STELLAR POPULATIONS IN M31 AND M33

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1. Introduction

M31 and M33 are the two nearest extragalactic spirals. They are therefore particularly suitable for studies of stellar populations. From integrated photometry spiral galaxies are known to consist of four components: (1) a nucleus, (2) a nuclear bulge, (3) an (exponential) disk and (4) a halo. These stellar components are embedded within a massive invisible halo.

2. The Nuclei of M31 and M33

All spiral galaxies appear to contain nuclei while no irregular galaxy is known to contain a nucleus. The nucleus of M33 has B = 14.5 ± 0.1 (Nieto & Aurière 1982), which corresponds to $M_B \simeq -10.3$. The internal velocity dispersion of this nucleus is small ($\sigma \leq 30$ km s^{-1}), which indicates that its mass-to-light ratio must be low. The spectrum of the nucleus of M33 (van den Bergh 1976) is composite, with K/H + Hε yielding a late A spectral type, while CH/Hγ gives type F3 - F4. The observed spectrum and integrated colors of the nucleus of M33 might be produced by either (1) a young metal-rich population or (2) by an old stellar population that is *very* metal-poor. Van den Bergh's observations showed that λ 4325 of Fe I was stronger in M33 than in the spectra of very metal-poor globular clusters. The conclusion that the nucleus of the Triangulum nebula consists of young relatively metal-rich stars is strongly supported by recent near-infrared spectra (Schmidt, Bica & Alloin 1990). O'Connell (1983) obtains a mean nuclear star formation rate over the last 1 Gyr of ~3 x 10^{-4} $M_\odot$ yr^{-1}. Gallagher, Goad & Mould (1982) estimate the mass of the nucleus of M33 to be ~10^6 $M_\odot$.

The nucleus of M31 has B = 13.6 ± 0.3, which corresponds to $M_B = -11.0$. This value is almost two orders of magnitudes brighter than an average globular cluster. Tremaine, Ostriker & Spitzer (1975) have suggested that the nucleus of the Andromeda nebula was formed from the

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debris of globular clusters that had been dragged inwards by dynamical friction. However, the observation (van den Bergh 1969) that more than 97% of the globulars associated with the Andromeda nebula have integrated spectra which indicate that they are metal poorer than the nucleus of M31, militates against this suggestion. Probably most of the stars in nucleus formed from gas that had already been enriched in heavy elements before it flowed into the center of M31. Sandage et al. (1969) find that the inner ~ 40" of M31 exhibits an ultraviolet excess. This observation might possibly be accounted for by assuming that tidal friction dragged in some globular clusters containing blue horizontal branch stars. The large rotational velocities and velocity dispersion in the nucleus of M31 (Dressler & Richstone 1988, Kormendy 1988) requires a high central mass concentration of 10^7 - 10^8 $M_\odot$ if the nucleus is ellipsoidal, or of $10^{6.5}$ - 10^7 $M_\odot$ if the nucleus is a disk. The observed strengths of the H_2O and CO bands at 2.1 μm and 2.3 μm (Baldwin *et al.* 1973, Persson *et al.* 1980), and the low strength of the dwarf-sensitive Wing-Ford band (Whitford 1974) all indicate that the high mass-to-light ratio of the nucleus is *not* due to the presence of a dwarf-enriched lower main sequence. Jones, Alloin & Jones (1984) reached a similar conclusion from observations of the gravity sensitive Ca II triplet. Population modelling by Schmidt et al. (1989) suggest that the average logarithmic metallicity of giant stars in the semi-stellar nucleus of M31 is $[Z/Z_\odot] \simeq +0.6$.

3. The Nuclear Bulges of M31 and M33

The nuclear bulge of M31, which accounts for ~ 30% of the total visual light of the Andromeda nebula (de Vaucouleurs 1958), has an effective major axis of 17!5 (3.7 kpc). Over the range 0!1 < $\tilde{\omega}$ < 10' Kent (1983) finds that available photometry and the bulge rotation curve can be fit with a model having a mass-to-light ratio (in solar units) of $M/L_B \approx 3\,(\sigma/160)^2$, in which σ is measured in km s^{-1}. Population modelling by Schmidt et al. (1989) suggests that the average logarithmic metallicity of giant stars in the nuclear bulge of M31 is $[Z/Z_\odot] \approx +0.3$. In this respect the stars in the bulge of the Andromeda nebula are similar to those in the bulge of the Galaxy (Whitford 1985), which are also found to be super metal-rich. According to Mould (1986) the brightest M31 bulge stars are about one magnitude more luminous in I than the brightest stars in the halo of the Andromeda nebula. IUE observations (Welch 1982), and direct imaging in U and B, show that the central bulge of M31 does not contain luminous metal-rich main sequence stars. In fact most population models for the bulge of the Andromeda nebula require no main sequence stars with spectral types earlier than G0V.

The existence of a tiny nuclear bulge in M33 remains controversial. Such a bulge was first reported by Patterson (1940) and confirmed by Boulesteix et al. (1979), who found it to have an effective radius of 2!75 and a luminosity of ~ 1% of that of the exponential disk of the Triangulum nebula. More recently Kent (1987) has, however, suggested that the decomposition of the integrated light of M33 into disk and bulge components has been affected by spiral structure. The existence of the nuclear bulge of M33 therefore remains to be established with certainty.

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4. The Disks of M31 and M33

According to Walterbos & Kennicutt (1988) the disk of M31 contributes 65% of the U light and 55% of the V luminosity of the Andromeda nebula. The disk scale-length of M31 decreases with increasing wavelength. It is 7.1 ± 0.4 kpc in U, 5.5 ± 0.3 kpc in R and 4.1 kpc in the K-band at 2.2 μm (Hiromoto *et al.* 1983). This suggests that the average age of stars in the disk of the Andromeda nebula decreases with radius. This conclusion is confirmed by Walterbos & Kennicutt (1988) who find that the disk of M31 becomes slightly bluer at large radii. The ring-shaped region of active star formation between 8 and 14 kpc from the nucleus is observed to be slightly bluer than are the zones on either side of this feature. The disk scale-length of M31 is comparable to, or slightly larger than, that of the Galaxy which lies in the range 3.5 - 5.5 kpc (Freeman 1987).

The distribution of late-type stars in the disk of M31 has been studied by Richer, Crabtree & Pritchet (1990). The carbon to late M star ratio in Baade's Field IV at 20 kpc from the nucleus was, perhaps surprisingly, found to be similar to that obtained by Richer & Crabtree (1985) in a field at only 11 kpc from the nucleus, in which the stellar metallicity is expected to be higher (Blair, Kirshner & Chevalier 1982).

Color-magnitude diagrams for disk stars, based on CCD images, are now available from the work of Crotts (1986), Hodge, Lee & Mateo (1988) and Hodge & Lee (1988). Unfortunately the latter two investigations do not reach deep enough to study the oldest population component of M31. Crott's data might perhaps be understood in terms of a model in which the dominant population of the outer disk consists of stars similar to, or slightly metal-richer than, those in the Galactic globular cluster 47 Tucanae, on which a lesser component resembling the intermediate - age Galactic cluster NGC 2158 is superimposed.

From digital stacking of Palomar Schmidt plates Innanen et al. (1982) found that the outermost part of the disk of M31 is warped. The fact that this warp is visible on both yellow and red-sensitive plates, shows that it is due to starlight, rather than to emission nebulosity. That the outermost "Population II suddenly swirls off to one side" was first noted by Baade (1963). It is of interest to note that the optical and radio (Newton & Emerson 1977, Cram, Roberts & Whitehurst 1980) images are warped in the same direction.

According to Kent (1987) the exponential disk of M33 has a scale-length of 9.'6 (2.2 kpc). Integrated photometry by de Vaucouleurs (1959) shows that the outer regions of the disk of the Triangulum nebula are slightly bluer (B - V = 0.50, U - B = -0.17) than are its inner regions (B - V = 0.59, U - B = -0.04). This effect might be due to a radial population gradient and/or to lower dustiness (Israel & Kennicutt 1980) of the outer metal-poor (Pagel & Edmunds 1981) regions of the disk.

From radial velocity observations Boulesteix & Monnet (1970) showed that the mass-to-light ratio of M33 increases by a factor of eight between 5' and 40' (1 - 9 kpc) from the nucleus. This observation constituted the first evidence for the existence of dark matter in the halo of the Triangulum nebula.

The resolution of the disk of M33 into stars was first achieved by the Earl of Rosse (1850). Lundmark (1921) found the brightest stars in the Triangulum nebula to have B ≃ 15.7. Counts of early-type stars over the face of M33 have been published by Madore, van den Bergh & Rogstad (1974). Their data showed no simple relationship between the surface density of OB stars and that of neutral hydrogen gas. Reasons for this are probably that (1) a significant fraction of the gas in the central regions of M33 is in molecular form (Wilson et al. 1988), (2) the thickness of the M33 gas layer may increase with radial distance (as it does in the Galaxy), so that there is no one-to-one correspondence between the *surface* density of young luminous stars and the *space* density of HI, and (3) a minimum gas density may be required to trigger star formation (Kennicutt 1989).

Freedman (1985) observed that the upper ends of the M31, M33 and LMC luminosity functions are similar. Humphreys & Sandage (1980) find that the brightest blue and red supergiants in M33 have M_V = -9.4 and M_V = -8.15, respectively.

According to Walker (1964) the ratio of the number of blue to red supergiants in M33 varies with distance from the nucleus. This conclusion was subsequently confirmed by Humphreys & Sandage (1980) but not by Freedman (1985). Recent CCD observations by Wilson (1990) show no gradient in the ratio of red to blue supergiants in the inner 2 kpc of M33. Data on OB associations at larger radii (and lower metallicities) should be obtained to confirm this conclusion.

Since M33 has a radial abundance gradient (Vilchez et al. 1988, Zaritsky et al. 1989) one would expect the WC-to-WN ratio to decrease with increasing galactocentric distance. This expectation is confirmed by Massey & Conti (1983). According to Schild, Smith & Willis (1990) line-widths of early WC stars in M33 also appear to correlate with galactocentric distance.

5. The Halos of M31 and M33

Mould & Kristian (1986) have obtained I versus V - I color magnitude diagrams for halo fields in M31 and M33. Their data show that the halo of the Triangulum nebula has a red giant branch similar to those of metal-poor globular clusters, whereas the stars in the halo of the Andromeda nebula appear to exhibit a high mean metallicity and a large metallicity dispersion. The existence of old stars of low metallicity in the halo of M33 is confirmed by the discovery of 6 RR Lyrae stars by Pritchet & van den Bergh (Pritchet 1988). Further support for the existence of a halo population in M33 is provided by the important discovery (Schommer et al. 1991) that old red star clusters with B - V ≥ 0.6 have a significantly larger velocity dispersion than do younger blue clusters. In this respect the oldest clusters in M33 differ from those in the Large Magellanic Cloud which appear to belong to a (thick) disk population (Freeman, Illingworth & Oemler 1983). The fact that M33 contains a significant halo population, but little or no nuclear bulge suggests that *the halo and bulge constitute separate building blocks of galaxies i.e. the halo is not just a continuation of the nuclear bulge to large radii.* According to Harris (1991) the globulars in M33 have $< M_V > = -7.0 \pm 0.2$, with a dispersion of 1.2 mag. Taken at face value this result suggests that the luminosity function of M33 globular clusters is similar to that of globulars associated with the Milky Way. It would be important to obtain accurate reddening values for individual globular clusters in M33 to strengthen and confirm this conclusion.

Mould & Kristian (1986) have studied the color-magnitude diagram of a halo field that is located 40' (8.4 kpc) from the nucleus of M31. They find that the majority of stars in this region have metallicities between those of the Galactic globular clusters M92 and 47 Tuc. From a more detailed study of the same zone in the halo Pritchet & van den Bergh (1988) showed that the average metallicity in the inner halo of M31 is [Fe/H] ≃ -1.0, with a dispersion $\sigma_{[Fe/H]} \simeq 0.3$. This mean metallicity is slightly higher than the average metallicity of M31 globular clusters. For 150 clusters Huchra, Brodie & Kent (1991) obtain $< [Fe/H] > = -1.21 \pm 0.02$. This value is significantly higher than $< [Fe/H] > = -1.40 \pm 0.01$ for 121 Galactic globulars (Brodie & Huchra 1991). The observation that the M31 globulars are, in the mean, somewhat metal-richer than their Galactic counterparts is consistent with the well-established correlation between mean metallicity of globular cluster systems and the luminosity of their parent galaxies (van den Bergh 1975,

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Mould, Oke & de Zeeuw 1991).

Huchra *et al.* (1991) find that all M31 globulars metal-richer than [Fe/H] = -0.5 are located within 10 kpc of the nucleus of that galaxy. However, no obvious correlation between metallicity and projected distance from the nucleus is seen for clusters with [Fe/H] < -0.5. Metal-rich clusters with [Fe/H] ≥ -0.8 in M31 appear to form a rotating disk that extends out to $\tilde{\omega} \simeq 5$ kpc. In the Milky Way all but one of the metal-rich disk ($|Z| < 2$ kpc) clusters are also located in a disk with $\tilde{\omega} \simeq 5$ kpc (Armandroff 1989). This result suggests that the metal-rich disk clusters in the Milky Way extend over a larger *fraction* of the optical disk than do those in the Andromeda nebula.

From Palomar 5-m spectra van den Bergh (1969) found that CN is stronger in M31 globular clusters than it is in Galactic globular clusters of similar metallicity. This conclusion has more recently been strengthened and confirmed by Burstein et al. (1984), Tripicco (1989), Brodie & Huchra (1990) and in the infrared by Davidge (1990). Burstein *et al.* have claimed that M31 globulars also exhibit significantly stronger Balmer lines than do Galactic globulars. However, CCD spectra by Tripicco, which cover the range λλ 3850 - 4200, appear to rule out a significant contribution of horizontal branch stars to the integrated spectra of M31 globulars.

For field stars in the inner halo of M31 Pritchet and van den Bergh (1988) conclude that the blue horizontal branch is probably weak. For 28 cluster-type variables in M31 these authors find $<P_{ab}> = 0.55$ days, which indicates that the RR Lyrae stars in the inner halo of the Andromeda nebula belong to Oosterhoff's type I.

The fact that the inner halo of M31 is both relatively metal-rich ([Fe/H] $\simeq$ -1.0), and rich in RR Lyrae stars, suggests that its stellar population is similar to that in the Galactic globular cluster NGC 6171. This conclusion is strengthened and confirmed by the location of the tip of the M31 giant branch in the V versus B-V color magnitude diagram (see Figure).

Observations of the halo planetary nebulae M31 - 290 and M31 - 372 (Henry 1990) yield logarithmic oxygen abundances of 8.54 and 8.05, on a scale where the logarithmic hydrogen abundance is 12. These observations provide direct evidence for a significant spread in the metallicity of stars in the halo of the Andromeda nebula.

Using the 3.6-m CFH telescope we have observed a number of areas in the halo of M31. These fields are located along both the minor axis (from 40' to 5° from the nucleus), and at an angle of 30° to the major axis (out to 2° from the nucleus). All fields were observed with an RCA CCD at the prime focus of CFHT (field 2' x 3'). Exposure times were typically 45 min to 1 hour through B and V filters.

Data reduction techniques were standard. We used DAOPHOT (Stetson 1987) to measure magnitudes, and calibrated each field using Landolt (1983) standard stars. The limiting magnitude of the data (S/N = 4) appears to be about V = 24.5 and B = 25. Here we briefly discuss the data for the innermost three fields. The outer fields are much sparser, due to the steep stellar density gradient in the halo of M31. A detailed analysis of the CMD's in these outer fields will have to await completeness and error analysis using DAOPHOT add-star experiments.

The color-magnitude diagrams for our fields are shown in Figure 1. The fields shown are M0 (40' from nucleus, originally studied by Pritchet and van den Bergh 1987), M1 (1° from nucleus along the minor axis), M2 (1°.5 from the nucleus along the minor axis) and E1 (40' along major axis and 40' along the minor axis from the nucleus. The figures also show fiducial sequences for some Galactic globular clusters with a range of metallicity, adjusted to the reddening and absorption of M31. The clusters shown are M92 [Fe/H = -2.24], M5 [Fe/H = -1.40], and 47 Tuc [Fe/H = -0.71] (Suntzeff, Kinman & Kraft 1991).

The fields M0, M1 and E1 show a prominent giant branch that reaches up to between V = 22.5

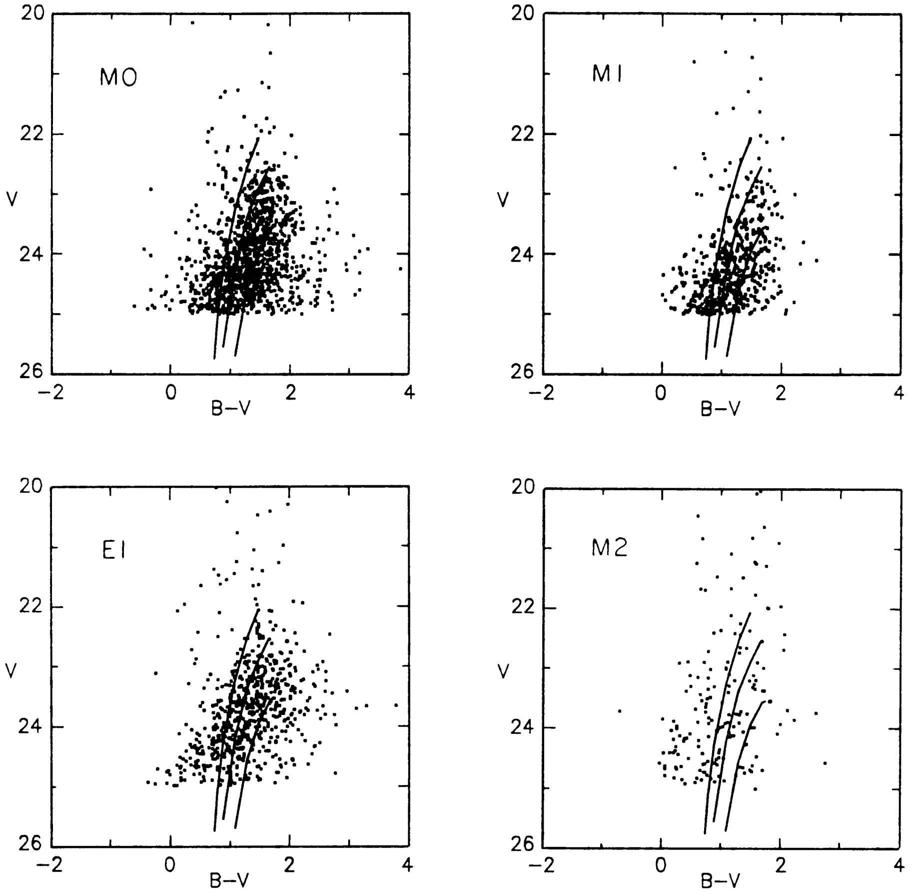

Figure 1 Color-magnitude diagrams for four M31 halo fields. M0, M1 and M2 are located along the minor axis at distances of 0°.67, 1°.0 and 1°.5 from the nucleus, respectively. Field E1 is located 40' along the major axis and 40' along the minor axis. Due to a steep stellar density gradient most stars in field M2 are probably Galactic foreground objects. No obvious metallicity differences are seen between fields M0, M1 and E1. The fiducial sequences shown are those of M92, M5 and 47 Tuc shifted by $E_{B-V} = 0.08$ and $A_V = 0.24$ mag.

and V = 23, which is intermediate in color between those of the giant branches of 47 Tuc and M5 - in good agreement with the results of Pritchet and van den Bergh (1987). None of the CMD's reach deep enough to show the horizontal branch. The principal conclusion from overlaying these CMD's, and also from comparing histograms of the color distribution of stars between V = 23 and 24, is that *the median B-V color of the halo giant branch in the three inner halo fields does not vary by more than ± 0.1 mag peak-to-peak in B-V.* Adopting d(B-V)/d[Fe/H] ≈ 0.5 at [Fe/H] = -1 (e.g. Pritchet & van den Bergh 1987), this maximum range in B-V corresponds to ± 0.2 in [Fe/H]. This indicates that, within the inner halo of M31, there is not a significant gradient in metallicity either perpendicular or parallel to the disk. The range in color is consistent with the observation that the V magnitude of the giant branch tip is the same for all three inner halo fields to within ± 0.2 mag peak-to-peak, correspoding to a metallicity difference of ± 0.3 in [Fe/H] (Pritchet & van den Bergh 1987).

Further results for these and other M31 fields are in preparation (Pritchet & van den Bergh 1992).

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