M 31 CLUSTER SYSTEM

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ABSTRACT: The present status of the search for globular clusters in M31 is reviewed and some outstanding properties of the cluster system as a whole are briefly discussed.

1. INTRODUCTION

The production of a complete and uncontaminated sample of clusters in M31 still represents an extremely difficult observational task since cluster candidates in M31 have sizes comparable to the seeing disk (10pc ~ 3.3 arcsec). Any revision of each existing sample has thus shown the presence of some level of both incompleteness and contamination.

Given the uniqueness of M31 for studying a very populous cluster system, many different attempts have been made by various authors to improve the search technique. It is thus important to understand whether the various approaches applied present the same pros and cons or whether they can be considered at least in part complementary. In fact, if they were to cover the selection of the whole spectrum of potential candidates, a coordinated effort might lead to eventually obtaining a complete sample (down to a given magnitude) necessary to study in detail the properties of the whole M31 cluster system and to compare it with those found in other galaxies.

Most of the searches in M31 are essentially based on visual inspection of images to distinguish clusters from stars and other types of non-stellar objects on a morphological basis. Pure eye-selections have been applied up to the search made with Kitt Peak plates by Sargent et al. (1977). In order to improve the selection, several complementary search techniques have been added by various groups (see list of references in Table I).

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2. THE SEARCHES

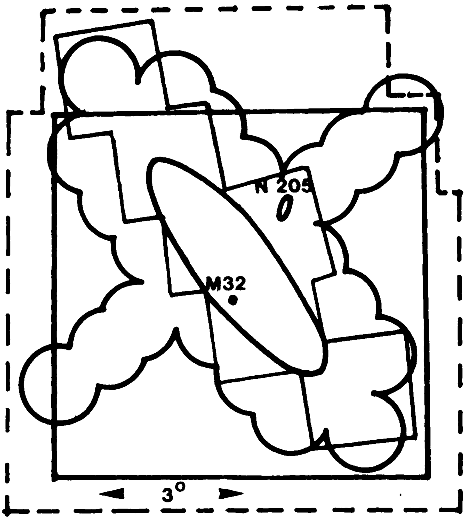

Fig. 1. Map of the areas covered by the 3 latest major searches.
a) composite circles: Sargent et al.(1977);
b) composite squares: Crampton et al.(1985);
c) large square and large dotted area: Battistini et al.(1986).

Table 1.
List of searches for globular clusters in M31

Reference	cluster names
Hubble 1932	H
Seyfert and Nassau 1945	
Mayall and Eggen 1953	M
Hiltner 1958	
Kron and Mayall 1960	
Johnson 1961	J
Vetesnik 1962	V
Baade and Arp 1964	B
Sandage 1971	S
Sharov 1973	Sh
Alloin et al. 1976	
Karimova and Sharov 1977	Sh
Sargent et al. 1977	KP,M31C,G
van den Bergh 1977	vdB
Hodge 1979	
Battistini et al. 1980	Bo
Huchra et al. 1982	CfA
Crampton et al. 1985	DAO, G
Wirth et al. 1985	WSB
Battistini et al. 1986	Bo

Table II

Results of the 'Bo-Survey' (Battistini et al.1986)

Homogeneity: Excellent		
Contamination: < 10 - 15 %		
Completeness: ~ 100% allowed by 'morphological method' > 80% absolute (down to V = 18)		
Class A	(very high confidence candidates)	254
Class B	(high condidence candidates)	99
	Total (high confidence candidates)	353
Class C	(plausible candidates, probability < 50%)	152
'Out of field'	(candidates in other lists)	31
'Rejected in field'	(inserted in previous lists)	
	miscellaneous non-stellar objs = Bo D	51
	too faint for classification in Bo-plates	18
	rejected	75

Table III

Comparison with the previous lists

Bo-Class	V	KP	Bo80	G	DAO	Bo86
A	182	232	190	248	0	254
B	30	55	43	82	2	99
C	8	25	49	57	27	152
D	11	10	0	43	34	218
'rejected'	22	15	6	52	36	0
'out of field'	3	18	0	27	10	0
Total	256	355	288	509	109	(723)

V = Vetesnik 1962 KP = Sargent et al. 1977
Bo80 = Battistini et al. 1980 G = Crampton et al. 1985
DAO = Crampton et al. 1985 (108 new candidates)
Bo86 = Battistini et al. 1986

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Fig. 1 shows a map of the areas systematically surveyed for globular clusters by the three latest searches. They have been carried out independently of any previous identification. Revisions "a posteriori" of all the candidates previously known in the considered areas have always been made. Table II presents the results of our latest survey (Battistini et al. 1986). Table 3 gives the comparison with other main samples by showing our classification of all the objects included in the various lists. A close inspection of the tables shows that updated efforts to find globular clusters in M31 using "morphological" criteria have led to a critical revision of the list rather than to a significant increase of the number of candidates. In fact, the total number of candidates has been increased mainly by increasing the limiting magnitude of the survey and by extending the studied area rather than by finding a conspicuous set of new candidates. In order to properly derive the total number of globular clusters in M31 one must correct for: a) contamination by spurious objects, b) incompleteness for the area of the sky not surveyed yet, c) incompleteness at faint magnitudes ($V > 18$) and in the highly reddened regions, d) incompleteness due to the possible losses of highly compact clusters (see sect. 3), e) asymmetries or peculiarities in the shape of the cluster luminosity function (here assumed to be a Gaussian with $\sigma = 1.2$ mag, see van den Bergh 1985 for a discussion). Many uncertainties still affect the various quoted steps, nevertheless we estimate N(tot) = 500 $\pm$ 50. This figure for the total number of clusters leads to values of S, the specific globular cluster frequency (Harris and van den Bergh 1981), ranging from 0.4 to 1.5 according to the slightly different asssumptions made on N(tot) and the total absolute luminosity of M31. As is well known, this confirms that S is higher in ellipticals than it is in spirals. The parameter S for the spheroid, probably more meaningful, turns out to be of about 5 $\pm$ 3.

3. THE "MISSING" CLUSTERS IN THE BULGE OF M31

The frequency distribution of clusters in M31 as a function of projected galactocentric distance is presented in Fig. 2 (taken from Wirth et al. 1985). Several relations have been derived up to now to describe the projected density profile of the cluster system. They differ from one another mainly due to differences in the sample used, but the main conclusion is susbtantially unaffected: the distibution follows an $R^{1/4}$ law rather well apart from the central region ($r < 3$kpc) where a flattening is evident using all the available lists. However, the actual existence of this flattening is still an open question. Harris and Racine (1979) noticed that if this were due to incompleteness in the survey of Sargent et al.

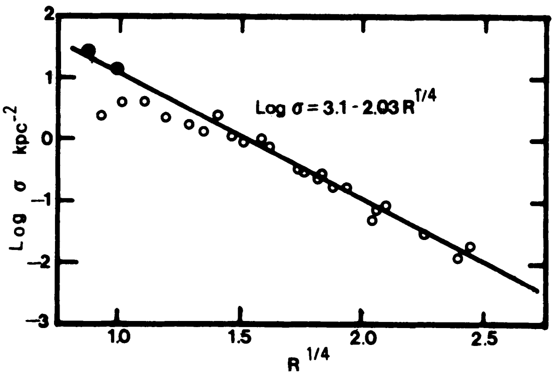

Fig. 2. The logarithm of the surface density of globular clusters in M31 as determined by Harris and Racine (circles) fitted to a de Vaucouleurs $R^{1/4}$ law. The inclusion of the "missing globulars" found by Wirth et al. would imply the values represented by the filled circles.

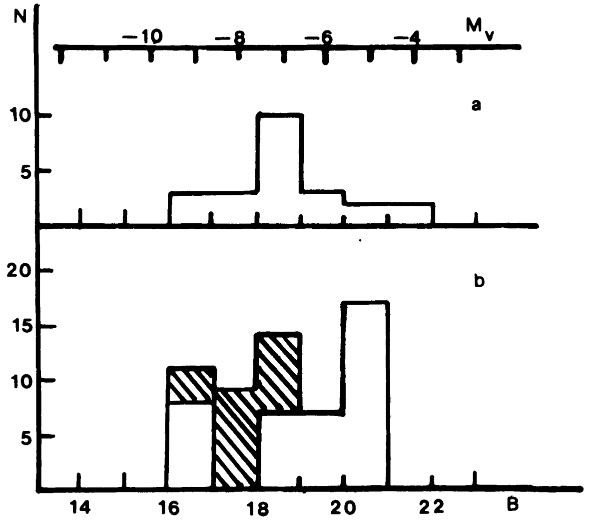

Fig. 3. a) histogram of the distribution in magnitude of the clusters in our own Galaxy having a core radius less than 0.4 pc. b) histogram of the distribution of the "excess-images" which should be the "missing globulars" according to Wirth et al. (1985); the known globular clusters are shown by shading.

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(1977), then some 140 objects including 20 brighter than V = 16 would have been missed in the inner 30 arcmin. The survey of Battistini et al. (1980) has slightly increased the number of candidates in the central region. However, even using that list, the flattening will remain. By comparing the Bahcall-Soneira model with the luminosity distribution of all the images detected in M31's bulge down to a B limiting magnitude of 21, Wirth et al. (1985) have found an excess of bright images in the luminosity range of globular clusters at M31's distance. They conclude thus that, if the optical candidates prove to be clusters, the derived flattening may simply be an observational effect due to the loss of very compact clusters not detectable with morphological techniques in the central regions. The two filled circles in their plot presented in Fig. 2 would show the claimed distribution. Battistini et al. (1986) have cast some doubts on the possibility that 20 new cluster candidates for the "missing" clusters can actually be detected. In particular, there is no doubt that some very compact clusters (like M80 in the Milky Way) have been lost in all the morphological surveys, however, the excess-count method used by Wirth et al. gives quite uncertain results when applied to M31 due to:(i) the statistical fluctuations in the counts; (ii) the uncertainties in the model used for the counts of foreground stars, and (iii) the possible contamination due to the brightest resolved objects in M31. Moreover, as shown in Fig. 3, the histogram of the distribution in magnitude of the "excess-images" in M31 and that of the very compact clusters in our own Galaxy looks highly different.

In conclusion, since the globular cluster candidates have been found mainly by morphological criteria, it is likely that all the available lists still suffer from similar biases which might affect some of the indications presently drawn from the study of the whole cluster system in M31. However, we do not believe that the discussed flattening might be totally due to incompleteness.

4. GENERAL CONSIDERATIONS AND DEDUCTIONS

1. The globular cluster candidates in M31 have been selected on the basis of their appearance without regard to their ages. This implies that one can use the word "globular" only in the "morphological" sense. As a consequence, these clusters should be compared with both the globular and the bright open clusters in the Milky Way (MW) and in the outer galaxies. In particular, it is important to estimate what fraction of the MW clusters we could classify as "globular" if we were using the same criteria used to select M31 candidates. Taking into account most of the factors possibly involved in this "simulation" we believe that "MW globular cluster candidates" would closely

resemble the sample actually observed in M31.

2. The fraction of the clusters bluer than (B-V)o = 0.5 (corresponding to the bluest globular in our own Galaxy) is decreasing along the sequence LMC - M33 - MW - M31. This suggests that there is a systematic variation which correlates to the galaxy-type sequence, like the bulge-to-disk ratio does.

3. The mean (B-V)o of clusters in M31 is slightly larger than in the MW. Even if strong uncertainties in the reddening of individual clusters are present, most of the available lists and methods converge toward this evidence. In particular, Harris and Racine (1979) found ⟨(B-V)o⟩ = 0.72 and ⟨(B-V)⟩o = 0.74 for MW and M31 globulars respectively. As well known, this may imply a slightly higher mean metallicity for the M31 clusters.

4. The cluster luminosity functions do not differ significantly in M31 and in the Galaxy. A more or less symmetric Gaussian distribution peaked at M = -7.2 ± 0.2 and σ = 1.2 mag fits the data. However, as shown and discussed by van den Bergh (1985), the cluster luminosity function appears to be correlated with the galactocentric distance. This may induce some caution on the use of globular clusters as distance indicators.

5. METALLICITY AND KINEMATICS OF M31 GLOBULAR CLUSTERS

It still remains difficult to determine whether there is a clear-cut metallicity gradient in the M31 cluster system. Most of the recent studies seem to suggest that only a mild radial gradient may exist and that, at the same time, if the gradient does exist, it is small compared to the observed metallicity dispersion at all galactocentric distances. Fig. 4 obtained from new IR data added to the whole set of previous IR measures (Bonoli et al. 1986) confirms this deduction. Moreover, one also has to notice that it is hard to deconvolve the possible metallicity gradient from the reddening law within M31.

The studies of the kinematical properties of M31 globular clusters lead to highly different conclusions if the still unpublished data presented by Searle (1984) will be confirmed. In fact, as can be seen in Table IV, all the previous data converge toward a scenario where the metal rich clusters lie in a rapidly rotating disk (within about 10 kpc of the center), and the metal poor clusters are in a slowly rotating halo, as in our Galaxy (Zinn 1985). Searle (1984), by increasing the sample, has found that: i) the M31 cluster system as a whole rotates with a low mean rotational velocity in the same sense as the disk, ii) the

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velocity dispersion of the clusters is large, and roughly one third of the clusters are in retrograde rotation with respect to the disk, iii) these rotational properties are independent of metallicity. These results cannot support the picture that globular clusters form early in the collapse of a single gaseous mass. It is thus clear that any significant difference in the [Fe/H]-rotational velocity relation between M31 and the Galaxy may give basic hints on the study of the early evolutionary phases of the galaxies.

Table IV

Kinematics of M31 globular clusters

Ref.	v(rot)	N(obj)	σ	Conclusions
				M31
vdB69			high	Objs near the nucleus with high metallicity: members of disk population ?
HS74		3	179±49	$Q \leqslant -0.46$ Correlation between:
		5	152±32	$Q \leqslant -0.44$ velocity dispersion
		13	133±18	$Q \leqslant -0.40$ and
		27	116±11	$Q \leqslant -0.25$ metallicity
		39	118± 9	$Q \leqslant -0.06$
HSvS82	160±40	32		14 objs with $x < -15'$ 18 objs with $x > +15'$
	negleg.	29	130	$\|x\| \leqslant 15'$ (peak-to-peak)
F83	200	26	90	[Fe/H]>-0.6,Rapidly rot disk
	little	30	90	[Fe/H]<-0.6,Slowly rot system (data from HSvS82)
S84	60	100	160	Rotational properties independent of metallicity. Roughly 1/3 of all clusters are in retrograde rotation respect to the disk.
				GALAXY
FW80	60±26		116±10	
Z85	152±29		71	[Fe/H]>-0.8 Disk system
	50±23		114	[Fe/H]<-0.8 Halo population

vdB69 = van den Bergh 1969
HSvS82 = Huchra et al. 1982
S84 = Searle 1984
Z85 = Zinn 1985
HS74 = Hartwick and Sargent 1974
F83 = Freeman 1983
FW80 = Frenk and White 1980

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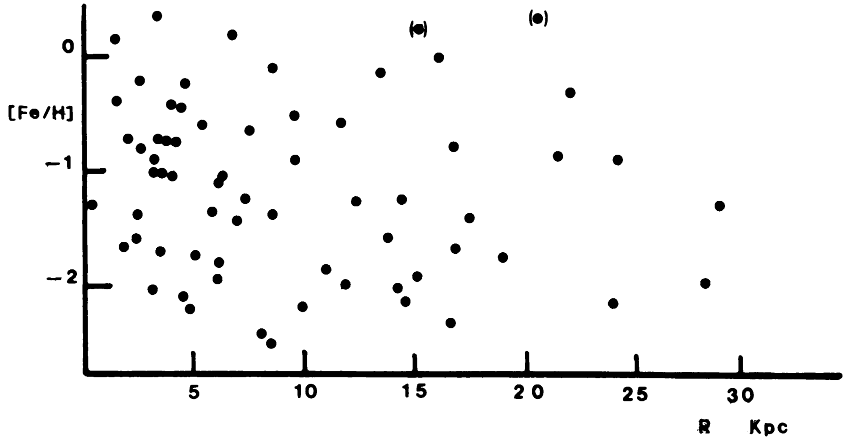

Fig. 4 The metal abundance of individual globular clusters in M31 as a function of projected galactocentric distance. [Fe/H]-values have been obtained through a (V-K)-[Fe/H] calibration based on the Zinn (1985) scale for galactic globular clusters.

6. THE STELLAR POPULATIONS OF M31 GLOBULAR CLUSTERS

One of the main reasons why the stellar populations in globular clusters are the subject of continuous study is the hope that we can describe galaxies of composite metallicity (Z) and age (t) by constructing models based on the studies of the integrated light of individual globular clusters of known Z and t. Searle first noticed that, at first approximation, from U to K the overall spectral distributions of the integrated light of individual globular clusters in M31 form a one-parameter family, and that Z is the parameter needed to rank the spectral flux distributions. This means that the integrated spectra of old populations of the same t and Z should be essentially the same. However, intrinsic differences in the integrated spectra of globular clusters, galactic nuclei, and elliptical galaxies have been found (Burstein 1985, and references therein) which have led to an extremely complex framework whose interpretation seems far from being reached. On the other hand, the present uncertainties in stellar population syntheses (Renzini 1986) do not permit the definition of stringent constraints to the models used for the comparison and interpretation of the observed indices and colors. In particular, the globular clusters of M31 present a wide set of spectroscopic indices systematically different both from the galactic globulars and from the elliptical galaxies (see Burstein 1985, for a review). **Table V** reports a quick summary of this observational

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evidence. Many alternative interpretations have been suggested (Burstein 1985, O'Connell 1986, Renzini 1986, and references therein). It is clear that a simultaneous fit of all the properties displayed by each individual spectral feature is impossible with the available models. However, there has been a growing claim that a substantial difference in age must be considered between the M31 and the MW globulars, in the sense that M31 globular clusters might be younger by 3 - 10 billion years. We still believe that no significant difference in age is present and that other mechanisms and phenomena (i.e. different "chemical trajectories", see Renzini 1986) may explain the quoted peculiarities. A complete understanding of these aspects is crucial for any use of globular clusters as basic tool for cosmological studies.

TABLE V

Summary of observed peculiarities in the integrated light of 'Old Stellar Populatons'

Plot (1) .vs. (2)	Regime 1	Regime 2	For fixed value of index (2), Regime 2 is
H_β .vs. Mg_2	M31 GC M32 Nuc M31 Nuc Ellipt.	MW GC	⇩
CN .vs. Mg_2	MW GC M32 Nuc M31 Nuc Ellipt.	M31 GC	⇧
⟨Fe⟩.vs. (J-K)o			- -
CN4170.vs.(J-K)o	MW GC M32 Nuc	M31 GC M31 Nuc	⇧
CO,H_2O.vs.(J-K)o	M31 GC MW GC	Ellipt. M31 Nuc M32 Nuc	⇧
CaII H,K	MW GC	M31 GC	⇧
UV 1500A	MW GC	Ellipt. M31 (Bo158 ??)	⇧
Sr II	M32	MW GC ([Fe/H]↑)	⇧

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DISCUSSION

DiFAZIO: You showed the comparison between the luminosity functions of clusters further and closer than 10 kpc; can you tell us if the comparison was made by normalizing the areas, taking a dimensionless abscissa (such as L/L_{max}) and then using a statistical test, or just comparing the two absolute magnitude histograms? The conclusions can differ substantially and only the first method gives a quantitatively reliable answer.

FUSI PECCI: I have taken the plot from the paper by Crampton et al. 1985 and, as far as I know, no normalization has been made.

HANES: Sidney van den Bergh (some years ago) deduced, from the distributions of color and magnitudes for globular clusters in M 31, that the reddening laws were not the same in M 31 and the Milky Way. Did you (a), find evidence for this or (b), consider this in doing reddening corrections?

FUSI PECCI: At the present stage of the project we have not yet obtained any independent estimate of the reddening of individual clusters in M 31. When necessary, we have used the reddenings obtained by Searle (See Frogel et al. 1980) if available, or the Harris and Racine (1979) approach which assumes (as a first approximation) the same reddening law in M 31 and the Milky Way.

LAUER: The distribution of clusters around M 31 does appear to be flat in the center. The Wirtanen and Searle objects pull a $R_{1/4}$ law out of a hat only by comparing excess stellar images near the nucleus with a relationship defined elsewhere by clusters selected on morphological grounds. This is mixing apples and oranges.

van den BERGH: In the Galaxy, globular cluster radii increase with galactocentric distance. If the M 31 clusters behave in the same way then it should be more difficult to distinguish clusters from stars near the M 31 nucleus than it is farther out.

GRINDLAY: If the total number of M 31 globular clusters is relatively constant, but the individual clusters have "changed" in the most recent surveys you discussed, then is it not possible that the complex (or lack of) correlations in M 31 cluster properties (as opposed to galactic globular clusters) might be due to the inhomogeneity still in the sample?

FUSI PECCI: The bulk of the cluster population (200-250 "bright" objects) forms a sample substantially unaffected by any revision. Since almost all the photometric and spectroscopic data on individual clusters come from this sample, the "changes" brought to the list have not affected the "growing" scenario. The degree of inhomogeneity in the search has been highly reduced by the latest survey and its influence on the reduction of any correlation (or lack of) should thus be low.

COHEN: Based on unpublished high spatial resolution images, many of the outermost M 31 globular clusters are spurious, consisting of either small galaxies or small random groupings of galactic stars.

FUSI PECCI: Searle (see Harris and Racine, 1979) has found that about 20% of the Sargent et al. (1977) list are spurious (particularly in the outer regions). In our survey, we have rejected some of their candidates because they seemed to be galaxies (usually the brightest and most rounded object in a very distant cluster of galaxies); but we have not found any indication of contamination due to groupings of galactic stars. There is no doubt however, that only very high spatial resolution images and/or spectroscopic observations will reduce the degree of contamination to a negligible level.

SCHOMMER: Several years ago, while taking spectra of M 33 clusters, Carol Christian and I observed a few M 31 clusters. We found that they had definitely different indices than the oldest clusters in M 33 or the Milky Way. This got us in some trouble with certain authors, but we naively interpreted this to be an age effect.

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