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Globular cluster candidates in the spiral galaxy NGC 2403

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Summary. A preliminary list of globular cluster candidates in the late-type spiral galaxy NGC 2403 is presented.

19 objects brighter than $V=20$ with images different from those of typical stars and galaxies were selected on a deep plate, taken with the Loiano 152 cm, F/8 telescope. Magnitudes and colors of all the candidates were then obtained from two B and two V plates. Spectra of objects in the list, obtained with the 2.7 m McDonald telescope, confirmed the cluster nature of some candidates and, coupled with color information, suggested the existence of a cluster population probably consisting of three components: i) young open clusters; ii) intermediate age clusters like those already found in the Magellanic Clouds and in other late spirals (M 33, NGC 253, NGC 55); iii) true globulars.

If confirmed, this result gives further support to the suggestion that massive clusters formed over a much longer period of time in Sc galaxies than in the Galaxy and in M 31.

Key words: clusters: globulars – galaxies: individual – galaxies: stellar content

1. Introduction

The importance of the study of star clusters lies in the large impact on themes like: earliest phases of star formation in galaxies, galaxy chemical composition and evolution, dynamics, X-ray source models, and possible definition of a single-step cosmic distance scale up to the distance of the Virgo cluster of galaxies.

In particular, the suggested "universality" of the globular cluster luminosity function and the occurrence of "populous" clusters of intermediate age, like those found in the Large Magellanic Cloud, M 33, NGC 55, and NGC 253 (see later for references), deserve a careful check in view of their general implications. In this frame, the study of the star cluster system in the spiral galaxy NGC 2403 (member of the M 81 group, Tamman and Sandage, 1968; de Vaucouleurs, 1975) is particularly important as galaxies in this group are not so far to prevent their bright stellar content from being resolved, and different methods for the determination of the distance can be applied.

NGC 2403 (R.A. = $7^h32^m.0$ DEC = $+65°43'$; $l^{II}=151°$ $b^{II}=+29°$) was classified Sc in the Hubble classification, Sc$^+$ in Holmberg's system (1958), Sc III by van den Bergh (1960) and SAB(s)cd by de Vaucouleurs (1975). The corrected distance modulus as reported by different authors spans from 26.7 (Madore, 1976), 27.1 (de Vaucouleurs 1979), and 27.6 (Tammann and Sandage, 1968).

Both the spiral structure and the stellar content closely resemble those present in M 33 which, according to Christian and Schommer (1982), presents evidence for a uniform distribution of bright clusters and perhaps the existence of a sizeable number of "populous" clusters. However, as far as the globular clusters are concerned, the galaxies in the M 81 group fall in a particularly unlucky range of distance. In fact, 28 pc [mean diameter of a typical globular cluster in the Galaxy (Alcaino, 1979)] are seen as $2''$–$3''$ in the range of distances quoted for this galaxy. Hence, NGC 2403 clusters are too far to allow in general the observation of an incipient resolution such as the one found in the best cases of M 31, and the expected number of clusters is too small (see below) to apply the technique of image-excess counts with respect to the foreground.

The expected number of clusters per magnitude interval can be derived for instance by making a comparison with M 33 or the LMC which have very nearly the same absolute magnitude as NGC 2403 (on any reasonable distance scale). This comparison suggests that 15–50 clusters fainter than $V \sim 18$ should be present. The brightest part of the luminosity function can thus be observed with deep plates taken in excellent seeing conditions.

As a first step, we have obtained a restricted number of cluster-like images selected by eye on a good seeing plate without any claim of completeness. Furthermore, color information and spectroscopic work have been undertaken to check the selection.

Since this study is a long term project, this paper presents a preliminary list of candidates for use of other investigators in the field.

2. Identifications

a) Photographic observations

A first list of candidates was prepared by selecting objects brighter than $V=20$ which appeared clearly "not stars and not galaxies" on a 098 – 04 + GG 455 plate exposed for 150 min with the F/8, 152 cm Ritchey-Chrètien telescope at Loiano (Bologna). The plate, covering a field of 72′ in diameter with a scale of 16.9 arcs mm^{-1}, is reproduced in Fig. 1. The limiting magnitude is about 21.5. The far west side of the plate was not searched because, given the declination of the galaxy and the position of the guiding probe with respect to the area covered by the plate, field rotation strongly affects the image structure. As a consequence,

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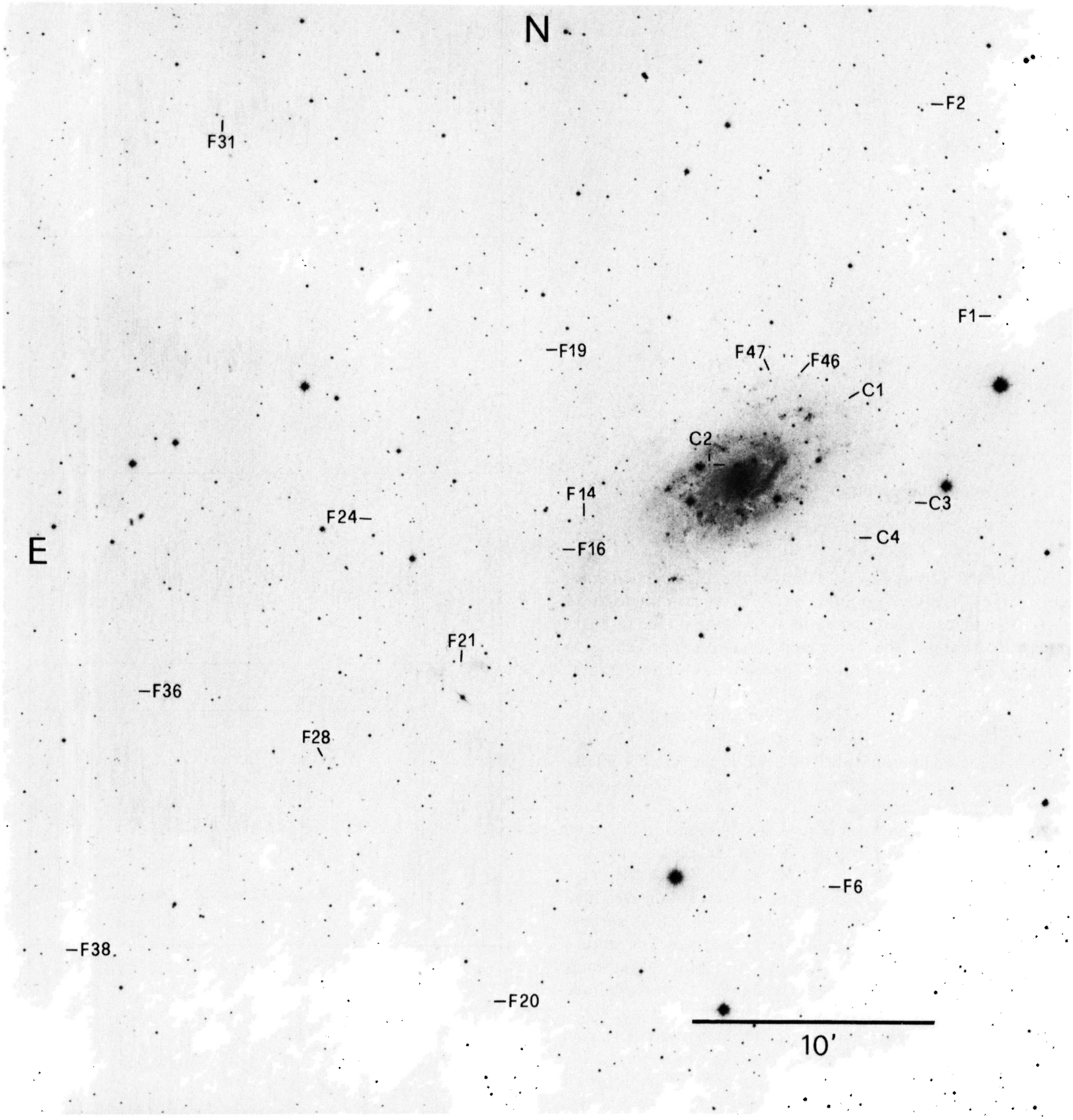

Fig. 1. Finding chart for the objects listed in Table 2 (plate No. 1172)

objects were selected up to 34′ and 14′, respectively, east and west of the galaxy, and 25′ north and south.

All the objects selected were then checked on the other available plates (see Table 1). In particular, we inspected a 103a-O plate, exposed 60 min without filter in excellent seeing conditions, in order to prevent large contaminations from stars. Four out of the five objects suggested as cluster candidates by Tammann and Sandage were independently selected by us. A cross check was also made against the lists of emission objects given by Véron and Sauvayre (1965), Hodge (1966), Tammann and Sandage (1968),

Table 1. Log of plates of NGC 2403

Plate	Date	Emulsion	Filter	Exposure
6	23-02-76	103aO		60
1172	21-10-79	098-04	GG455	150
1262	30-12-80	103aD	GG455	120
1334	26-11-81	103aD	GG455	140
1336	26-12-81	IIaO	GG385	100
1337	02-01-82	IIaO	GG385	130

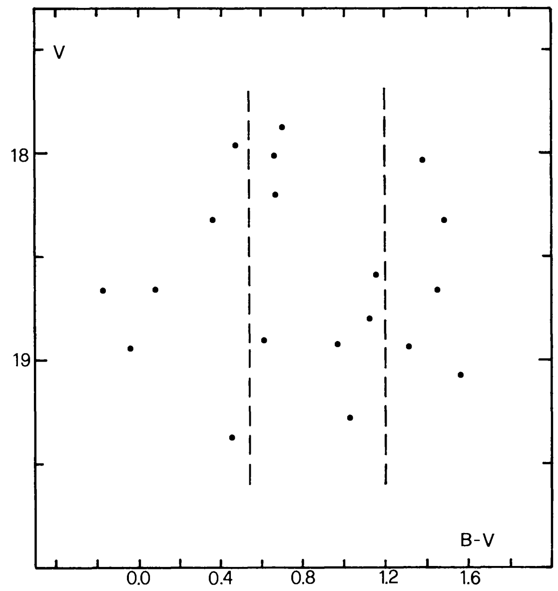

Fig. 2. Color-magnitude diagram for the objects listed in Table 2

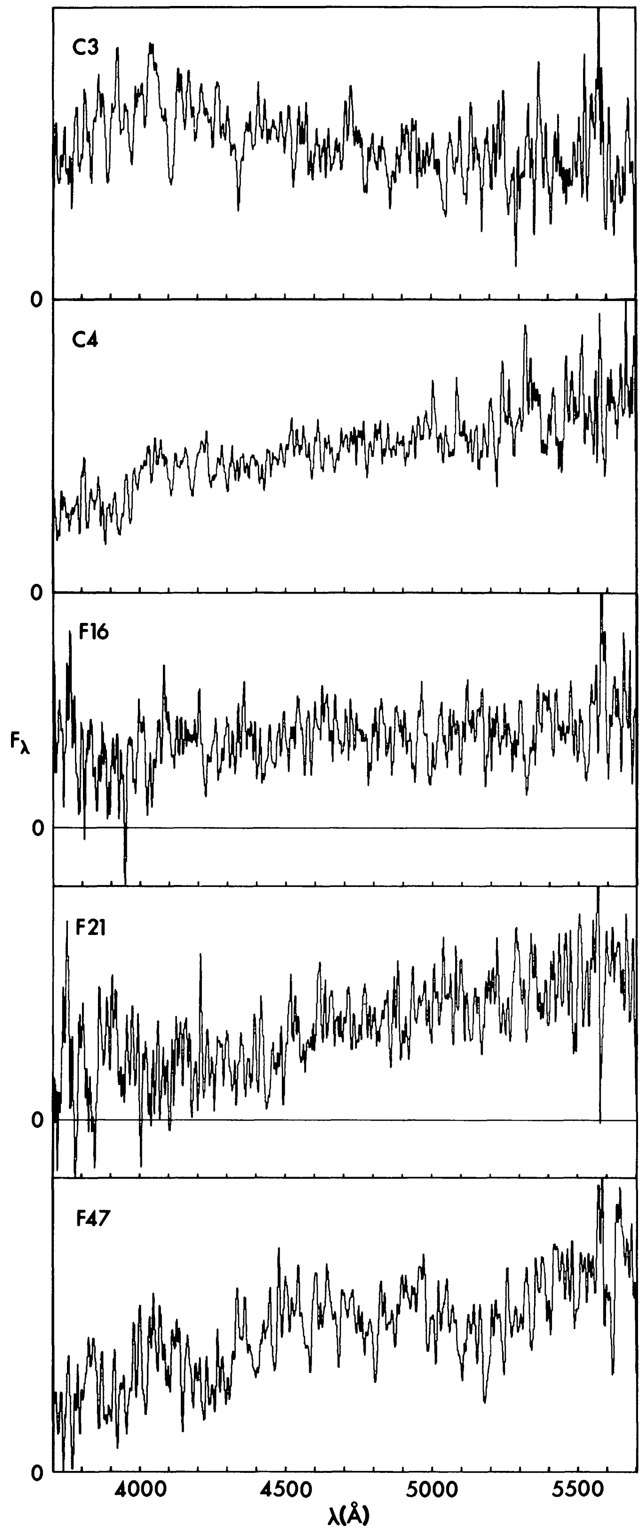

Fig. 3 Spectra of some of the objects listed in Table 2 obtained at 2.7 m McDonald telescope, with a 600 line mm^{-1} grating and integration times of about 90 min

and Sandage and Tammann (1974). Given the red extended color system of the plate used for the selection, we cannot exclude, however, a significant contamination of the sample due to background galaxies. Some hints of the contamination due to emission line objects and galaxies may be deduced from photographic photometry of the objects included in the sample.

All the images of candidates and standard stars (Tammann and Sandage, 1968) were digitized with the PDS microdensitometer at ESO (Munich) from two B and two V plates (see Table 1). The rasters were made in density mode using a 20 μm square aperture and a 15 μm step size. The data were reduced using the method developed by Buonanno et al. (1979, 1980), widely used for globular cluster photometry in our own Galaxy and in M 31 (Battistini et al., 1982; Buonanno et al., 1982 and references therein). The data arrays, smoothed by a convolution weighted mask, were than fitted by a two-dimensional fitting surface, making use of the formula proposed by Moffat (1969). The volume under the fitting surface is proportional to the apparent brightness of the object and in order to define the zero point of the magnitude scale we used the photoelectric sequence given by Tammann and Sandage (1968). This calibration gives $\sigma = 0.1$ mag (r.m.s. deviation between measured values and standard magnitudes) for all the plates reduced. Mean B and V magnitudes were obtained for all the candidates simply averaging magnitudes from both B and V plates. Figure 2 shows the color-magnitude diagram for all the candidates down to $V = 19.5$, this being the photometric limit.

After obtaining the $B-V$ color, we divided candidates into three groups with respect to their $B-V$:

(i) $(B-V) < 0.54$. This limit is suggested by the color of the bluest globular cluster in our own Galaxy, NGC 7492. Taking for this cluster $(B-V)_0 = 0.48$ (Harris and Racine, 1979) and $E(B-V)_{\mathrm{NGC\,2403}} = 0.06$ (Tammann and Sandage, 1968), one obtains the derived value $B-V = 0.54$. This value might well be increased since it is possible that the foreground reddening has been underestimated (de Vaucouleurs, 1978). However, also using twice the quoted reddening, the following discussion would be unaffected. Spectroscopic observations are necessary to check whether any of the objects with $(B-V) < 0.54$ belongs to a

Table 2

N	R.A. (1950)	Dec.	V	B–V	
(B–V) < 0.54					
C3*	7 30 53.65	65 42 5.8	18.66	–0.17	
C1	7 31 20.72	65 46 10.3	18.94	–0.04	
F14	7 32 13.51	65 39 39.7	18.66	0.08	in HII region
C2	7 32 14.15	65 43 24.8	18.32	0.36	
F2	7 30 50.81	65 58 19.2	19.37	0.45	slightly elongated
F46	7 31 39.55	65 47 10.4	17.96	0.47	compact
0.54 < (B–V) < 1.2					
F1	7 30 22.14	65 49 46.9	18.90	0.61	
C4*	7 31 15.49	65 40 35.4	18.01	0.66	compact
F31	7 33 53.25	65 52 7.0	18.20	0.67	
F6	7 31 57.59	65 37 51.5	17.87	0.70	
F16*	7 32 26.38	65 39 2.9	18.92	0.97	
F19	7 32 46.28	65 48 39.4	19.28	1.02	
F47*	7 31 15.18	65 45 1.1	18.79	1.12	compact
F38	7 36 22.79	65 22 26.1	18.58	1.15	
(B–V) > 1.2					
F36	7 33 52.34	65 35 8.2	18.93	1.31	
F28	7 33 32.68	65 39 11.9	18.03	1.38	
F21*	7 32 58.07	65 41 46.9	18.66	1.45	z = .14
F20	7 32 52.27	65 35 4.3	18.32	1.48	
F24	7 33 2.17	65 45 10.3	19.07	1.56	

* see spectrum in Fig. 3.

population of "populous clusters", like those found in the Large Magellanic Cloud (van den Bergh, 1975 and references therein), in M 33 (Melnick and D'Odorico, 1978; Christian and Schommer, 1982) and those suggested to be present in NGC 55 (Da Costa and Graham, 1982; Liller and Alcaino, 1983a) and in NGC 253 (Liller and Alcaino, 1983b).

(ii) $0.54<(B-V)<1.2$. Objects lying in this region of the C–M diagram are considered "classical globular clusters" candidates, remembering however that the degree of contamination of the sample due to background galaxies must be studied.

(iii) $(B-V)>1.2$. Beyond this limit we expect to find only very few highly reddened clusters, if any. This sample should contain essentially galaxies, since the surface density of galaxies in this field is expected to be many times the surface density of globular clusters. Rainey (1977) has counted field galaxies in the V band in other fields, from which we can conclude that about 450–500 galaxies brighter than $V=19.5$ should appear in the 0.74 sq.deg. considered field. This number would be slightly reduced upon accounting for differential foreground absorption by the presence of the galaxy. There is thus a good chance that the red side of the middle sample $(1.0<(B-V)<1.2)$ is also significantly contaminated by redshifted galaxies with cold spectra.

Table 2 shows coordinates, magnitudes and colors of selected objects divided into three groups with respect to the color criteria discussed above.

b) Spectroscopic observations

In order to have a preliminary check on the real nature of our candidates, a small amount of spectroscopic work has been accomplished at McDonald Observatory. The image-dissector scanner was used at the 2.7 m telescope, with a 600 line mm^{-1} grating in first order, giving a spectral range from 3700 Å to 6300 Å. Apertures were slots $3'' \times 4''$, and integration times were about 90 min for each of the five observed objects. Relatively good spectra were obtained of two objects selected as candidates by Tammann and Sandage (1968) and belonging, respectively to our groups ii and i: C 4 has an ordinary cluster spectrum, while C 3 (see Fig. 3) has an A-type spectrum typical of clusters of intermediate age. Objects F 21, F 47, and F 16 were also observed, but the spectra are poor. F 21 (group iii) appears to show a step in the continuum at 4550 Å and the overall shape of the spectrum is consistent with that of a galaxy at $z=0.14$. The color of this object (Table 2) is fully consistent with an elliptical galaxy at this redshift. Objects F 47 and F 16 appear to have steps in their continua at 4000 Å, and so may be clusters of NGC 2403, but we emphasize that since the spectra are poor, this claim is not definitive.

3. Discussion

A general discussion of the properties of the cluster system in NGC 2403 must be postponed until data for the complete survey are available. Nevertheless some indications can already be drawn on the basis of the results presented in this paper.

The candidate cluster population selected in this preliminary search can be considered composed basically of three groups: a) three bright, blue, presumably young clusters, with $B-V<0.1$; b) a group of objects with $0.3<(B-V)<0.54$, which may be clusters of intermediate age (10^8–10^9 yr like the "blue globulars" found in

LMC (van den Bergh, 1975); c) a sample of red objects with $0.54 < (B-V) < 1.2$, which should include true globulars and probably a few galaxies.

If confirmed by further investigation, the existence of three components in the NGC 2403 cluster population would be extremely important. In fact, it would give further support to the suggestion derived from the study of LMC, SMC, M 33, NGC 55, and NGC 253 that "late-type galaxies tend to have rather different star formation histories than more massive earlyer type galaxies like the Milky Way and M 31" (Christian and Schommer, 1982).

The existence of "blue globulars" in NGC 2403 is supported also by the absolute magnitudes of the candidates. Given the distance moduli in literature, they have $-9 < M_v < -8$, closely resembling those of similar objects in the LMC, M 33, and NGC 55. Therefore, although due to incomplete sampling no statistical comparison can be made with the cluster population in other galaxies, the suggested similarity between NGC 2403 and M 33 finds further support.

As far as the three very blue candidates are concerned, according to their colors and absolute magnitude they should be young open clusters analogous to some of the brightest found in our own Galaxy and in M 31. For two of them, C 1 and C 3, Tammann and Sandage (1968) suggested properties similar to those derived for NGC 457, NGC 663, and h and χ Persei.

As mentioned in Sect. 2b, we obtained a spectrum for cluster C 3. Inspection of Fig. 3 reveals immediately that the spectral energy distribution has its maximum in the blue and that hydrogen lines are strong. Its integrated spectral type is early A, similar to cluster "0" in M 31 (see Table 1 in van den Bergh, 1969) which has $M_v = -9$. However, assuming the observed $B-V$ is indicative of the color index of the turn-off – $(B-V)_t$ – and using the calibration of $(B-V)_t$ in terms of cluster age made by Janes and Adler (1982) for open clusters in the Galaxy, one has for cluster C 3 an age in the range $7\,10^7 - 2\,10^8$ yr. With this estimate of the age, this cluster would be a member of groups IV or V in the age classification scheme made by Harris (1976). Inspection of the H–R diagram typical for clusters of these groups (see Figs. 5 and 6 of Harris' paper) indicates that the large majority of the bright stars are late B or A-type stars with a mean absolute magnitude in the range $M_v = -3$ to -1. This means that the observed integrated spectrum may be compatible with the expected stellar population of the cluster based on the $B-V$ color alone.

Finally, considering the candidate "true globulars" the only object for which we have up to now a fairly good spectrum is C 4. It appears to be old (age > few G yr) and moderately metal-poor based on the similarity of its spectrum with McDonald spectra of the M 31 globulars Bo 148 and Bo 135.

Given the role played by NGC 2403 in the establishment of the extragalactic distance scale, further spectrophotometric work will be done on the candidates already found, and a new more complete search will be pursued on deeper plates taken with a larger telescope with the aim of the determination of the whole observable part of the luminosity function to be used as distance indicator.

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