The R observations were used to estimate reddening variations in the inner regions of M33, which could affect the determination of luminosities and metallicities from the observed magnitudes and colors. Images of the central regions of M33 reveal a complex pattern of dust absorption. The reddening is clearly non–uniform within 2 kpc of the nucleus. These reddening variations will not affect the present photometry, but would affect optical determinations of metallicities.

Before presenting the CMDs, we first discuss the metallicity, kinematics, stellar distribution and completeness.

3 Metallicity

The interpretation of the photometry of M33 will depend on the metallicity. Unfortunately, there is no direct determination of the metallicity of the M33 bulge, because it was not known until recently that there was a bulge. However, there are a number of spectroscopic metallicity determinations of the M33 disk, nearly all the way to the nucleus.

There is a well known metallicity gradient in the disk of M33. Previous abundances from O/H and N/H measurements of HII regions and supernovae remnants are (after converting to Fe assuming Solar abundance ratios): [Fe/H] = 0.0 for the inner kiloparsec, and [Fe/H] = –0.9 for r = 5 kpc (e.g. Searle 1973, McCall et al. 1985, Vilchez et al. 1989, Zaritsky, Elston & Hill 1989 , Pagel & Edmunds 1981)

Also, Christian & Schommer (1983) find that the clusters within r $\leq$ 9 arcmin have [Fe/H] = –1.6 to 0.0, with a mean of about –0.7. They argue that the age–metallicity relation of clusters in this central region shows similar evolution to the LMC, while outside the 9 arcmin region it is similar to the SMC. According to these results, the age–metallicity relation for the inner regions gives ages of 15, 2, and 0.1 Gyr for mean metallicities [Fe/H] = $-1.6, -0.5$, and -0.2, respectively.

Schmidt, Bica & Alloin (1990) and Kormendy & McClure (1993) obtain metallicities for the M33 nucleus as well. The mean abundance of the nucleus is [Fe/H] $\leq$ 0.0, which can be attributed to a

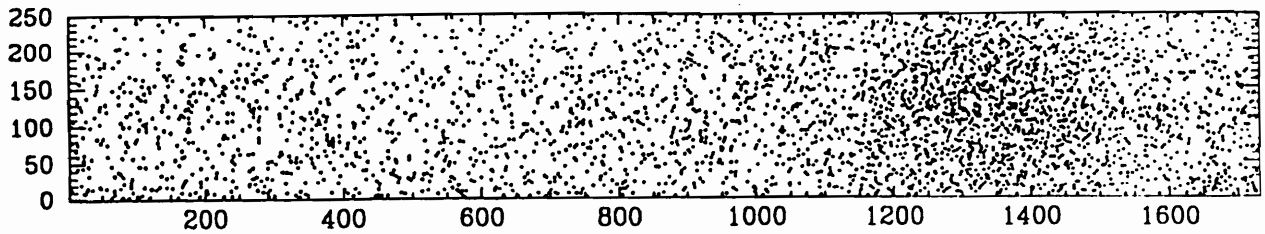

Figure 1: Distribution of 3300 stars detected in the 18×2.5 arcmin H mosaic. North is to the left, East is up.

young population with [Fe/H] = 0.0 plus an old population with [Fe/H] = −.5 to −1.0.

There are also metallicity determinations of the M33 halo. Mould & Kristian (1986) give [Fe/H] = −2.2 for the M33 halo field stars at 7 kpc from the center. Likewise, the "halo" clusters identified from the kinematics show metal-poor compositions, $-1.0 \leq [Fe/H] \leq -2.2$ (Schommer et al. 1991).

The metal abundance of the M33 bulge will probably not be higher than that of the nucleus or the inner disk. It may well be that the M33 bulge is significantly more metal-poor than the inner M33 disk.

The new metallicity scale of the Galactic bulge from McWilliam & Rich (1994) is more metal–poor than the previous one (Rich 1988) by about 0.5 dex. Thus, the Galactic bulge now appears to be more metal–poor than the underlying disk. The bulge of M33 is much smaller than the bulges of the Milky Way and M31, and embedded in a less luminous galaxy. It is likely that the M33 bulge is even more metal–poor than these other bulges.

On the other hand, by analogy with the MW we expect the M33 bulge to be more metal rich than the M33 halo ([Fe/H] ≥ −2). We adopt [Fe/H] = −0.5 for the M33 bulge, accepting that there could be a metallicity spread, and that the range of possible mean abundances covers [Fe/H] = −1.0 to 0.0.

The choice of a mean metal abundance would mostly affect the age determinations of the M33 bulge. According to the models of Bessell et al. (1991), more metal–poor populations reach brighter magnitudes at the same age. Thus, by adopting a more metal–poor abundance, we will derive an older age, and viseversa.

4 Distribution of Stars and Completeness

We have investigated the distribution of red and blue stars in the central regions of M33. The stars detected in the IR mosaics show remarkably uniform distribution (Figure 1), in contrast with the optical images. The complex aspect of the optical images is due to the dust lanes and innermost stellar associations identified by Humphreys & Sandage (1980) and Wilson (1990). In particular, these authors pointed out the existence of a large stellar association (Assoc. 1) 1.5 arcmin South of the nucleus. To decide whether the presence of this association affects the distribution of stars observed in the blue and in the red, we have plotted the cumulative counts of stars as function of distance from the center of M33, comparing the region N of the nucleus with the S, for both the R and H images. The H images show no major difference between the distribution of stars in N and S fields. The R images, however, show very different distributions of stars as function of distance for both regions (Figure 2). The S region has many more stars due to the presence of Association 1, which are absent in the N field.

Thus, to determine the spatial distribution of M33 bulge stars, one should look at the region just North of the nucleus, otherwise the results are biased by the presence of Association 1. Unfortunately, the available VI frames taken by HST are located just South of the nucleus, where the influence of Association 1 is critical.

In all, more than 3300 stars were detected and measured in the JHK mosaics. Stringent criteria have been applied to accept only stars with good photometry: we require small photometric errors ($\sigma_i \leq 0.2 - 0.3$ mags), and a small centering range ($\delta_r \leq 1.5$ pixels). Only about 2/5 of all the stars in the sample pass the selection criteria and, as expected, the rejected stars lie preferentially in the central,

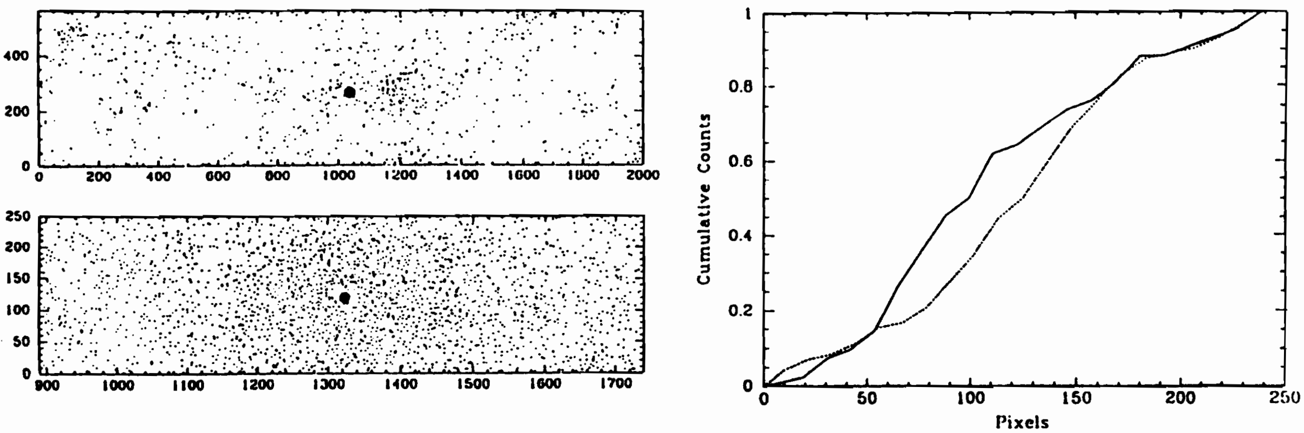

Figure 2: Right: stars found in the central 8.5×2.5 arcmin field of M33, showing non–uniform distribution in the optical image (top panel) with respect to the near–IR image (bottom panel). The M33 nucleus is marked with a circle. Association 1 to the S of the nucleus is evident in the R image. Left: Cumulative counts in the R frame *vs* distance from the nucleus for both the S region (solid line) and the N region (dashed line).

high–density region. This selection ensures that only high–quality data are plotted in the color–color diagrams and CMDs.

The detection of stars becomes progressively incomplete and the photometric quality degrades towards the inner regions, within about 40 arcseconds of the nucleus, due to overlapping of stars and crowding. Inspection of the HST frames taken by the team lead by Westphald in 1991 shows that the inner regions are indeed very crowded. However, none of the conclusions of this report or of MOR are affected by this.

Renzini (1993) first pointed out the problem of overlapping stars as a possible cause for the bright magnitudes observed in the bulges of M31 and in M32. We have estimated if this is a significant problem to be taken into account for our observations of M33. Renzini (1993) shows how to compute the expected number of stars present within a resolution element as function of the total surface brightness of the field and the lifetime of the stellar phase. We have repeated this procedure for different regions of M33, taking the B surface photometry of Kent (1987). It is concluded that most of our observations are not affected by "optical binaries", and that our conclusions are not changed. As an extra check, we have inserted artificial stars into our frames, and find that the bright stars are not all chance superpositions of stars.

5 IR Color–Magnitude Diagrams of M33

The observed CMD for the central 2 kiloparsecs of M33 shows a well defined supergiant branch extending to K = 13.5, sharply peaked at $\langle J-K \rangle = 1.0$, with a total color range from J–K = 0.7 to 1.3. This luminous extended supergiant branch corresponds to young stars in the M33 disk (Figure 3, right panel). There is also a much more populated fainter red giant branch appearing at K $\leq$ 16. This is dominated by the old or intermediate age populations of the M33 bulge. These giants are in general redder, and cover a much wider color range, from J–K = 0.6 to about 2.4, with a mean $\langle J-K \rangle = 1.2$.

The foreground Galactic stars are not very numerous, as expected. No correction for differential reddening within the field studied has been applied to our IR photometry. The range of reddening values determined from optical photometry of blue stars varies from E(B–V) = 0.2 to 0.3 (Wilson et al. 1990). However, there are localized compact clouds of much larger absorption ($A_V \geq 2.5$ mag).

The bright plume is very tight, the color dispersion is very small compared with the bulk of the bulge population. This indicates that the dispersion in J–K of the M33 bulge giants is not due to photometric errors or differential reddening, it is intrinsic. We conclude that a wide range of metallicity in the M33 bulge is needed to explain the color range.

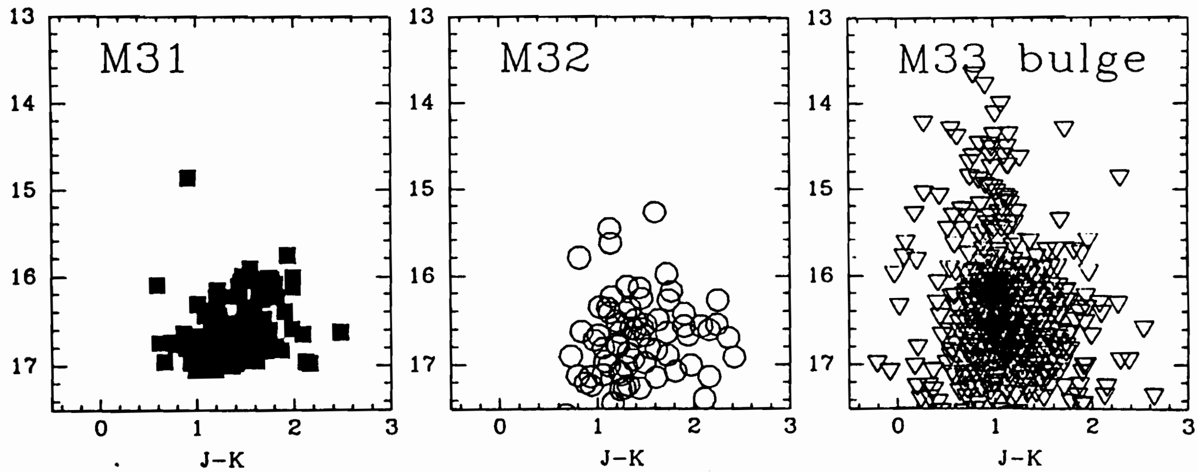

Figure 3: Color–magnitude diagrams for the brightest stars observed in the bulges of three Local Group galaxies. Left: the dwarf elliptical galaxy M32, data from Freedman (1992) for $(m-M)_{M32} = 24.4$. Middle: the bulge of M31, data from Rich & Mould (1991) for $(m-M)_{M31} = 24.4$. Right: the inner 2 arcmin of M33 for $(m-M)_{M33} = 24.5$, showing a narrow plume of red young supergiants, and a large concentration of more numerous, older bulge giants.

5.1 Comparison with Previous IR Photometry of M33

Previous IR photometric studies of M33 have been made by Mould et al. (1990), Madore et al. (1985), and Humphreys, Jones & Sitko (1984). We do not attempt a detailed, star–by–star comparison between these works and the present data, because there is not enough overlap between the samples. However, there is an excellent overall agreement in the morphologies of the CMDs and color–color diagrams. For example, the brightest stars in our CMDs match the colors and magnitudes of the M supergiants in the M33 disk observed by Humphreys, Jones & Sitko (1984). Also, the long period variables studied by Kinman, Mould & Wood (1987) and by Mould et al. (1990) match the location of the giants observed here.

5.2 Comparison with IR photometry of M32 and the M31 bulge

Rich & Mould (1991), Rich et al. (1993), Davies et al. (1992), and DePoy et al. (1993) studied the LF and CMD of the M31 bulge in the near–IR, arriving at contradictory conclusions concerning the nature of the brightest giants. Freedman (1992) and Elston & Silva (1992) studied the LF and CMD of M32 in the near–IR, both reaching the conclusion that there is an intermediate age population in M32. These observations are critically reviewed by Renzini (1993), who points out the effects of crowding as discussed in Section 4.

Figure 3 shows a comparison between M32, the bulge of M31, and the bulge of M33. We have not accounted for the disk stars in the M33 panel, to emphasize the difference between disk and bulge. These spheroidal populations are similar, which might be expected if the M33 bulge is more metal–poor. However, the differences are within the limits given by the uncertainty of the distance moduli and zero–point errors of the photometry.

There are fewer red stars in the bulge of M33 than in the bulge of M31. Also, stars with very red J–K colors in the MW bulge are IRAS sources. The lack of similar sources in the M33 bulge is probably related to its very low 12 μm luminosity as seen in the surface photometry of Bothun (1992). This is also probably a metallicity effect, since we expect the M33 bulge to be more metal–poor than the bulges of the two bigger spirals of the Local Group.

5.3 Comparison with IR Photometry of the MW Bulge

Recently, Frogel et al. (1990) presented IR photometry for several bulge fields along the minor axis of the MW. As argued before, the M33 bulge may be more metal–poor than the MW bulge. It is then fair to compare the M33 bulge with the outer fields in the MW bulge, which are more metal poor than Baade's window. The morphology of the CMDs of the M33 bulge is not significantly different than that of the MW bulge fields, aside from the presence of a young plume in the inner regions of M33.

5.4 Comparison with IR photometry of Globular Clusters

The metal–poor Galactic globular clusters do not have stars exceeding $M_{bol} = -4.0$ (e.g. Frogel et al. 1983). At the distance of M33 these stars would have $K \geq 18$, and thus be out of reach of the present photometry. The fact that we see a large number of brighter giants implies that the bulge of M33 is not made only of halo–like stars.

Comparison with metal–rich clusters is still an open issue. Frogel & Elias (1988) found that the brightest variables in metal–rich globular clusters reach $M_{bol} = -4.5$. For example, the brightest giants in NGC 6553 are variable and reach $H = 6.5$, with expected amplitudes of ± 0.5 mag (Davidge & Simons 1994). Depending on the distance to NGC 6553, this translates to $M_{bol} \approx -4.8$. At the distance of M33 these stars would reach $H \approx 17$, and would have $J\text{–}K \approx 1.3$. Given their variability, we cannot exclude the possibility that some of the giants observed in the M33 bulge are like the bright variable stars in NGC 6553.

5.5 Comparison with theoretical models

MOR compared the LFs of M33 with the model predictions of Lattanzio (1991), and with the observations of Magellanic Cloud clusters by Mould el al. (1990). Here we compare the CMDs with the models of Bessell et al. (1987, 1991).

From the CMDs and color–color diagrams of the M33 bulge, there are noticeable differences between the bright supergiants and the more numerous, fainter, red supergiants. We interpret these differences as being due to different masses and chemical compositions (Bessell et al. 1987, 1991). If we adopt a mean metallicity of $[Fe/H] = -0.6$, then 1 $M_{\odot}$ models of Bessell et al. (1991) fit the observed luminosities of the bulk of the M33 bulge population. The brighter red plume seen in Figure 3 gives masses greater than 5 $M_{\odot}$. However, spectroscopy is needed to estimate metallicities, otherwise the ages are not well constrained. We also note that most of the stars in the M33 bulge, except for the brightest supergiants, are much redder than expected from the models.

5.6 Color–Magnitude Diagrams of the M33 Disk

The mean abundance of the M33 disk is $Z = 0.01 - 0.02$ (McCall et al. 1985), similar to that of the LMC. The CMD of the M33 disk resembles very closely that of the Bar West field of the LMC (Frogel, Mould & Blanco 1990). It also resembles that of the LMC clusters of SWB (Searle, Wilkinson and Bagnuolo 1980) type IV–VI (Aaronson & Mould 1985), which are characterized by the presence of luminous C stars. There are C stars present in the disk of M33, according to our photometry. This is not new and not surprising, but it is reassuring, since Cook et al. (1986) already discovered C stars in some disk fields of M33. In contrast, C stars are lacking in the MW bulge.

A comparison between the arm and inter–arm regions reveal the presence of larger numbers of bright young supergiants in the spiral arms, as expected since they are regions of more intense star formation.

A comparison between different regions of the disk shows that the N and S disk look similar. The inner and outer disk appear different, with the outer disk lacking so many red stars in proportion. The LF of the inner and outer disk are also different.

5.7 Comparison Between the M33 Bulge and Disk

Due to the viewing angle, it is impossible to observe a pure bulge field in M33, the central regions also contain disk and halo stars. We can compare the color–magnitude and color–color diagrams for the

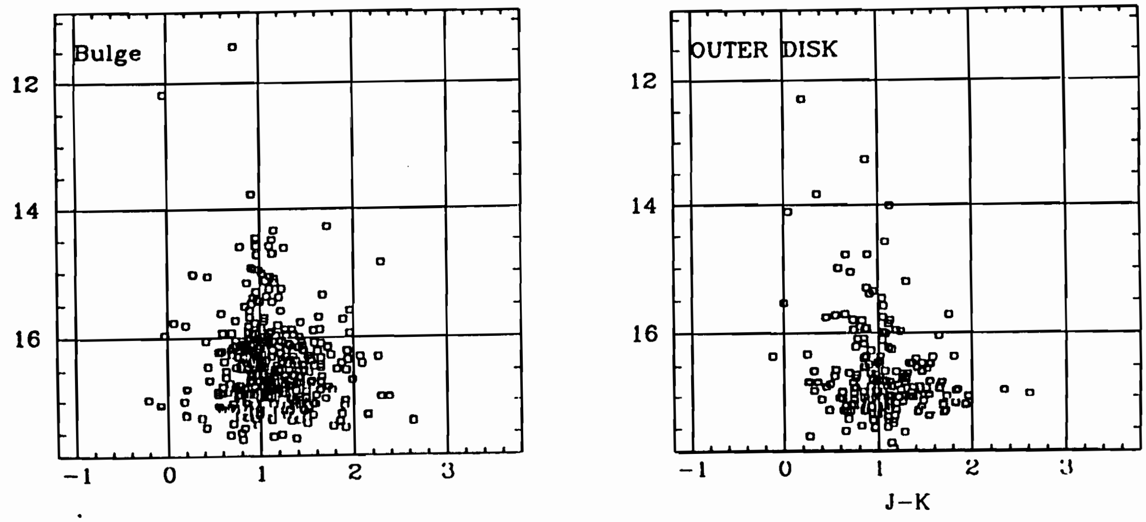

Figure 4: Left: Color–magnitude diagram of the region north of the M33 nucleus, excluding all known stellar associations. This should be more representative of the M33 bulge population. Right: CMD of the outer M33 disk, at about 2.2 kpc from the nucleus.

bulge ($40'' \leq r \leq 2'$), the inner disk ($2.5' \leq r \leq 4'$), and the outer disk ($6' \leq r \leq 14'$). The inner disk and bulge appear similar, indicating that the bulge/disk transition is not very well defined. A spatial census of the brightest stars reveals very clearly where the bulge starts contributing significant number of stars. MOR show that the number counts in the central 2 arcmin rise well above the exponential profile expected for the M33 disk (their figure 1). The luminosity functions constructed for different regions also show that, within this radius, there is a sharp increase in the fainter, redder giants, which is characteristic of a bulge population. The LF of the bulge in particular shows two clear breaks, due to the presence of a relatively young population and an intermediate age population.

There are a few differences between the CMDs for the M33 bulge and disk. The bulge has a substantially larger population of faint red stars than the disk, and the bulge region has few C stars in comparison with the disk. Also, in the bulge and the disk there are few extremely red sources like the IRAS Miras, that are common in the MW bulge.

Figure 4 (left panel) shows the 'pure bulge' population of M33 for the stars within the range 0.5' $\leq$ r $\leq$ 1.5', constructed by avoiding the known stellar associations catalogued by Wilson et al. (1990). From this figure we confirm that there has been a recent episode of star formation in the inner 2 arcmin of M33, as found by MOR from the luminosity functions at 1.6 μm.

5.8 Comparison with Association 1

Association 1 dominates the central region of M33: the blue isophotes change orientation by about 90 degrees due to its presence (Bothun 1992). A comparison between associations and the M33 bulge reveals that the associations have more brighter supergiants, and a larger ratio of blue/red stars, as expected.

MOR present a LF for Association 1, which shows stars reaching $M_{bol} = -8.0$. The CMD of the region of Association 1 looks very much like that of the stellar populations in the arms.

6 Conclusions

We have compared the bulge of M33 with those of the MW, M31 and M32. We conclude that the stellar populations in bulges of these Local Group galaxies look very similar, within the uncertainties in metallicities and distances. The only clear difference is seen in comparison with the metal–poor halo globulars of the MW: the bulges do not seem to be as old as the halo globulars clusters. There is a trace of a younger stellar component in the inner regions of M33, but it is not clear if these stars are associated with the M33 bulge or inner disk.

As pointed out by MOR, the underlying presence of an old (~15 Gyr) population cannot be ruled out in the inner regions of M33. We argue that the bulge of M33 contains a mixture of stars of different ages and metallicities.

Kinematic information is essential to properly characterize a bulge. For M33, kinematic information is only available for the nucleus, the halo and the disk. From Kormendy & McClure (1993): $\sigma_{nucleus} = 21 \pm 3$ km/s for $r < 3$ arcsec, and $\sigma_{nucleus} = 34 \pm 5$ km/s at $r = 10$ arcsec. From Schommer et al. (1991), the young disk has $\sigma_{young\ disk} = 9 \pm 4$ km/s, while the older disk has $\sigma_{old\ disk} = 25$ km/s. On the other hand, the M33 halo clusters have $\sigma_{halo} = 70$ km/s (Schommer et al. 1991). From these data, we can estimate $\sigma_{bulge} = 35$ to 70 km/s, depending on the degree of rotation.

Spectroscopic observations are clearly needed to provide more information on the kinematics. Such observations would also give metallicities.

Acknowledgements

We are very grateful to Tim Bedding for comments on the manuscript.

References

Aaronson, M., & Mould, J. 1985, ApJ, 288, 551

Bessell, M. S., & Wood, P.R. 1984, PASP, 96, 247

Bessell, M. S., Brett, J. M., Scholz, M., & Wood, P. R. 1987. AAS, 77, 1

Bessell, M. S., Brett, J. M., Scholz, M., & Wood, P. R. 1991. AAS, 89, 335

Bica, E., Barbuy, B., & Ortolani, S. 1991, ApJ, 382, L15

Bothun, G. D. 1992, AJ, 103, 104

Christian, C. A., & Schommer, R.A. 1983, ApJ, 275, 92

Cook, K. H., Aaronson, M.,, & Norris, J. 1986, ApJ, 305, 634

Carney, B. W., Latham, D. W., & Laird, J. B. 1989, AJ, 97, 823

Davidge, T. J., & Simons, D. A. 1994, AJ, 107, 240

Davies, R. L., Frogel, J. A., & Terndrup, D. A., 1991, AJ, 102, 1729

De Poy, D. L., Terndrup, D. A., Frogel, J. A., Atwood, B., & Bloom, R. 1993, AJ, 105, 2121

Elias, J., Frogel, J., Mathews, K., & Neugebauer, G. 1981, AJ, 87, 1029

Elston, R., & Silva, D. R. 1992, AJ, 104, 1360

Freedman, W. L. 1992, AJ, 104, 1349

Freeman, K. 1970, ApJ, 160, 811

Freeman, K., Illingworth, G., & Oemler, A. 1983, ApJ, 272, 488

Frogel, J. A., & Elias, J. H. 1988, ApJ, 324, 823

Frogel, J., Mould, J., & Blanco, V. M. 1990, ApJ, 352, 96

Frogel, J., Persson, S. E., & Cohen, J. G. 1990, ApJ, 352, 96

Frogel, J., & Whitford, A. 1987, ApJ, 320, 199

Humphreys, R. M., Jones, T. J., & Sitko, M. L. 1984, AJ, 89, 1155

Humphreys, R. M., & Sandage, A. 1980, ApJS, 44, 319

Kent, S.A. 1987, AJ, 94, 306

Kinman, T. D., Mould, J.R., & Wood, P. R. 1987, AJ, 93, 833

Kormendy, J., & McClure, R. D. 1993, AJ, 105, 1793

Lattanzio, J. C. 1991, ApJS, 76, 215

Madore, B. F., et al. 1985, ApJ, 294, 560

McCall, M., Rybski, P. M., & Shields, G. A. 1985, ApJS, 57, 1

Minniti, D. 1994, ApJ submitted

Minniti, D., Olszewski, E., & Rieke, M. 1993, ApJ, 410, L79

Mould, J., Graham, J. R., Neugebahuer, G., Matthews, K., & Elias, J. 1990, ApJ, 349, 503

Mould, J., & Kristian, J. 1986, ApJ, 305, 591

Pritchet, C. J. 1988, in ASP Conf. Ser. No. 4 "The Extragalactic Distance Scale", eds. S. van den Bergh & C. J. Pritchet (ASP: Provo), p. 59

Pagel, B., & Edmunds, M. G. 1981, ARA&A, 19, 77

Renzini, A. 1992, in I.A.U. Symp. 153 "Galactic Bulges", eds. H. Dejonghe & H. Habing (Dordrecht:Kluwer), p. 151

Rich, R.M. 1988, AJ, 95, 828

Rich, R.M. & Mould, J.R. 1991, AJ, 101, 1286

Rich, R.M. & Mould, J.R., & Graham, J. R. 1993, AJ, 106, 2253

Schmidt, A. A., Bica, E., & Alloin, D. 1990, MNRAS, 243, 620

Schommer, R.A., Christian, C. A., Caldwell, N., Bothun, G. D.,& Huchra, J. 1991, AJ, 101, 785

Searle, L. 1971, ApJ, 168, 327

Searle, L., Wilkinson, A., & Bagnuolo, W. G. 1980, ApJ, 239, 803

Vilchez, J. M., Pagel, B. E. J., Diaz, A. I., Terlevich, E. & Edmunds, M. G. 1988, MNRAS, 235, 633

van den Bergh S. 1991, PASP, 103, 609

Wilson, C. D. 1990, AJ, 101, 1663

Wilson, C. D., Freedman, W. L., & Madore, B. F. 1990, AJ, 99, 149

Wyse, R. F. G., & Gilmore, G. 1992, AJ, 104, 144

Zaritsky, D., Elston, R., & Hill, J. M. 1989, AJ, 97, 97