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THE STELLAR POPULATIONS OF M 31[1]

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ABSTRACT

Available data on stellar populations in the Andromeda nebula = M 31 = NGC 224 are reviewed. A distance modulus $(m-M)_0 = 24.3 \pm 0.1$ (estimated error), corresponding to a distance of 725 ± 35 kpc, and a foreground reddening $E_{B-V} = 0.08$ will be adopted throughout this paper. Population I and Population II distance indicators give distances to M 31 that agree to better than 5%.

The high rotational velocity and large velocity dispersion observed in the semistellar nucleus of the Andromeda nebula demonstrate that it contains a compact mass of $\sim 10^7\ \mathfrak{M}_\odot$. Spectroscopic observation of line and molecular features now rules out the possibility that the high mass-to-light ratio observed in the nucleus of M 31 is due to a dwarf-enriched mass spectrum of star formation. Such observations also militate against the hypothesis that the dominant stellar population of the nucleus consists of stars that once belonged to globular clusters that were captured by tidal friction. The semistellar nucleus of M 31 and its dynamical center appear to be separated by $\sim 0''.5$ (1.8 pc).

The halo of M 31 is found to be rich in RR Lyrae stars that belong to Oosterhoff Type I. The mean metallicity of stars in the halo remains controversial. The color-magnitude diagram of the halo of M 31 appears to show that the blue horizontal-branch population is weak.

Key words: M 31–galaxies–stellar populations

1. Introduction

M 31, which is the most luminous galaxy in the Local Group, is a spiral of type Sb I–II. Its integrated magnitude and colors are $B_T = 4.36$, $(B-V) = 0.91$, and $(U-B) = 0.50$ (de Vaucouleurs 1958). This integrated brightness agrees well with CCD photometry by Pierce & Tully (1991) who obtain $B_T = 4.39$. On the sky M 31 covers an area of $92' \times 197'$ (Holmberg 1958), corresponding to linear dimensions of 19×42 kpc. This large size makes the Andromeda nebula particularly suitable for detailed studies of its structure and stellar content.

According to de Vaucouleurs (1958), M 31 consists of two principal components: (1) a nuclear bulge with an $r^{1/4}$ profile, which contributes ~ 30% to the total luminosity of the Andromeda nebula in yellow (V) light, and (2) an exponential disk, which accounts for ~ 70% of its V light. Additionally, M 31 contains an extended halo component and a semistellar nucleus.

Baade (1944) showed that the disk of the Andromeda nebula is dominated by young stars of Population I. Furthermore, he proposed that the bulge component of M 31 consists of globular-cluster-like stars of Population II. Apparent confirmation of this hypothesis was provided by his observation (Baade 1951) that the nuclear bulge of the Milky Way System contains numerous RR Lyrae variables. The first doubts about Baade's simple two-population model of stellar populations in galaxies were raised by Morgan & Mayall (1957), who showed that "cyanogen giants", i.e., luminous *metal-rich* stars, appeared to provide the dominant contribution to the integrated spectrum of the nuclear bulge of M 31. This conclusion was subsequently strengthened and confirmed by the spectrophotometry of van den Bergh & Henry (1962) and by Thuan & Oke (1976). Furthermore, McClure (1969), Oke & Schwarzschild (1975), and Thuan & Oke (1976) were

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[1] One in a series of invited review papers currently appearing in these *Publications*.

able to show (see Fig. 1) that the CN strength in the nucleus of M 31 is even greater than it is in the bulge of that galaxy. These observations showed (see Morgan & Osterbrock (1969) for a review) that the dominant contribution to the integrated light of the bulge and nucleus of M 31 is provided by CN-strong giant stars. A similar situation prevails in the Galactic nuclear bulge (Whitford 1985) in which the dominant population component is now known to consist of super-metal-rich stars. The metal-poor RR Lyrae stars in the nuclear bulge belong to a minority constituent that provides only a negligible contribution (except perhaps in U) to the total integrated light.

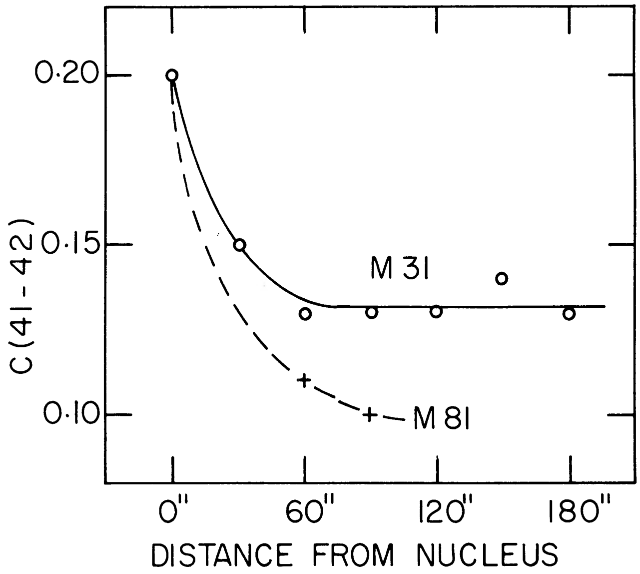

FIG. 1–Cyanogen strength as a function of distance from the nuclei of M 31 and M 81. The figure shows that metallicity increases toward the centers of these galaxies.

A very useful atlas of M 31 has been published by Hodge (1981). A good bibliography, complete to May 1973, is provided by Brosche, Einasto & Rümmel (1974). Various catalogs of different kinds of objects in M 31 are listed by Battistini (1988). A summary of observational parameters for M 31 is given in Table 1.

2. Foreground Reddening

Assuming the standard relation between hydrogen column density and absorption in the direction of M 31, Burstein & Heiles (1984) find a Galactic foreground absorption $A_B = 0.32$ mag, corresponding to $E_{B-V} = 0.08$. From an analysis of IRAS observations, Walterbos & Schwering (1987) derive values of the Galactic foreground reddening in the range $0.06 \lesssim E_{B-V} \lesssim 0.09$. Massey, Armandroff & Conti (1986) find a minimum reddening $E_{B-V} = 0.08$ for the M 31 OB associations studied by them. This value will be adopted in the subsequent discussion. From DDO photometry of late-type foreground field stars McClure & Racine (1969) found a slightly

TABLE 1

Summary of M31 Data

Parameter	Value	Reference
α (1950)	$00^{h}\,40^{m}00\overset{s}{.}3$	Dressel & Condon 1976
δ (1950)	+41° 00′ 03″	
Radial velocity	-300 km s^{-1}	Rubin & Ford 1970
Type	Sb I-II	van den Bergh 1960
Foreground reddening	$E_{B-V} = 0.08$	Burstein & Heiles 1984
True distance modulus	24.3 ± 0.1	See Table 2
Distance	725 ± 35 kpc	
Optical size	92′ x 197′ (19 x 42 kpc)	Holmberg 1958
Position angle	$37\overset{\circ}{.}7 \pm 0\overset{\circ}{.}2$	de Vaucouleurs 1958
Neutral hydrogen size	55′ x 315′ (12 x 66 kpc)	Newton & Emerson 1977
Inclination	$77\overset{\circ}{.}5$	de Vaucouleurs 1959
Disk scale-length(R)	5.5 ± 0.3 kpc	Walterbos & Kennicutt 1988
B_T	4.36 ± 0.02	de Vaucouleurs 1958
$(B-V)_T$	0.91	de Vaucouleurs 1958
$(U-B)_T$	0.50	de Vaucouleurs 1958
M_V	- 21.1	

higher reddening $E_{B-V} = 0.11 \pm 0.02$. Finally, Schmidt-Kaler (1967) derived $E_{B-V} = 0.12 \pm 0.04$ from a comparison between the colors of little-reddened open clusters in M 31 and the Galaxy. The value $A_V = 0.06$, corresponding to $E_{B-V} = 0.02$, which Feast (1991) has recently derived for Cepheids in the outer part (Baade's Field IV) of M 31 conflicts with all other recent determinations of the foreground reddening in the direction of the Andromeda nebula.

Modern determinations of the distance to the Andromeda nebula have been based on (1) H-band (1.65-μm) photometry of seven Cepheids (Welch et al. 1986) and multicolor observations of Cepheids by Freedman & Madore (1990), (2) comparison of the red-giant branches of globular clusters in M 31 (Christian & Heasley 1991) with red giants of similar metallicity in Galactic globulars, (3) comparison of M 31 halo red giants with similar objects in Galactic globular clusters (Mould & Kristian 1986), (4) comparison of the maximum-magnitude versus rate-of-decline relations for novae in M 31 and in the Galaxy (Capaccioli et al. 1989), and (5) magnitudes of RR Lyrae variables in the halo of M 31 (Pritchet & van den Bergh 1987a). From these data, which have been compiled in Table 2, the mean unweighted true distance modulus of M 31 is $(m-M)_0 = 24.3 \pm 0.1$ (estimated error). The corresponding distance to the Andromeda nebula is 725 ± 35 kpc. With this distance, and the reddening value adopted above, one obtains $V_0 = 3.21$ and $M_V = -21.1$ for M 31. Including an (uncertain) correction for internal absorption (Sandage & Tammann 1981) the intrinsic stellar luminosity of the Andromeda nebula is $M_V^{oi} \simeq -21.9$, corresponding to $5 \times 10^{10} L_{\odot} (V)$.

Very recently Tonry (1991) has compared surface brightness fluctuations in the nuclear bulge of M 31, with similar fluctuations in distant E and S0 galaxies, to calibrate the extragalactic distance scale.

3. The Nucleus of M 31

The semistellar nucleus of M 31 (= BD +40 148) appears to be a physical entity that is distinct from the central bulge of the Andromeda nebula (Light, Danielson & Schwarzschild 1974). High-resolution balloon observations show that the nucleus is elliptical with dimensions of $1''.0 \times 1''.6$ FWHM (3.5 × 5.6 pc). According to Light et al. (1974) the nuclear magnitude is $V = 12.6 \pm 0.3$, which corresponds to $M_V = -11.9$, i.e., the nucleus of M 31 is ~ 80 times more luminous than an average globular cluster. The fact that the position angle of the nucleus ($\phi = 63° \pm 5°$) differs significantly from that of the major axis of M 31 itself ($\phi = 37^{\circ}.7 \pm 0^{\circ}.2$) supports the notion that the nucleus must be a distinct dynamical entity. Tremaine, Ostriker & Spitzer (1975) have suggested that the nucleus of M 31 was built up from globular clusters that were dragged inward by dynamical friction. A strong argument against this hypothesis is provided by the observation (van den Bergh 1969) that more than 97% of the globular clusters in M 31 have integrated spectra that are metal poorer than the semistellar nucleus of the Andromeda nebula. This observation suggests that *the dominant stellar population in the nucleus of M 31 was not derived from objects similar to typical presently existing globular clusters.* One cannot, however, exclude the possibility that the inner bulge of M 31 once contained a population of super-metal-rich clusters that were sucked into the nucleus by dynamical friction. Alternatively, the nucleus of M 31 might have formed by inflow of gas that had already been strongly enriched in heavy elements by evolving stars. Spectroscopy shows no evidence for the kind of activity that is observed in AGNs, or more weakly in the nucleus of the nearby spiral M 81 (Peimbert & Torres-Peimbert 1981).

Spiller et al. (1990) find that the compact nucleus of M 31 is significantly bluer ($(V-K) = 2.1 \pm 0.4$) than the inner bulge ($(V-K) = 3.6 \pm 0.2$) of that galaxy. Furthermore, Sandage, Becklin & Neugebauer (1969) find that the inner ~ 40″ of the M 31 bulge exhibits an ultraviolet excess which is not observed at longer wavelengths. These observations might possibly be accounted for by the hypothesis that globular clusters captured by tidal

TABLE 2

Modern Distance Determinations

Method	Reference	$(m-M)_o$
Cepheids	Welch et al. 1986	$24.26^a \pm 0.16$
Cepheids	Freedman & Madore 1990	$24.38^a \pm 0.12$
Cluster red giants	Christian & Heasley 1991	~ 24.3
Halo red giants	Pritchet & van den Bergh 1988	24.23 ± 0.15
Novae	Capaccioli et al. 1989	24.27 ± 0.20
RR Lyrae	Pritchet & van den Bergh 1987a	24.33 ± 0.15
Carbon stars	Richer et al. 1990	$24.45^a \pm 0.18$

[a] A true distance modulus $(m-M)_o = 18.45$ was assumed for the LMC.

friction, which contain metal-poor stars (and some blue horizontal-branch stars), provide a (small) contribution to the light of the nucleus and inner bulge of M 31 at short wavelengths. This speculation is consistent with IUE observations by Welch (1982) which appear to indicate that hot highly evolved stars are more concentrated in the nucleus of M 31 than are the more metal-rich red giants.

During the last quarter century the kinematics and dynamics of the nucleus of M 31 have been the subject of numerous observational and theoretical studies. Recently the nature of this nucleus has become more tightly constrained by high-resolution observations obtained by Dressler & Richstone (1988) and by Kormendy (1988). These observations show that the central few parsecs of the nucleus of M 31 exhibit both rapid rotation and a large velocity dispersion. The rotational velocity of the nucleus reaches a peak of 149 ± 5 km s^{-1} at 1."1 from the center of the galaxy. The maximum apparent velocity dispersion is 245 km s^{-1}. These high velocities require a central black hole or compact massive object of mass 10^7–10^8 $\mathfrak{M}_\odot$ if the nucleus is ellipsoidal, or $10^{6.5}$–10^7 $\mathfrak{M}_\odot$ if the nucleus is a disk. (For a disk, projection effects do not dilute the large velocity near the center, so less rotation and dispersion are required to fit the radial-velocity observations.) Dressler & Richstone (1988) argue against a central disk because the Stratoscope balloon observations (Light et al. 1974) give no indication that the isophotes of the nucleus become flatter as one approaches the center.

From their Palomar 5-m observations Dressler & Richstone (1988) arrive at the puzzling conclusion that the maximum velocity dispersion and center of rotational symmetry in the nucleus of M 31 deviate from the center of light by ~ 0."5 (1.8 pc). Note, however, that the kinematical center of M 31 appears to coincide with the center of symmetry of the bulge isophotes just outside the nucleus! This displacement of the kinematical center of M 31 would, if real, require that either (1) the light distribution in the center of M 31 is strongly affected by absorption, (2) the central distribution of light is asymmetrical due to the recent capture of a dwarf galaxy, or (3) the central asymmetry represents a true dynamical oscillation of the nuclear stellar population around the center of mass. Recently Mould et al. (1989) have obtained an infrared image of the nucleus of M 31. They find that their 2.2-μm image has its highest brightest contours offset by 0."4 to the NE relative to the centroid of the lower surface brightness isophotes. This confirms the offset that Light et al. (1974) had previously discovered at optical wavelengths. Since interstellar dust scattering is ~ 15 times smaller at 2.2 μm than it is in the blue, this appears to rule out dust absorption as the primary cause of the nuclear asymmetry in M 31. Because the merger time scale with a dwarf galaxy is expected to be only ~ 10^7 yr, the a priori probability that a merger is taking place at the present time is very low. This appears to leave a real separation of ~ 0."5 between the position of the optical nucleus of M 31 and its dynamical center as the most probable (but puzzling) alternative.

The nucleus of M 31 is clearly in a very low state of activity. This is, no doubt, due to the fact that it is located in a relatively gas-poor environment. Van Speybroeck et al. (1979) found that the nucleus of the Andromeda nebula coincides (at the 90% confidence level) with a 10^{38} erg s^{-1} X-ray source. However, this conclusion is not confirmed by the more recent X-ray source list of Trinchieri & Fabbiano (1991). An extended radio source with a half-power beam width of 120" × 80" and a 1.4 GHz flux density of 0.24 × 10^{-26} W m^{-2} Hz^{-1} (Pooley & Kenderdine 1967) is centered on the nucleus. However, no point source ($\lesssim$ 20") with $S > 5 \times 10^{-29}$ W m^{-2} Hz^{-1} is observed to be coincident with the nucleus. A modern and detailed VLA study of the center of M 31 would clearly be very desirable.

For more than 20 years the nature of the stellar population in the nucleus of M 31 has been a subject of numerous papers and lively controversy. The main questions at issue were: (1) are the stars in the nucleus super metal rich, (2) is the nuclear luminosity function enriched in dwarf stars, and (3) does the nucleus contain significant numbers of young main-sequence stars with spectral types earlier than G0 V?

From five-color intermediate-band DDO photometry McClure & van den Bergh (1969) concluded that super-metal-rich μ Leonis-type giants are required to account for the observed colors of the nucleus of M 31. From spectroscopic observations of weak blends of iron-peak lines near λ7400 Pritchet & Campbell (1980) surmised that the stars in the nucleus of M 31 have near-solar iron-peak abundances, even though CNO and/or Mg and Na appear to be overabundant. This conflicts with the more recent work of Rich (1988) who finds that both weak and strong Fe lines in Galactic bulge stars (which are presumably similar to those near the center of M 31) are just as enhanced as those of Mg and Na, i.e., bulge stars are truly super metal rich.

In order to explain the high $\mathfrak{M}/L$ values of the nucleus of M 31, Spinrad & Taylor (1971) and Faber & French (1980) proposed that the stellar luminosity function in the nucleus of the Andromeda nebula was greatly enriched in low-luminosity dwarf stars. However, Baldwin et al. (1973) and Persson et al. (1980) showed that this suggestion appeared to be at variance with the observed strengths of H_2O and CO bands at 2.1 μm and 2.3 μm. Finally, Whitford (1974) demonstrated that the low strength of the dwarf-sensitive Wing-Ford band near 9910 Å in the spectrum of the nucleus of M 31 was incompatible with highly dwarf-enriched population models. A similar conclusion was drawn from observations of the gravity-sensitive Ca II triplet by Jones, Alloin & Jones (1984). However, a possible "fly in the ointment" was that the strength of λ8190 of Na I appeared to require a substantial dwarf enrichment. This problem now appears to have been resolved by Alloin & Bica's (1989) evidence suggesting that the enhanced absorption around 8200 Å is *not* due to strengthening of the Na I lines but rather to another absorber, possibly a molecular band, at $\lambda \simeq$ 8205 Å.

In summary, it now appears that a dwarf-enriched stellar main-sequence population is incompatible with presently available spectroscopic constraints. As a consequence it no longer appears possible to avoid the conclusion that *a compact massive object is required to account for the high rotation and velocity dispersion that is observed in the central region of M 31.*

IUE observations (Welch 1982) and direct imaging in U and B show that the central bulge of M 31 does not contain luminous metal-rich main-sequence stars. In fact, most population models require no main-sequence stars with spectral types earlier than G0 V at all. Population modeling by Schmidt et al. (1989) suggests that the average logarithmic metallicity of giant stars in the semistellar nucleus of M 31 is $[Z/Z_\odot] \simeq +0.6$, whereas the bulge population is somewhat less metal rich with $[Z/Z_\odot] \simeq +0.3$. Somewhat surprisingly Davidge, De Robertis & Yee (1990) find no evidence for a systematic radial gradient in the equivalent width of the 3360 Å band of NH in the central region of M 31.

4. The Nuclear Bulge

The integrated colors of the nuclear bulge of M 31 are $(B-V) = 1.02$ and $(U-B) = 0.48$ (de Vaucouleurs 1961). According to de Vaucouleurs (1958), ~ 30% of the total visual light of M 31 is contributed by this bulge, which has an effective semimajor axis $a_e = 17\farcm5$ (3.7 kpc) and an apparent flattening $b_e/a_e \simeq 0.6$. According to Richstone & Shectman (1980), the rotational velocity in the bulge of M 31 is sufficient to account for its observed flattening. CCD photometry by Kent (1983) shows that the inner part of the radial-luminosity profile of the bulge deviates significantly from an $r^{1/4}$ law. According to Kent (1987) the isophotes of the nuclear bulge of M 31 are distinctly "boxlike". Jones et al. (1984) find no spectroscopic evidence for any changes in the nature of the stellar population in the innermost 30″ (100 pc) of the bulge.

A compilation of velocity dispersion measurements in the bulge of M 31 has been published by Lawrie (1983). The unweighted mean bulge (excluding the nucleus) velocity dispersion is $< \sigma > = 146 \pm 6 \text{ km s}^{-1}$. According to McElroy (1983) the bulge velocity dispersion drops rapidly beyond $a = 1'$ (0.2 kpc) and reaches 100 km s^{-1} at $a = 3'$ (0.6 kpc). Over the range $0\farcm1 < a < 10'$ Kent (1983) finds that available photometry and the bulge rotation curve can be fit with a model in which the mass-to-light radio (in solar units) is given by

$$\mathfrak{M}/L_B \simeq 3\,(\sigma/160)^2 \ . \qquad (1)$$

This value is only half as large as that obtained earlier by Simien, Pellet & Monnet (1979).

Rocket UV observations show no detectable point sources in the nuclear bulge of M 31. From this observation Bohlin et al. (1985) conclude that the bulge contains no main-sequence stars hotter than B0 V. Ultraviolet observations by Deharveng et al. (1982) limit the star-formation rate in the bulge of M 31 to $\sim 1 \times 10^{-4}\, \mathfrak{M}_\odot \text{ yr}^{-1}$, if a Salpeter luminosity function is assumed. This compares to $3 \times 10^{-2}\, \mathfrak{M}_\odot \text{ yr}^{-1}$ of gas ejected by planetary nebulae in the bulge of M 31 (Ford & Jacoby 1978a). To prevent a buildup of gas in the nucleus one therefore has to assume that the center of the Andromeda nebula is continuously cleansed by stellar winds (van den Bergh 1957). What little gas does remain in the nuclear bulge exhibits an intricate spiral-like pattern (Ciardullo et al. 1988). Remarkably this spiral pattern appears more nearly face-on than does M 31 itself. This observation might possibly be understood by assuming that the gas collected from evolving stars in the bulge has collapsed into a disk whose plane is tipped relative to that of the stellar disk. This speculation is supported by more recent observations by Boulesteix et al. (1987). Jacoby, Ford & Ciardullo (1985) estimate that the total mass of ionized gas in the nuclear bulge of M 31 is 1500 $\mathfrak{M}_\odot$. According to Ciardullo et al. (1988) the density of this gas falls off by at least two orders of magnitude in the central arc minute of the galaxy.

The intricate pattern of dust patches superimposed on (and embedded in) the bulge of M 31 is beautifully shown on a photograph published by Johnson & Hanna (1972). According to Hodge (1980) the number of visible dust clouds in M 31 drops off steeply with radius. Reasons for this are probably that (1) dust clouds are easier to see when they are projected on the smooth bright central regions of the bulge, and (2) the metallicity (and hence dustiness of the gas) decreases as a function of radial distance from the nucleus.

Fabbiano, Trinchieri & van Speybroeck (1987) and Makishima et al. (1989) find that the X-ray spectrum of the bulge of M 31 is essentially indistinguishable from that of Galactic low-mass X-ray binaries. The distribution of luminous X-ray sources with $L_x \geq 10^{37}$ erg s^{-1} in the bulge of the Andromeda nebula has been investigated by Vader et al. (1982). The region studied by these authors is free of star formation, so that none of the sources are likely to have high-mass Population I progenitors. Vader et al. (1982) find that over the inner 8′ (1.7 kpc) of M 31, the radial frequency distribution of field (i.e., nonglobular cluster) X-ray sources and the radial luminosity profile of the bulge are essentially indistinguishable. Furthermore, their data show that the innermost region of the bulge of M 31 contains 38 luminous X-ray sources, compared to only 8 such sources in a volume of comparable size surrounding the Galactic nucleus. Taken at face value these results suggest that the bulge of M 31 contains ~ 4 times as many luminous X-ray sources per unit volume as does the Galactic nuclear bulge. This difference is most likely due to a higher volume density of old stars (and low-mass binaries) in the bulge of M 31, although differences in physical conditions between the core regions of M 31 and the Galaxy might also play a role.

A comparison between some of the properties of the nuclear bulges of M 31 and the Galaxy are given in Mould (1986). In the infrared he was able to resolve the nuclear bulge of M 31 at ~ 1 kpc from the nucleus. Mould found that *the brightest bulge stars in the Andromeda nebula are about one magnitude more luminous in the I band than are the brightest stars in the halo of this galaxy.* From *J*- and *K*-band photometry, Rich & Mould (1991) find that the luminosity function of red giants in the bulge of M 31 extends to $\mathfrak{M}_{\mathrm{bol}} = -5.5$, whereas observations of the Galactic nuclear bulge population in Baade's Window ($\ell = 1^{\circ}\!.0$, $b = -3^{\circ}\!.9$) appear to exhibit a cutoff at $\mathfrak{M}_{\mathrm{bol}} = -4.2$, i.e., the Galactic bulge at $Z = -0.6$ kpc does not contain red giants with bolometric luminosities similar to Mira stars with $P \sim 800$ days. Due to projection effects it is not clear whether such objects occur throughout the bulge of the Andromeda nebula or if they are confined to a disk; as seems to be the case for the most metal-rich globular clusters in M 31 (Huchra, Brodie & Kent 1991). It is not yet entirely certain whether the presence of objects resembling Mira stars with $P \sim 800$ days implies that the bulge of M 31 contains a super-metal-rich intermediate-age population.

Rich et al. (1989) have discovered an exceptionally luminous star of type M0 Ie which has brightened by 5 mag in two years. Mould et al. (1990) report that this object has now faded away, suggesting that it was a peculiar kind of nova.

5. The Disk of M 31

According to Walterbos & Kennicutt (1988) the disk of M 31 contributes 65% of the *U* and 55% of the *V* luminosity of the Andromeda nebula. Hodge & Kennicutt (1982) and Kent (1987) show that the position angle of the major axes of the disk and bulge differ by $\sim 10°$. This offset has been taken as evidence for triaxiality of the bulge (Lindblad 1956; Stark 1977). From photoelectric photometry published by de Vaucouleurs (1958) the disk scale length along the major axis of M 31 is 24′ (5.1 kpc) in blue light. From the data of Walterbos & Kennicutt (1988) it appears that this disk scale length decreases with increasing wavelength. It is 7.1 ± 0.4 kpc in *U* and 5.5 ± 0.3 kpc in *R*. This trend seems to continue toward the infrared. *K*-band (2.2-μm) data by Hirimoto et al. (1983) give an infrared scale length of only 4.1 kpc. These results suggest that the mean age of disk stars decreases with radius. Published photometry (Burgess 1976; Hoessel & Melnick 1980; Lee et al. 1982; Hodge & Kennicutt 1982; Walterbos & Kennicutt 1987) shows that the disk of the Andromeda nebula has remarkably uniform colors with $0.9 \lesssim (B-V) \lesssim 1.0$ and $0.45 \lesssim (U-B) \lesssim 0.55$. These colors (which have not been corrected for foreground and internal reddening) suggest that the integrated light of the disk is dominated by an old stellar population (Tinsley & Spinrad 1971).

Walterbos & Kennicutt (1988) find that the disk of M 31 becomes slightly bluer at large radii. A similar trend is shown by the $(B-K)$ colors of Battaner et al. (1986). This effect might be due to lower mean stellar metallicity, to a larger relative contribution of young stars, and/or to a decrease in the dustiness of the interstellar gas in the outer disk of M 31 (Hodge 1980; Hodge & Lee 1988). The ring-shaped region of active star formation between 8 and 14 kpc from the nucleus is found to be slightly bluer than are the zones on either side of this feature.

Blair, Kirshner & Chevalier (1982) have used spectroscopic observations of H II regions and supernova remnants to show that the gas in M 31 exhibits a radial abundance gradient similar to that found in other intermediate and late-type spirals. They find the oxygen abundance to be a factor of two higher, but nitrogen and sulfur similar, to the O, N, and S abundances in the Orion nebula.

The distribution of late-type stars in the disk of M 31 has been studied by Richer, Crabtree & Pritchet (1990). The ratio of carbon stars to late-M stars in Baade's Field IV at 20 kpc from the nucleus is found to be 0.15, which is (perhaps surprisingly) close to the value that Richer & Crabtree (1985) found in a field at only 11 kpc from the nucleus, in which the stellar metallicity is expected to be higher.

From the *I*-band luminosity function of carbon stars Richer et al. (1990) derive a distance modulus $(m-M)_0 = 24.45 \pm 0.18$. This value is in good agreement with the other modern distance determinations listed in Table 2.

Color-magnitude diagrams for disk stars, based on CCD images, have been published by Crotts (1986), Hodge, Lee & Mateo (1988), and Hodge & Lee (1988). The latter two investigations do not, however, reach deep enough to study the oldest population component of the M 31 disk.

Crotts (1986) has also studied a small halo field located $2^{\circ}\!.9$ from the nucleus of M 31 and two fields situated near the outer edge of the disk in directions toward the major and minor axes of the Andromeda nebula. The color-magnitude diagram of stars in the major axis field (which is located 19 kpc from the nucleus) is difficult to interpret because observational errors in the $(g-r)$ color index are large at $r \simeq 23$. The data might, perhaps, be understood in terms of a population model in which the dominant population of the outermost disk consists of stars similar to, or slightly metal richer than, those in the Galactic globular cluster 47 Tucanae, on which a small component, similar to the intermediate-age Galactic open cluster

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NGC 2158, is superimposed. Stars with a broader range in metallicities may be required to account for the color-magnitude diagram of Crotts' minor axis field.

Van den Bergh & Racine (1967) find that the disk of M 31 resolves at $V = 21.8$, rather than at $m_{pv} = 21.2$, as claimed by Baade (1958). Their fainter resolution limit, which yields $(m - M)_V \simeq 24.4$, is consistent with the modern distance determinations listed in Table 2.

From digital stacking of Palomar Schmidt plates Innanen et al. (1982) found that the outermost parts of the disk of M 31 are warped. The fact that this warp shows up in both yellow and red light indicates 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, p. 73). It is of interest to note that the optical and radio (Newton & Emerson 1977; Cram, Roberts & Whitehurst 1980) images of M 31 are warped in the same direction. The 21-cm radio isophotes do, however, appear to remain close to the fundamental plane of M 31 out to somewhat greater distances from the nucleus than do the optical isophotes.

6. The Halo of M 31

In a halo field at a projected distance of 1°.8 (23 kpc) from the nucleus Crotts (1986) finds a sparse population of giant stars. Most, but not all, of these red giants are redder than those on the giant branch of 47 Tuc. A halo field near the minor axis of M 31, which is located 40′ (8.4 kpc) from the nucleus, has been studied by Mould & Kristian (1986). They find that the majority of stars in this field have metallicities *between* those of the Galactic globular clusters M 31 and 47 Tuc. A more detailed study of the color-magnitude diagram of this field by Pritchet & van den Bergh (1988) shows that the stars in the inner halo of M 31 exhibit a considerable spread ($\sigma_{[Fe/H]} \simeq 0.3$) in metallicity with an average value $[Fe/H] \simeq -1.0$. This is slightly higher than the average metallicity of M 31 globular clusters for which Huchra, Brodie & Kent (1991) obtain $< [Fe/H] > = -1.21$. Pritchet & van den Bergh (1988) find that *the blue horizontal-branch population appears to be weak in the halo of M 31.* Nevertheless, these authors find this halo to be rich in RR Lyrae variables. For 28 cluster-type variable stars they find $< P_{ab} > = 0^{\mathrm{d}}.55$, which suggests that *the RR Lyrae stars in the halo of the Andromeda nebula belong to a population similar to that in Galactic globular clusters of Oosterhoff's Type I.*

In a more distant field at a projected distance of 1°.5 (18 kpc) from the nucleus Christian & Heasley (1991) note a considerable spread in metallicity for halo stars. However, they find that the majority of red giants in this field are redder (metal richer) than those on the giant branch of 47 Tuc. This result appears to conflict with those obtained previously by Mould & Kristian (1986) and by Pritchet & van den Bergh (1987a). In particular, it is difficult to understand how the halo of M 31 can be rich in RR Lyrae variables if the majority of its stars are so metal rich. A study of the color-magnitude diagrams of several fields in the outer halo of the Andromeda nebula will be presented in Pritchet & van den Bergh (1992).

7. The M 31 Cluster System

The M 31 cluster system was first studied by Hubble (1932). In this pioneering paper Hubble discussed magnitudes, radial velocities, and the projected distribution of 140 clusters, the majority of which are now known to be globulars. Hubble noted that the M 31 clusters appear, on average, to be significantly fainter than those in the Galaxy. Had he followed up on this observation Hubble might have anticipated Baade's (1954) discovery that the distance to M 31 is twice as large as had been assumed previously. Additional early papers on M 31 clusters are by Seyfert & Nassau (1945), Mayall & Eggen (1953), and Kron & Mayall (1960). Positions and magnitudes for all clusters known in the early 1960s are given by Vetešnik (1962a,b, 1965). More recent lists of M 31 clusters are provided by Sargent et al. (1977) (the Kitt Peak catalog), Battistini et al. (1980), Buonanno et al. (1982), Crampton et al. (1985), Battistini et al. (1987) (the Bologna catalog), and Huchra et al. (1991). Racine (1991) used high-resolution imaging of cluster suspects to weed out background galaxies that contaminated some earlier cluster catalogs. From a complete halo sample of clusters with $V < 18$ Racine finds that the projected cluster surface density follows an R^{-2} law for the region with $28' < R < 102'$ ($6 < R$ (kpc) < 22) and then drops off faster at larger radii. It is not yet clear if this apparent cutoff is real or whether it is due to incompleteness of the cluster sample at large distances from the center of the Andromeda nebula.

Observations of the projected surface density of globular clusters (Harris & Racine 1979) shows a drop below that expected from a de Vaucouleurs $R^{1/4}$ law at small ($R <$ 1 kpc) radii. A search for these "missing" bulge clusters has been made by Wirth, Smarr & Bruno (1985). It is not yet clear whether these missing clusters have all (or in part) been destroyed, after they were first dragged inward by dynamical friction (Tremaine et al. 1975), or if they have simply not been discovered because globular clusters are smaller (and therefore more difficult to recognize) at small galactocentric distances (van den Bergh, Morbey & Pazder 1991). A search for clusters in the nuclear bulge of M 31, that takes advantage of the excellent seeing that often occurs on Mauna Kea, might prove very rewarding.

A compilation of all early photoelectric *UBV* photometry of clusters in M 31 and its companions is given by van den Bergh (1969). A critical discussion of subsequent photometry is contained in van den Bergh (1990). These photometric data, and the spectroscopy of van den Bergh (1969), show that *the globular clusters in M 31 and the Galaxy exhibit a similar range of metallicities, but that the mean metal abundance of the M 31 clusters is slightly* *higher than that of their Galactic counterparts.* A similar conclusion is reached by Huchra et al. (1991) who obtain $< [\mathrm{Fe/H}] > \simeq -1.21 \pm 0.02$ from the spectra of 150 M 31 clusters, compared to $< [\mathrm{Fe/H}] > \simeq -1.40 \pm 0.01$ for 121 Galactic globulars. The contrary conclusion by Hanes (1977) and by Elson & Walterbos (1988), who find no difference in the mean metallicities of the globulars in these two systems, is probably due to the fact that these authors relied on photographic photometry of M 31 clusters. Such photometry can suffer significant systematic errors for clusters that appear projected on a bright unresolved nebular background. The observation that the M 31 globulars are, in the mean, somewhat metal richer than those associated with the Galaxy is consistent with the well-established correlation between the mean metallicity of globular-cluster systems and the luminosity of their parent galaxies (van den Bergh 1975; Mould, Oke & de Zeeuw 1991).

From the spectra of 36 clusters van den Bergh (1969) found no obvious dependence of cluster metallicity on distance from the center of M 31. A more complete picture is provided by the spectra of clusters for which Huchra et al. (1991) have published accurate metallicity data. These authors find that all clusters more metal rich than $[\mathrm{Fe/H}] = -0.5$ are located within a projected radius of 10 kpc from the nucleus of M 31. However, no obvious correlation between metallicity and projected distance from the nucleus is seen for clusters with $[\mathrm{Fe/H}] < -0.5$.

An interesting difference between the M 31 and Galactic cluster systems is that the metallicity distribution of clusters associated with the Milky Way System exhibits a minimum near $[\mathrm{Fe/H}] = -0.9$. In Huchra et al.'s data no such minimum is seen for the metallicity distribution of globular clusters in M 31.

Figure 2 shows that metal-rich clusters with $[\mathrm{Fe/H}] \gtrsim -0.8$ in the Andromeda nebula appear to form a rotating disk that extends out to $R \simeq 5$ kpc. In the Milky Way System all but one (NGC 6838) of the metal-rich disk ($|Z| < 2$ kpc) clusters also lie in a disk with $R < 5$ kpc (Armandroff 1989), i.e., the metal-rich clusters extend to similar *linear* radii in M 31 and the Galaxy. These results suggest 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.* It would be important to check this tentative conclusion by obtaining additional accurate spectroscopic metallicity observations of clusters in M 31.

An interesting similarity between the globular-cluster systems associated with the Milky Way and the Andromeda nebula is that neither one of them exhibits a correlation between cluster luminosity and metallicity (Armandroff 1989; Huchra et al. 1991). A correlation between cluster luminosity and $(J-K)$ color, that was suspected by Sitko (1984), has not been confirmed by Bònoli et al. (1987).

Huchra et al. (1991) find that the M 31 cluster system at large radii is rotating with a semiamplitude of 60 ± 14 km s^{-1}, with no distinction between metal-rich and metal-poor clusters. According to them the overall velocity dispersion in the M 31 cluster system is 155 km s^{-1}, from which (for an assumed distance of 725 kpc) they obtain a mass of $(3.3 \pm 0.5) \times 10^{11}\ \mathfrak{M}_\odot$. This mass is consistent with those obtained from the optical rotation curve of M 31 by Rubin & Ford (1970) and in the 21-cm line of hydrogen by Roberts & Whitehurst (1975).

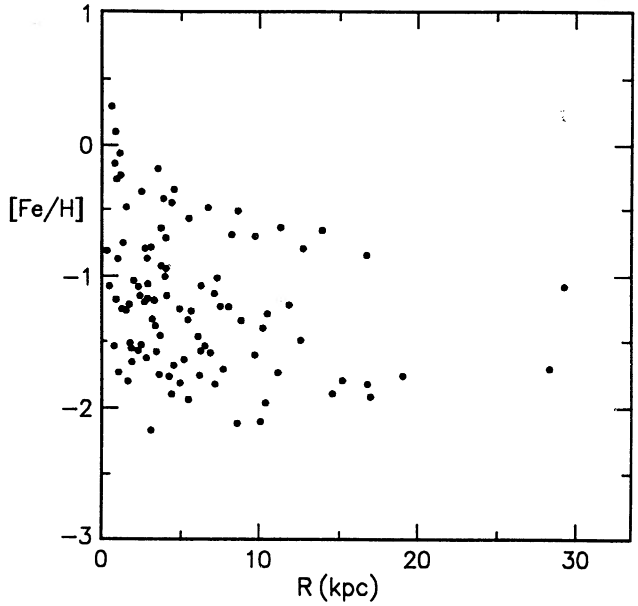

FIG. 2–Cluster metallicity according to Huchra et al. (1991) versus projected radial distances for D(M 31) = 725 kpc. Note that clusters with $[\mathrm{Fe/H}] > -0.5$ only occur at $R < 10$ kpc.

Figure 3 illustrates the wide range in metallic line strengths exhibited by globular clusters. Van den Bergh (1969) found that the strength of λ4226, λ4325, H+K, and the G band were particularly useful parameters for characterizing the metallicities of clusters. More recently Brodie & Huchra (1990) have used the H and K lines of Ca II, the CN and CH (G-band) features, the magnesium b triplet, the magnesium hydride troth, and the sodium D doublet to derive a cluster metallicity index for globular clusters. Van den Bergh (1969) found that *CN is stronger in M 31 globular clusters than it is in Galactic globulars of similar metallicity.* This conclusion has subsequently been confirmed by Burstein et al. (1984), Tripicco (1989), Brodie & Huchra (1990), and in the infrared by Davidge (1990). Burstein et al. (1984) have claimed that M 31 globulars also have significantly stronger Balmer lines than do Galactic globulars. However, CCD spectra covering the range λλ3850–4200 by Tripicco (1989) appear to rule out a significant contribution of horizontal-branch stars to the integrated spectra of M 31 globulars. It would clearly be very important to push color-magnitude diagrams of M 31 globulars slightly below the level of the horizontal branch so that the structure of their horizontal branches can be studied in detail.

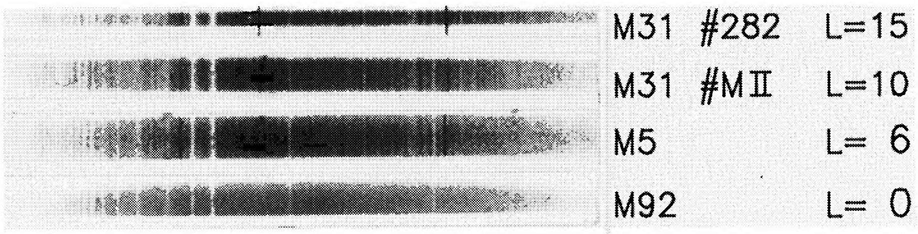

FIG. 3–The figure illustrates the wide range in cluster line strengths exhibited by Palomar 5-m image-tube spectra of globular clusters in M 31 and the Galaxy.

From the strength of Sr II λ4077 Tripicco (1989) concluded that the light of metal-rich globular clusters near 4000 Å is dominated by dwarfs. However, Frogel, Persson & Cohen (1980) find, from measurements of infrared CO and H_2O bands, that late-type dwarfs do *not* make a significant contribution to the integrated light of the clusters in M 31.

Obtaining color-magnitude diagrams for individual stars in M 31 globular clusters was a priority objective of the Hubble Space Telescope. This challenge has now been taken up by workers taking advantage of the excellent image quality obtainable at the Canada-France-Hawaii telescope. The color-magnitude diagram of the metal-rich cluster M II (G1) has been obtained by Heasley et al. (1988). These authors observe that the position of the red-giant branch of this metal-rich cluster is similar to that of the metal-rich Galactic globular cluster 47 Tuc (Da Costa & Armandroff 1990). Christian & Heasley (1991) find that the metal-poor cluster M IV (G2 19) has a red-giant branch similar to that of the Galactic globular M 15 (Da Costa & Armandroff 1990). It is particularly noteworthy that the M IV cluster giants are found to be bluer (metal poorer) than the M 31 field halo stars surrounding this cluster, which is situated at a projected distance of 1°5 from the nucleus of M 31. A comparison between the color-magnitude diagrams of M II and M IV is shown in Figure 4.

With the high spatial resolution available at the Canada-France-Hawaii telescope it is now also becoming possible to study the structure of individual globular clusters associated with the Andromeda nebula. Pritchet & van den Bergh (1984) found that the luminous M 31 globular M II has $\epsilon = 1 - b/a = 0.22 \pm 0.02$. This makes it marginally flatter than ω Centauri ($\epsilon \simeq 0.20$), which is the most lightly flattened (and most luminous) Galactic globular. Additional observations of the flattenings of M 31 globulars are by Spassova, Staneva & Golev (1988), Lupton (1989), and by Davoust & Prugniel (1990). The latter authors find that the brightest M 31 clusters are also the roundest. This conclusion conflicts with the result of van den Bergh & Morbey (1984), who find that the brightest clusters in the Magellanic Clouds are the flattest, and with the observation that the particularly luminous clusters ω Cen and M II are highly flattened.

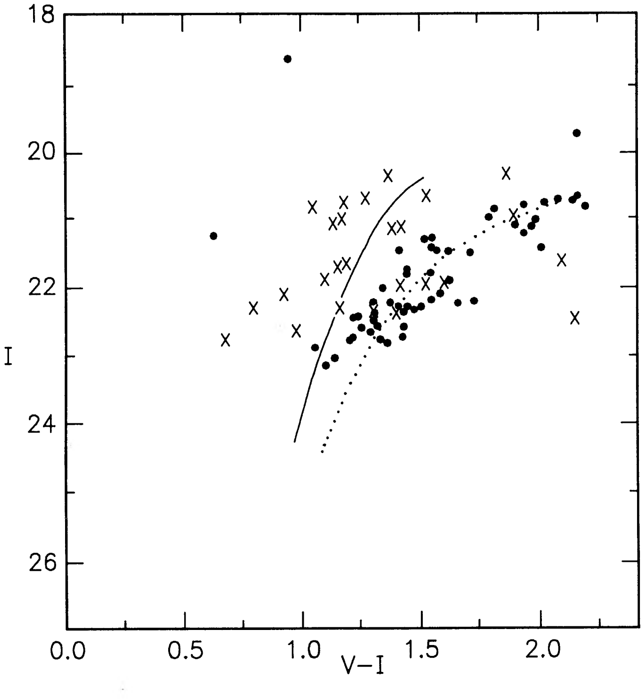

FIG. 4–Comparison of the color-magnitude diagrams of the metal-poor cluster M IV (crosses) and of the metal-rich cluster M II (dots).

Clearly it would be very desirable to obtain additional information on the structure of globular clusters in M 31 from images obtained in superb seeing. As a first step in this direction Cohen & Freeman (1991) have determined tidal radii of 30 clusters associated with M 31 on images obtained with the Palomar 5-m telescope. These authors tentatively conclude that the M 31 globulars have mass-to-light ratios and orbital eccentricities very similar to those of Galactic globulars.

The luminosity function of globular clusters in the halo of M 31, where contamination by open clusters can be neglected, has been discussed by Racine & Shara (1979). More recently van den Bergh (1985) has used cluster colors to discriminate against open clusters and background galaxies. He finds that the M 31 data are adequately represented by a Gaussian luminosity function with $<V> = 17.2 \pm 0.2$ ($M_V = -7.35$) having a dispersion of 1.2 mag. Van den Bergh (1985) estimates the total M 31 cluster population to be 276, from which the specific cluster frequency $S = 0.6$. This value is quite typical for spiral galaxies (Harris 1991). Incompleteness of the data at $V \gtrsim 18$ would decrease the average luminosity of M 31 clusters and increase their estimated number. Note, however, that the estimate of 276 clusters given above is close to the value 270 ± 50 derived independently by Racine (1991).

The open clusters in M 31, which occur exclusively in the disk of this galaxy, have been studied by Hodge et al. (1987). These authors find that such open clusters have a wide range in colors and, hence, presumably in ages. The brightest open cluster has $V = 16.76$ which, neglecting reddening within M 31, corresponds to $M_V = -7.8$, i.e., these objects are much less luminous than the populous clusters in the LMC. The luminous object vdB 0, which has $V = 14.94$ ($M_V = -9.6$), may be a compact young association. The 33-day Cepheid H 40 (Hubble 1929) appears to be a member of vdB 0.

8. OB Associations and Spiral Structure

Spiral arms are like chameleons: they can change their appearances (see Table 3) in different locations. Baade (1963, p. 64) writes: "The sequence in the spiral structure begins essentially with dust in the inner arm, then stars of Population I become prominent and dust grows less conspicuous, and finally both fade out." The spiral structure in M 31 is most clearly outlined by H II regions (Baade & Arp 1964; Arp 1964; Pellet et al. 1978) and OB associations (van den Bergh 1964). Both H II regions and associations reach their maximum strength in the broad gaseous ring between 40′ and 70′ (8–15 kpc) from the nucleus of the Andromeda nebula. Rectified (i.e., deprojected) *plots of the distribution of OB associations in M 31 clearly show (see Fig. 5) spiral arm segments, but no "grand design" spiral pattern* (but see Braun (1991) for a contrary conclusion). It should, perhaps, be emphasized that detailed studies of this type are somewhat hampered by the fact that the fundamental plane of this almost edge-on galaxy is warped. It is tempting to assume (Schwarzschild 1954) that this warping is due to tidal effects induced by M 32.

As a result of the relatively low overall level of star formation in M 31 (Shara & Moffat 1986; Walterbos 1988; Humphreys, Massey & Freedman 1990) it is possible to trace the outer boundaries of individual associations in M 31 out to much greater radii than is possible in the Galaxy or in M 33 (Humphreys 1979; Humphreys & Sandage 1980). On the basis of the degree of subclustering, luminosities of the brightest stars, and the frequency of H II regions it is possible (van den Bergh 1964) to assign approximate relative ages to associations in M 31. Figure 5 shows that the youngest associations tend to be concentrated in distinct spiral arc-like features.

A catalog containing 11,438 stars in M 31, which is complete to $V \simeq 18.8$, has been published by Berkhuijsen et al. (1988). Berkhuijsen & Humphreys (1989) find that most luminous blue stars are located in an annulus with $40' < R < 70'$ ($8 < R < 15$ kpc). This annulus is also seen prominently in IRAS observations of infrared emission by Habing et al. (1984).

On the basis of their *UBV* colors, Berkhuijsen & Humphreys (1989) estimate the total number of O-type stars in M 31 to be ~ 300. The distribution of OB stars in the Andromeda nebula is found to be similar to that of W-R stars (Moffat & Shara 1983, 1987). Finally, Berkhuijsen & Humphreys (1989) find that the slope of the bright end of the stellar luminosity function in M 31 is similar to that in other nearby resolved late-type galaxies (Freedman 1985).

Nedialkov, Kourtev & Ivanov (1989) have made a blink survey to isolate the brightest blue and red stars in the Andromeda nebula. These authors find that the brightest blue star has $V = 16.1$, whereas the brightest red star is

TABLE 3

Baade's Spiral Arms in M31

Arm[a]	Distance (kpc)		Arm[a]	Distance (kpc)		Remarks
N1	3′.4	0.7	S1	1′.7	0.4	Dust arms containing no supergiants or HII regions
N2	8.0	1.7	S2	10	2.1	Dust arms with a sprinkling of supergiants. First HII regions appear in N3 and S3
N3	25	5.3	S3	30	6.3	
N4	50	11	S4	47	9.9	Maximum display of Population I. Dust inconspicuous
N5	70	15	S5	66	14	
N6	91	19	S6	95	20	Spiral arms defined by scattered groups of supergiants. No dust patches visible
N7	110	23	S7	116	24	

[a] N and S refer to arms on the north-following and south-preceding sides of the major axis.

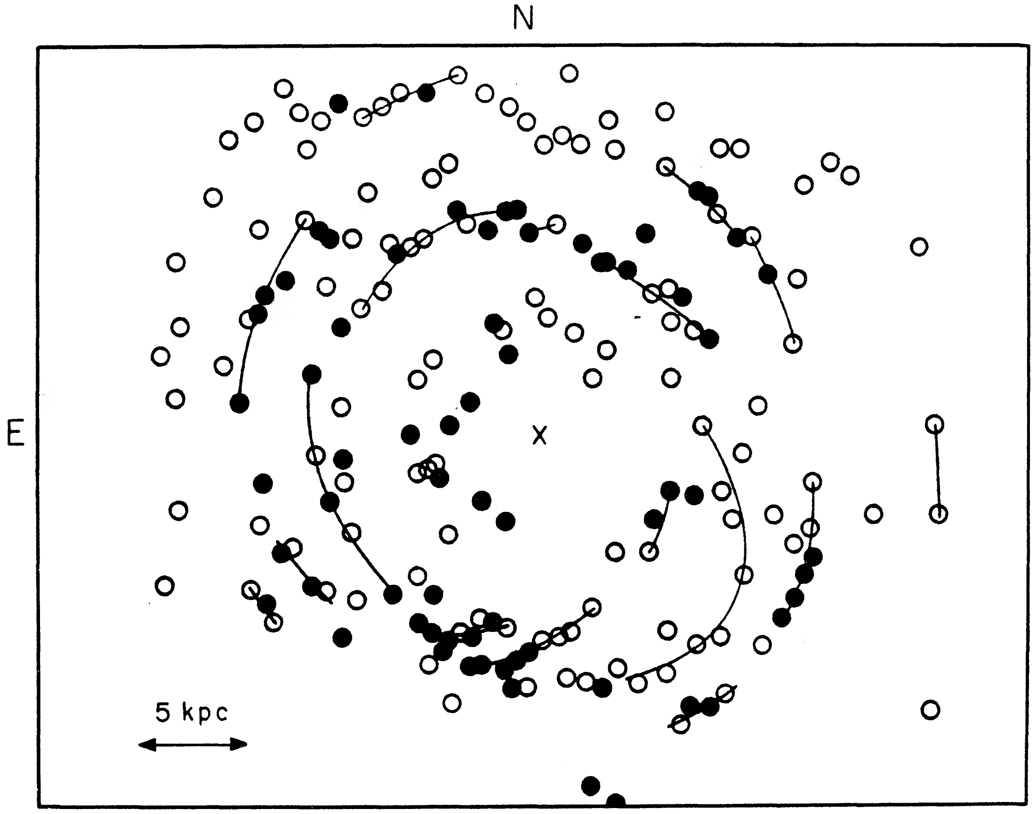

FIG. 5–Deprojected distribution of OB associations in M 31. Cross marks position of the nucleus. Filled circles are young associations.

found to have $V = 16.2$. These objects are significantly fainter than AF Andromedae, and the brightest Hubble-Sandage variable in M 31, which (see Fig. 6) reached $B(\max) \simeq 15.6$ at maximum light. Spectroscopy and multicolor photometry of the brightest red supergiants in M 31 have been published by Humphreys et al. (1988). After correcting for reddening (which typically amounts to $A_V \simeq 0.6$) they find that the brightest M-type supergiants in M 31 have $M_V \simeq -8$. This is similar to the luminosity of the brightest red supergiants in M 33 (Humphreys & Sandage 1980). Humphreys et al. (1990) point out that their preliminary, and still incomplete, Herzsprung-Russell diagram for M 31 shows an apparent lack of the most massive stars with initial masses $> 60\,\mathfrak{M}_\odot$.

The most detailed study of the associations in M 31 is by Efremov, Ivanov & Nikolov (1987). These authors find 210 associations in the Andromeda nebula. Some of these associations represent subgroups of luminous stars within the larger OB associations outlined by van den Bergh (1964). As a result the frequency distribution of the diameters of associations given by Efremov, Ivanov, and Nikolov peaks at much smaller diameters ($D \sim 80$ pc) than is the case for the associations outlined by van den Bergh ($D \sim 80$–200 pc). The diameters of the associations, as defined by Efremov et al., are very similar to these which Hodge (1986) finds in the Magellanic Clouds.

A few sparse and very distant OB associations in M 31 have been found by Richter (1971). The color-magnitude diagram of an association in Baade's Field IV (Hodge et al. 1988), which is located $\sim 96'$ (20 kpc) from the nucleus, is found to resemble that of the solar neighborhood. CCD photometry of OB associations close to the nucleus of M 31 has been published by Massey et al. (1986). These authors find that the ratio of WC to WN stars in these associations is similar to that in the solar neighborhood. Massey, Conti & Armandroff (1987) find that M 31 W-R stars are relatively weak lined for their linewidth. These authors speculate that this might indicate that the stellar wind laws for luminous stars in the Andromeda nebula are different from those in other nearby galaxies. Some support for this suggestion is provided by IUE observations of the ultraviolet spectra of two luminous stars in M 31 by Hutchings, Massey & Bianchi (1987), who find that resonance absorption lines are very weak indicating low outflow velocities. Recently this conclusion has been confirmed for four stars in M 31 by Bianchi, Hutchings & Massey (1991).

9. Variable Stars

The first systematic study of the variable stars in M 31 was undertaken by Hubble (1929). Among the 50 variables he discovered, 40 turned out to be Cepheids.

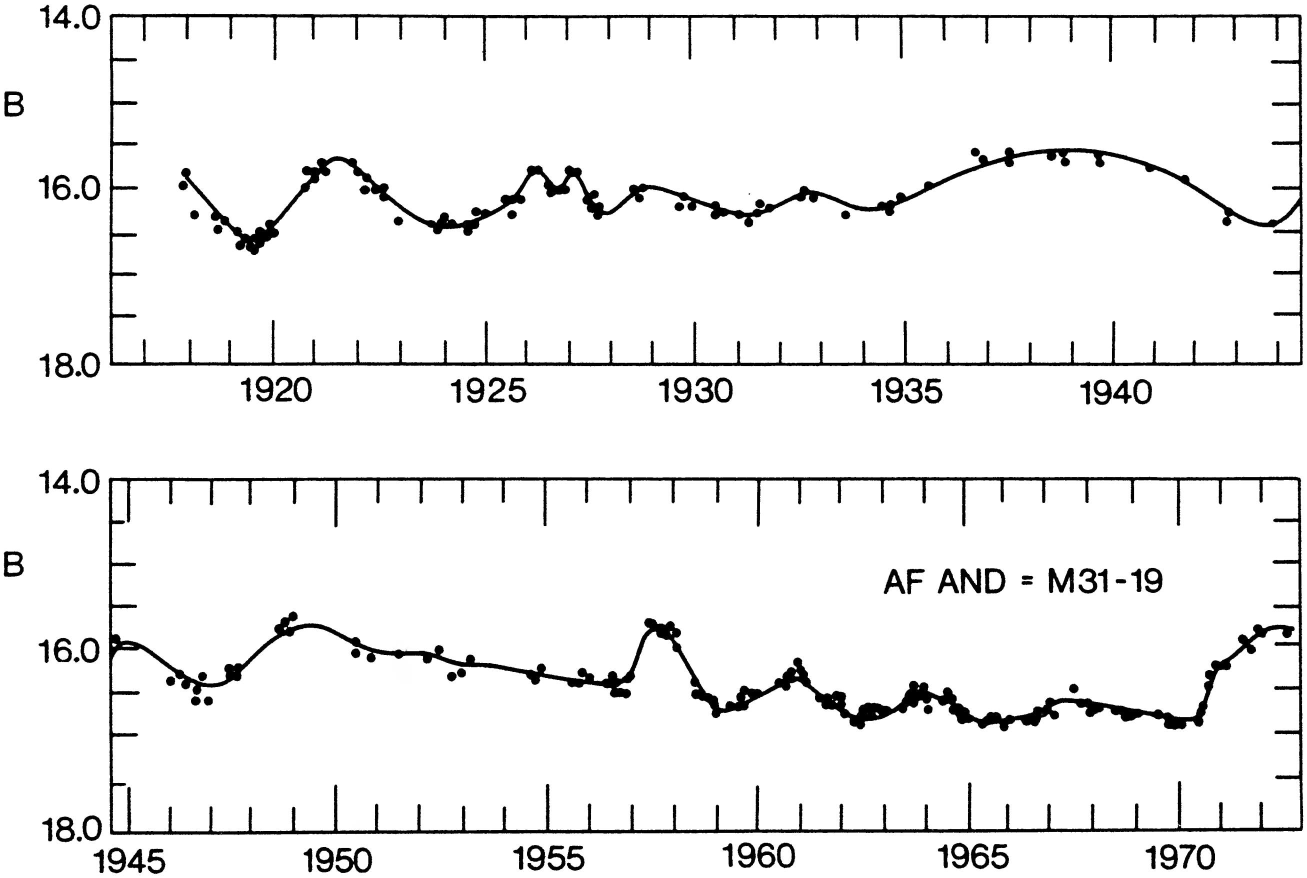

FIG. 6–Light curve of AF And, the brightest Hubble-Sandage variable in M 31.

Subsequent photographic photometry of fields in M 31 was carried out by Gaposchkin (1962) and by Baade & Swope (1963, 1965). The Baade & Swope (1963) paper clearly showed that the period-luminosity relation for W Virginis stars is parallel to, but about two magnitudes fainter than, that of classical Cepheids. More recently, Welch et al. (1986) obtained single-phase H-band observations of 22 Cepheids in M 31. Finally, Freedman & Madore (1990) have published multiwavelength observations of 38 Cepheids located in fields that are situated 3 kpc, 10 kpc, and 20 kpc from the nucleus of the Andromeda nebula. After corrections for reddening Freedman and Madore find no significant difference in the distance moduli of M 31 derived for these three fields, in which the Cepheids are expected to have significantly different metallicities (Blair et al. 1982). They therefore concluded that *the Cepheid period-luminosity relation is independent of metallicity.* (This conclusion has, however, been questioned by Feast 1991.) Alternatively, one might, of course, assume that the ratio of total-to-selective absorption exhibits a radial change that compensates for radial variation in the period-luminosity relation. Table 2 shows that the Cepheid distance determinations to M 31 are in excellent agreement with those derived by means of other techniques.

The most luminous class of blue variable stars in galaxies was first discussed by Hubble & Sandage (1953). Four objects of this type (V19 = AF And, AE Andromedae, V15, and VA1) are known in M 31. The light curves of these objects exhibit cyclical variations over time scales of years. The light curve of AF And, which is the brightest Hubble-Sandage variable in M 31, is illustrated in Figure 6. Light curves of the other Hubble-Sandage variables in M 31 are shown in Sharov (1990). Spectroscopy of these objects is reported by Humphreys (1975, 1978) who finds that they have a strong, hot continuum with no Balmer discontinuity. P Cygni and η Carinae in the Galaxy, and S Doradus in the LMC, are nearby objects that belong to the same class. Many Hubble-Sandage variables exhibit excess infrared radiation, which Humphreys et al. (1984) attribute to free-free emission from their extended atmospheres. Kenyon & Gallagher (1985) find that AE And and AF And have P Cygni profiles on all strong permitted lines, which indicate outflow velocities of ~ 100–300 km s^{-1} and mass-loss rates of 1–5 × 10^{-5} $\mathfrak{M}_\odot$ yr^{-1}. Such dense, low-velocity winds might be produced by either (1) very massive stars evolving off the main sequence, or (2) by less massive binaries that are presently in a state of rapid mass exchange. η Car, which is located in a very active star-forming region, most likely is a single massive star. On the other hand AF And is situated in a relatively quiescent region, which suggests that its age might be greater than that which can be attained by a single massive star. *The situation in regard to the nature of Hubble-Sandage variables is reminiscent of that for supernovae of Type Ib. On the one hand van den Bergh (1988) argues for massive W-R type progenitors, while Shigeyama et al. (1990) favor models in which the progenitors of SN Ib are objects that became helium stars by mass loss and mass exchange in close binary systems.*

10. Novae and Supernovae

Hubble's (1929) pioneering study of the novae in M 31 was followed up by Arp (1956), who discovered 30 novae with the Mount Wilson 1.5-m telescope during the period June 1953–January 1955. More recently a second major survey has been undertaken at the Asiago Observatory by Rosino (1964, 1973), by Capaccioli et al. (1989), and by Rosino et al. (1989). After correcting their observations for various sources of systematic error, Capaccioli et al. derive a rate of 29 ± 4 novae yr^{-1}. The observations of the light curves in both of these surveys yield strong evidence for the existence of a maximum magnitude versus rate of decline relationship for novae, with fast novae being more luminous at maximum than slow ones. Within the accuracy of presently available data this relationship does not seem to depend on the position of a nova in M 31. From a comparison of the maximum magnitude versus rate of decline relations in the Galaxy and M 31 Capaccioli et al. (1989) obtain a distance modulus $(m-M)_B = 24.52 \pm 0.23$. About 5% of the novae in the Andromeda nebula appear to belong to a separate class which falls $\gtrsim 1$ mag above the standard maximum versus rate of decline relation. Of seven novae which Pritchet & van den Bergh (1987b) observed in Virgo giant elliptical galaxies one also belongs to this class. A suspected recurrent nova in M 31 falls ~ 2 mag below the standard maximum magnitude versus rate of decline relationship (Capaccioli et al. 1989).

Novae are very easy to discover by means of their Hα emission. Unfortunately, Ciardullo et al. (1990) find no correlation between maximum Hα magnitude and the rate at which the Hα luminosity declines. During a systematic and homogeneous search for Hα emission in eight partially overlapping fields near the nucleus of M 31, Ciardullo et al. (1987) were able to discover 35 novae. Their data show that *the frequency distribution of novae in the region within 9′–14′ (2–3 kpc) of the nucleus closely follows that of the B light in the bulge of M 31.* From the much less homogeneous data collected by Hubble (1929) and Arp (1956), Ciardullo et al. conclude that the nova frequency drops off much faster than *B* light over the range $15' \lesssim R < 60'$ (3–13 kpc). This conclusion cannot, however, be regarded as firmly established. This is so because of (1) the low completeness of more-or-less haphazard nova searches in fields at large distances from the center of M 31 and (2) severe coma at large radii on plates centered on the nucleus.

Only a single supernova, S Andromedae = SN 1885 (de Vaucouleurs & Corwin 1985), has been observed in M 31 during historical times. This object exploded 16″ (56 pc) from the nucleus of the Andromeda nebula. If the probability of a supernova occurrence is proportional to apparent surface brightness then *the a priori probability that any supernova should occur so close to the nucleus as did S And is only ~ 0.5%.* This, and the fact that SN 1885 had an unusual light curve, encourage the speculation that the occurrence of this peculiar object might (in some unspecified way) be tied to its proximity to the nucleus. (With a transverse velocity of 200 km s^{-1} the travel time from the nucleus to the point of explosion would be only 3×10^5 yr). The remnant of S And has recently been discovered by Fesen, Hamilton & Saken (1989), who observed it as an absorption feature in the Fe I line at 3860 Å. This discovery shows that (1) S And produced iron-rich ejecta and (2) these ejecta are still relatively cold. Dickel & D'Odorico (1984) find that the present 6-cm luminosity of S And is < 0.4 times that of Tycho's supernova remnant in the Galaxy.

Supernova remnants in M 31 have been discussed by D'Odorico, Dopita & Benvenuti (1980), Dennefeld & Kunth (1981), Blair, Kirshner & Chevalier (1981), Blair et al. (1982), and by Dickel et al. (1982). From a comparison of the SNR diameter/frequency distributions in M 31 and M 33 Dennefeld & Kunth (1981) conclude that the supernova rate in the Triangulum nebula is approximately twice as high as it is in the Andromeda nebula. This difference is, no doubt, due to the relatively low level of star-forming activity in M 31 (Berkhuijsen 1984; Walterbos 1988).

11. Planetary Nebulae

Over 300 bright planetary nebulae (pn) in M 31 have been discovered by Ford & Jacoby (1978a,b). A deeper survey of planetaries in the nuclear bulge of the Andromeda nebula has been carried out by Lawrie & Ford (1982). From their data Lawrie and Ford estimate that M 31 contains 2800 ± 350 planetaries within the first three magnitudes of the pn luminosity function. More recently Peimbert (1990) has estimated that M 31 contains a total population of 8000 ± 1500 planetary nebulae, from which he obtains a total formation rate of 0.3 yr^{-1}.

Nolthenius & Ford (1987) have used radial-velocity observations of 37 planetaries with $R > 15$ kpc to study the dynamics of the M 31 outer disk. They find that ~ 1/3 of the objects in their sample are kinetically associated with a halo population. For the disk planetaries Nolthenius and Ford find a radial scale length of 4.8 kpc, which is comparable to that which Walterbos & Kennicutt (1988) obtained for the optical light of the M 31 disk. From a velocity dispersion of 38 km s^{-1} at $<R> = 19$ kpc

Nolthenius & Ford (1987) derive a surprisingly large disk scale height of 1–3 kpc.

Jacoby & Ford (1986) find that the abundances derived from pn at $<R> = 19$ kpc are similar to those in the Orion nebula at a Galactocentric distance $R \simeq 9$ kpc. This suggests that M 31 experienced considerably more enrichment of its interstellar medium during its early evolution than did the Galaxy. Furthermore, direct observations of the halo planetaries M 31-290 and M 31-372, for which Henry (1990) finds logarithmic oxygen abundances of 8.54 and 8.05, respectively (on a scale on which the hydrogen abundance is 12), provides direct evidence for inhomogeneity of the stellar population in the halo of the Andromeda nebula.

12. X-Ray Sources

The X-ray sources in the Andromeda nebula have been studied by the Einstein Observatory and, more recently, with the Ginga satellite. A catalog of 100 sources in M 31, with X-ray luminosities $\gtrsim 6 \times 10^{36}$ erg s^{-1}, is given by Trinchieri & Fabbiano (1991). An additional seven sources are identified with foreground or background objects (Crampton et al. 1984), and one source is identified with the dwarf elliptical galaxy M 32. Among the 100 sources belonging to M 31 itself, Crampton et al. (1984) identify 18 with globular clusters, while an additional four sources are possibly associated with M 31 globulars. A Kolmogorov-Smirmov test shows that *there is no significant difference between the metallicity distribution* (Huchra et al. 1991) *of the M 31 X-ray clusters and that of all clusters with spectroscopic metallicity determinations.*

From observations with the Ginga satellite, Makishima et al. (1989) estimate the total 2–20 keV luminosities of M 31 to be 5×10^{39} erg s^{-1}. They conclude that the integrated X-ray spectrum of M 31 is practically indistinguishable from that of Galactic X-ray binaries. From observations with the Einstein observatory Trinchieri & Fabbiano (1991) find that the total X-ray luminosity of M 31 is approximately equally divided between the bulge ($r < 5'$) and the disk ($r > 5'$). Identified sources account for $\sim$ 75% of the bulge luminosity and for all of the observed disk emission. The sources associated with M 31 appear to exhibit no radial luminosity gradient. Their luminosity distribution can be represented by a power law of the form $N(L) \propto L^{-0.8}$. Extrapolation of this relation to lower luminosities suggests that all of the $\sim$ 25% of the bulge luminosity, that is not accounted for by identified sources, could be due to individual faint sources.

The integrated spectrum of the bulge is consistent with a population of soft low-mass X-ray binaries. Grindlay (1985) has speculated that such bulge X-ray binaries were formed by tidal capture in globular clusters that have since disrupted. However, Vader et al. (1982) find that the number of field X-ray sources in the bulge of M 31 is too large to be accounted for by disruption of globular clusters that were dragged inward by tidal friction. Finally, Collura, Reale & Peres (1990) find that at least two of the X-ray sources in M 31 are variable.

13. Desiderata

1. A sensitive high-resolution radio study of the nucleus and central bulge of M 31 could place interesting constraints on the present level of activity in the nucleus of the Andromeda nebula.
2. Additional color-magnitude diagrams of the halo of M 31 need to be obtained to resolve the conflict that presently exists between the observational results of Mould & Kristian (1986), Pritchet & van den Bergh (1987a), and Christian & Heasley (1991). It would be particularly important to determine if the halo of the Andromeda nebula exhibits a metallicity gradient.
3. It would be particularly valuable to obtain deep color-magnitude diagrams showing the structure of the horizontal branches of globular clusters in M 31.
4. The high-resolution camera on the CFHT should be used to search for very compact globular clusters near the nucleus of M 31.
5. A long-term CCD survey of M 31 with a small telescope could provide valuable data on the radial variation of nova rates and on nova light curves.

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