

Large scale star formation in galaxies*

I. The spirals NGC 7217, NGC 1058 and UGC 12732. Young star groupings in spirals

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Abstract. We present multiband photometric observations of three spiral galaxies selected in a sample suited for the study of young stellar groupings and their relationship with the parent galaxy and the galactic environment. Star forming regions have been identified using an objective technique based on a multivariate statistical analysis. Maps of young star groupings are given for each galaxy. The luminosity functions of the young star group populations show a remarkable similarity with a slope in the range -1.52 to -1.33 . The size distributions peak around the *classical* 100 pc value of the Local Group associations for two out of the three galaxies. NGC 1058 shows smaller associations (peak at ~ 50 pc). The total number of young groups per unit B absolute luminosity of the galaxy is significantly greater in UGC 12732. The activity of star formation is in all three galaxies clearly stronger in the central regions.

Key words: galaxies: individual: NGC 7217 – galaxies: individual: NGC 1058 – galaxies: individual: UGC 12732 – galaxies: stellar content – stars: formation – methods: statistical

1. Introduction

A few recent papers have pointed out the importance of the determination of correlations among star forming region characteristics (size, luminosity, etc.) with those of the parent galaxy to gain insights on star formation processes and modes. For instance, Elmegreen et al. (1994, 1996) suggest the existence of a linear scaling between the largest complex size in a galaxy and the size of the galaxy itself. Moreover, Elmegreen & Salzer (1999) find that the largest complex size in each galaxy (in their sample of 11 galaxies) scales with the square root of the total galaxy B–luminosity. These scaling laws are consistent with the largest complex size being equal to 1/2 of the characteristic

Jeans length in the ambient gas, if the gas velocity dispersion is always the same in a marginally stable ISM. In this picture, the time–scale of star formation is longer (about 50 Myr) for larger galaxies than for smaller ones when the size difference is a factor of 10. This means that in large galaxies star forming regions should contain both evolved stars and young OB stars, while in smaller galaxies only OB stars are expected in such regions. As a consequence, a correlation between the average age (or colour) of the star forming regions and galaxy luminosity is expected. A related prediction is that star forming regions in small galaxies should be much brighter, but not much larger relative to the host galaxy than those in giant spirals. It has been clearly shown by Hodge (1986) that any astrophysical considerations deduced from the collection of heterogeneous data should be carefully handled. Indeed, many biases are introduced by the difference in the quality of observational data as well as by some degree of subjectivity unavoidably present in any *by–eye* identification of star groupings. In order to minimize the uncertainties just described, it would be worth dealing with a homogeneous set of observational data (taken with the same telescope and equipment) and using an objective method for identifying blue star groupings and determining their main properties. Although OB associations in Local Group galaxies are important to study, it is not possible to derive significant correlations among star-forming region properties and their parent galaxy characteristics using only Local Group galaxies, due to the relative scarcity of galaxies in the Local Group. For the reasons and purposes discussed above we decided to start a project which consists of: *i*) the collection of multiband photometric data for a large set of galaxies beyond the Local Group; *ii*) their treatment with the cluster analysis algorithm described in Adanti et al. (1994). Some preliminary results are presented in Wyder et al. (1998).

This paper is the first of a series in which we will present and discuss our determination of the young stellar groupings (hereafter YSGs) in various spirals, chosen among almost face–on galaxies with a radial velocity limit that corresponds to a moderate distance ($\lesssim 16$ Mpc) and small enough in angular size to be included in a single CCD frame. A relevant by–product of

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* Tables 1, 2, 3 are only available in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via <http://cdsweb.u-strasbg.fr/Abstract.html>

this work is an accurate list of YSG targets to be investigated with higher resolution observations (e.g. HST–ACS).

We can note that the philosophy of the present project is the same followed by Bresolin et al. (1998), who analysed HST data of several nearby galaxies with an automatic technique suited just for resolved stellar fields.

2. Observations and data reduction

Data for the galaxies NGC 7217, NGC 1058 and UGC 12732 were obtained with the 3.5m telescope at Apache Point Observatory¹ using SPIcam, a camera which consists of a 1024×1024 backside illuminated and thinned SITe CCD with read-out noise of 5.7 electrons/pixel and gain of 3.4 electrons/ADU. The image scale is $0.28''/\text{pixel}$, yielding a field of view of $4.8' \times 4.8'$. UGC 12732 and NGC 7217 were observed in the U, B, V and I bands on the night of 1997 November 24 while U, B, V and R images of NGC 1058 were obtained on 1998 November 21. Both nights were photometric during the time when the observations were taken, as judged from an all sky IR camera at the observatory and the standard star observations described below.

Exposure times for all three galaxies were 1200 s in U and 600 s in each of the remaining filters. The UGC 12732 and NGC 7217 images consisted of single exposures while the total exposure time in each filter for the NGC 1058 images was divided among three exposures. Between these individual exposures of NGC 1058, the telescope was offset several arcseconds in RA and Dec to assist in the removal of defects in the CCD. The seeing averaged about $1.0''$ (FWHM) for the UGC 12732 images and about $1.3''$ for NGC 7217 and NGC 1058.

While the V image of NGC 7217 was being exposed, the telescope focus changed, producing an out of focus image. On the night of 1997 August 3 a 300 s V image of NGC 7217 was obtained under non-photometric conditions. Comparing aperture magnitudes of several stars in the field between the August 3 and November 24 images, we were able to calibrate the in focus V image from August 3 and it is this image that will be used in the following analysis.

All of the images were reduced using standard routines in IRAF.² The reduction included the subtraction of the bias level determined from the overscan region of the CCD as well as division by an average twilight flat field image in each filter. An average of several bias frames obtained at the end of the night showed no structure, so an average bias frame was not subtracted from the data.

In some cases the flat field division resulted in a spatial gradient in the sky background across the image. The APO 3.5m has little baffling which may have lead to some contamination of the flat field frames with scattered light. This scattered light

was most apparent in the V, R and I band images where the background sky counts are greatest but is likely present in the U and B data as well. For example, after division by the flat field, an overall gradient of 3% in the sky in the I band image remained. In addition to the likely presence of scattered light in the flat fields, the I band images in particular have a fringing pattern due to the presence of a strong night sky line within the I passband. In the 600 s exposures of UGC 12732 and NGC 7217, the fringes have an amplitude of 200–300 ADU in a background of 6000–7000 ADU. No correction was applied to correct for the fringe pattern. For this reason the I band data are subject to larger uncertainties than for the other bands.

The fractional pixel offsets between all of the exposures of each galaxy was determined using the positions of several stars in the field. Once the offsets were known, the images were shifted to the nearest fraction of a pixel using the task IMSHIFT in IRAF with linear interpolation.

For the NGC 1058 data, the individual exposures in each filter were averaged together and cosmic rays removed using the IRAF task IMCOMBINE. As the UGC 12732 and NGC 7217 data only consist of a single exposure in each filter, a different method was used to remove the cosmic rays. Cosmic rays were removed in these images using the task COSMICRAYS, an IRAF task that identifies pixels which deviate strongly from the surrounding pixels and replaces the value in those pixels with the average of the values in the surrounding pixels. This procedure eliminated almost all of the cosmic rays, mostly leaving those hits that affected more than one pixel.

The UBVR observations of NGC 1058 from the night of 1998 November 21 were calibrated using observations of photometric standard stars from Landolt (1992). The standard stars range in colour from -1.1 to 0.8 in U–B, from -0.3 to 1.1 in B–V and from -0.1 to 0.6 in V–R and were observed several times throughout the night between airmasses from 1.1 to 1.6. Instrumental aperture magnitudes for all of the standard star observations were extracted using a $7''$ radius aperture radius.

On the night of 1997 November 24, observations of three stars in Selected Area 92 of Landolt (1992) were used to determine the calibration for the UGC 12732 and NGC 7217 data. The stars range in colour from 0.2 to 1.3 in U–B, 0.7 to 1.1 in B–V and 0.8 to 1.2 in V–I and were observed at airmasses ranging from 1.2 to 1.5. As for the 1998 data, instrumental magnitudes were extracted for each observation of the three standard stars. Since this standard field does not have any very blue stars, we have fixed the colour coefficients for the UBV data for this night to be the same as determined above from the 1998 data to insure that our calibration is valid for the blue colours typical of YSGs.

3. The identification techniques

Since the procedure adopted for the identification and classification of star groupings in unresolved galaxies is fully described in Adanti et al. (1994), we just give here a quick overview of the method. This technique relies on a combined application of Principal Component Analysis (PCA) and Cluster Analysis

¹ APO is privately owned and operated by the Astrophysical Research Consortium (ARC), consisting of the University of Chicago, the Institute for Advanced Study, Johns Hopkins University, New Mexico State University, Princeton University, the University of Washington and Washington State University.

² IRAF is distributed by the Association of Universities for Research in Astronomy, Inc., under contract to the National Science Foundation.

(CA) to multicolour data of galaxies. The availability of various sets of colours and fluxes allows every pixel of the galaxy image to be represented as a point in the space of the variables (i.e. of fluxes and colours). PCA and CA result in an artificial image of the galaxy, where pixels are grouped into classes according to their relative distances in the space of variables. Our methodology has a large range of possible applications, and we, in particular, proved its reliability for the determination of star forming regions through a detailed test on M 31 (see Adanti et al. 1994). We applied our automatic identification of YSGs on a set of M 31 images artificially degraded in resolution to simulate it as it would appear at a distance of 10 Mpc. The results were found in good agreement with previously available identifications (van den Bergh 1964; Efremov et al. 1987).

In order to make the whole identification procedure easy to handle and its interpretation straightforward, we have implemented a friendly IDL based interface. The use of this facility is particularly convenient for projects – like the present one – which require an extensive analysis for a large set of galaxies.

The background correction for YSGs is intrinsically a difficult task to perform, because it is not possible to apply the procedures usually adopted for individual stars. YSGs indeed tend to be located in an environment rich with unresolved structure (dust lanes, stars and clusters, etc.). In any case we found that an effective identification of YSGs requires a subtraction of the underlying large scale luminosity gradients of the galaxy. This subtraction makes, first of all, the individual structures emerge better from the background. Furthermore, if we do not perform the subtraction before the application of our CA technique, we found that many of the classes resulting from the CA algorithm are used to account for the overall luminosity profile of the galaxy, thus limiting the classes available to delineate the structures (e.g. YSGs) that we are interested in.

A reliable estimate of the large scale galaxy luminosity profile has been obtained as follows: 1) areas where no evidence of spiral arms and other structures were selected throughout the images; 2) for each radial bin the 20th percentile of the photon counting distribution was determined; 3) an analytical fit to this radial distribution was performed. Our adopted choice of a low level (the 20th percentile) in the flux distribution (see point 2) is justified by the necessity of removing “luminous” structures (e.g. faint, diffuse spiral arms) incidentally present in the selected sampling areas. An a-posteriori check of the influence of the percentile level showed that the final identification of YSGs is just marginally affected: a variation of the threshold in the 10–30th percentile range does not affect the number of identified objects, while has a negligible influence (< 5%) on their sizes. We found that a decreasing exponential law well represents the radial luminosity profiles (in the various bands) for the galaxies studied here. Correlation factors are always greater than 0.97. Fig. 1 shows an example of the obtained fitting profile.

While the above procedure is good enough to improve the identification of YSGs, it is clearly insufficient to estimate a reliable local background for each YSG. Thus, we attempted to determine the local background in a more sophisticated way: we selected a rectangular region surrounding the YSG and fitted a

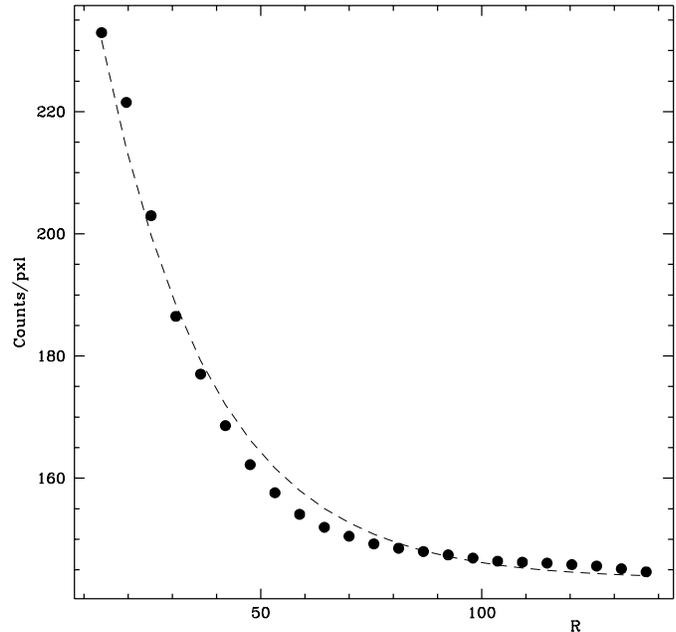


Fig. 1. Background radial profile (in the B-band in counts/pixel) for the galaxy NGC 1058 used in the identification of YSGs as described in Sect. 3. The radius R is in arcsecs.

plane to the background values. As an estimate of the error we take the standard deviation of the residual counts after the fitted background subtraction. This error can go up to 0.5 mag (at low luminosities) in all the photometric bands, rendering colours for YSGs unreliable. Even for the luminosities we feel confident only on a statistical use of them (e.g. luminosity functions), rather than on individual values. However, these uncertainties do not affect the identification of YSGs or the determination of their morphological parameters.

4. Results

4.1. NGC 7217

The galaxy NGC 7217 is an almost face-on spiral of Sb type, with no major neighbours (the nearest galaxy is the small irregular NGC 7292, at about 1.3 Mpc distance). NGC 7217 is 15.5 Mpc distant (assuming $H_0=75$ km/sec/Mpc) with an integrated B magnitude of 11.17 mag and isophotal diameter $D_{25} = 3.9'$. The physical scale of the galaxy image is 21 pc/pixel. Images of NGC 7217 show, as already noted by Verdes–Montenegro et al. (1995) and Buta et al. (1995), a 3-ring structure characterized by a high H_α luminosity, suggesting an active current star formation rate. In particular, the outermost ring (about 6 kpc from the galactic centre) contains about 2/3 of the neutral hydrogen mass in the galaxy. Usually, the presence of rings in galaxies is associated with evidence of bar-like structures (see Buta & Crocker 1991 and references therein). However, NGC 7217 is remarkably axisymmetric and no bar has been detected so far even in the infrared.

The application of our classification algorithm for this galaxy led to an identification of 149 YSGs, which are shown

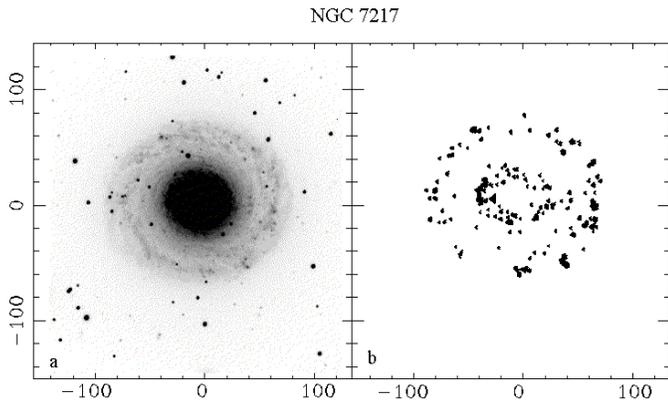


Fig. 2. **a** B-band image of NGC 7217 with North up and East to the left. **b** map of the YSGs identified by our algorithm in NGC 7217. Coordinates are in arcseconds, with the offset at the galactic centre.

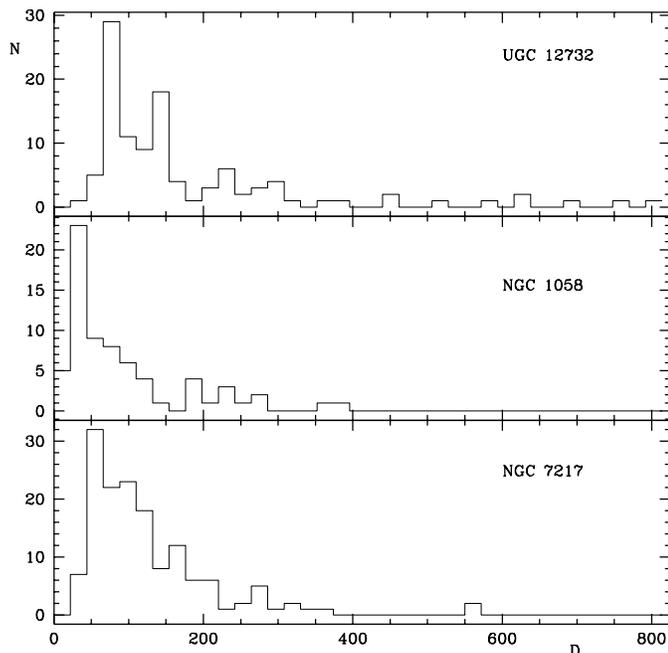


Fig. 3. The size (D , in pc) distribution of the YSGs in NGC 7217, NGC 1058 and UGC 12732. The size is defined to be the average of the x and y extents of the YSG in the image.

in Fig. 2b. We clearly recover in this figure the multiple ring-like structure. The main characteristics of the groups are given in Table 1. The size, D , has been defined as the average between the x and y elongations of the object on the frame. The size histogram based on the data of Table 1 (see Fig. 3) peaks around 100 pc (average and standard deviation of 130 pc and 84 pc, respectively) similarly to Local Group galaxies. If the YSG luminosity was negative after background subtraction, we entered n.a. (not available) for the integrated B magnitude and surface brightness Σ_B in this table, as well as in Tables 2 and 3.

We converted the integral magnitudes for each YSG to absolute luminosities using our assumed distance. Luminosities were corrected for a galactic foreground extinction of $A_B = 0.41$ mag, i.e. the value listed in the Third Reference

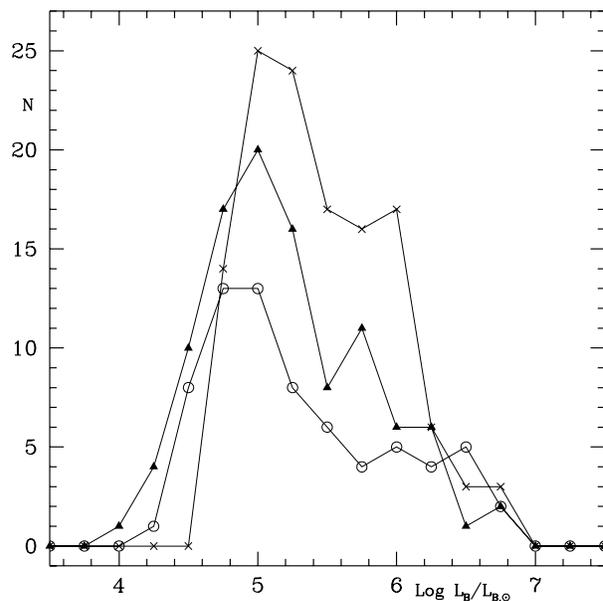


Fig. 4. The B-band differential luminosity function for the YSGs in NGC 7217 (crosses), NGC 1058 (open circles) and UGC 12732 (black triangles). In its bright range the luminosity function in all three galaxies can be fitted by a power law with slopes -1.46 ± 0.20 , -1.33 ± 0.26 and -1.52 ± 0.25 in NGC 7217, NGC 1058 and UGC 12732, respectively.

Catalogue of Bright Galaxies (RC3) (de Vaucouleurs et al. 1991). The resulting differential luminosity function is shown in Fig. 4. At its bright end the luminosity function can be approximated as a power law while the distribution turns over below $\log(L_B/L_{B,\odot}) = 5.0$ due to incompleteness. Fitting a power law of the form $dN \propto L^\alpha dL$ to the points brighter than the turnover, we find $\alpha = -1.46 \pm 0.20$.

In Fig. 5, we show the YSG B-band surface brightness averaged over concentric circular annuli as a function of the galactocentric radius. The YSG positions were corrected for the galaxy's inclination using the optical minor to major axis ratio of 0.83 and position angle of 95° from the RC3. The YSG B-band luminosity per unit area is related to the high mass star formation rate. Fig. 5 shows that the peak values of the star formation rate in the two rings are an order of magnitude higher than in the inter-ring region assuming that the dust absorption, IMF and YSG age distribution do not vary with galactocentric distance.

4.2. NGC 1058

NGC 1058 is a nearly face-on field Sc galaxy with $B=11.89$ mag and $D_{25} = 3.0'$ at a distance of 8.4 Mpc. The physical scale of our CCD images is 11 pc/pixel. This galaxy shows a clear knotty structure not organized into spiral arms. Some recent studies by Ferguson et al. (1998a,b) of its $H\alpha$ regions indicate the presence of a radial metallicity and reddening gradient in the sense that

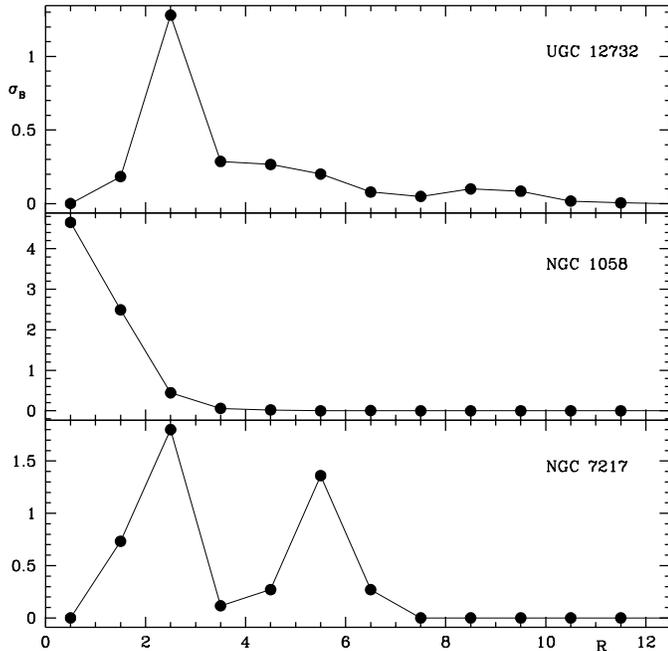


Fig. 5. The surface luminosity density (σ_B , in $10^6 L_{B,\odot} \text{ kpc}^{-2}$) of YSGs averaged over concentric circular annuli as a function of the galactocentric radius (R , in kpc) in NGC 7217, NGC 1058 and UGC 12732. The YSG positions were corrected for the galaxy inclination.

inner regions are more metal rich and more reddened, a trend often observed in spirals. As for NGC 7217, Table 2 gives all the relevant data for the set of 69 YSGs identified in this galaxy, whose map is shown in Fig. 6b.

The size distribution of Fig. 3 peaks at 50 pc with average value and standard deviation of 104 pc and 109 pc, respectively. There is no clear correlation between the size and the galactocentric distance.

In Fig. 4 we show the YSG B-band luminosity function; the decreasing tail corresponds to a slope of $\alpha = -1.33 \pm 0.26$. The B-band luminosity surface density of YSGs shown in Fig. 5 monotonically decreases, falling quickly by a factor of about 15 at a galactocentric distance of 3 kpc.

4.3. UGC 12732

According to the data in the RC3, the galaxy UGC 12732, is classified as type Sm with an integrated B magnitude of 13.8 and optical diameter $D_{25} = 3'$. This galaxy is at 12.4 Mpc distance which corresponds to a scale of 17 pc/pixel in our images. Its nearest neighbor is the Scd galaxy NGC 7741 which is at a projected distance of 160 kpc and has a radial velocity that is within 6 km s^{-1} of UGC 12732's velocity.

Our images show that the galaxy consists of a smooth low surface brightness inner region with a single long arm of YSGs starting from SW of the centre and circling around to the north side of the galaxy. In addition there is a second much broader and smoother arm extending to the south of the main body of the galaxy. There are many other YSGs scattered throughout the

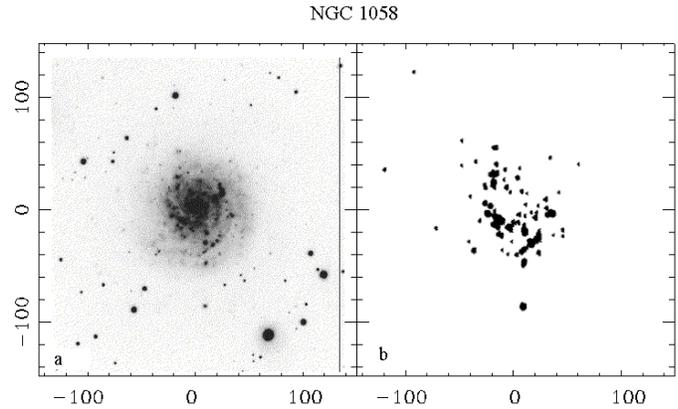


Fig. 6. **a** B-band image of NGC 1058 with North up and East to the left. **b** Map of the YSGs identified in NCC 1058. Coordinates as in Fig. 2.

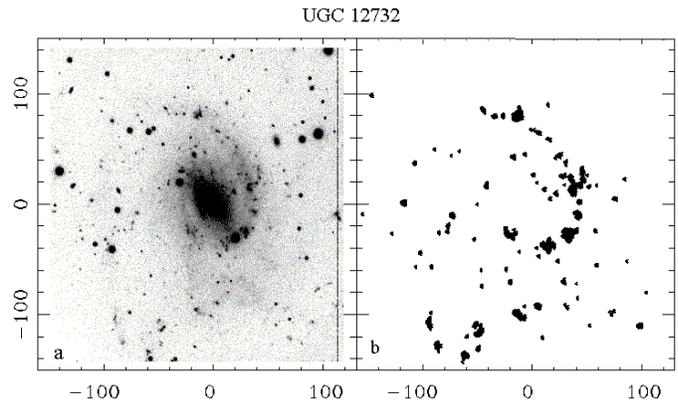


Fig. 7. **a** B-band image of UGC 12732 with North up and East to the left. **b** Map of the YSGs identified in UCC 12732. Coordinates as in Fig. 2.

image in areas where there is no detectable background light from the galaxy itself.

The HI properties of UGC 12732 were recently studied by Schulman et al. (1997) based upon data from Arecibo and the VLA. Their data show that the HI extends throughout the field of our images with a diameter of $11.6'$ at an HI level of 10^{19} atoms cm^{-2} . This diameter is almost four times larger than the optical galaxy. There is a depression in the HI gas coinciding with the optical centre of the galaxy while the two arms visible in our optical data are detected in HI as well at a level of $5\text{--}6 \times 10^{20}$ atoms cm^{-2} .

We identify 108 young star groups in this galaxy. Their measured properties are listed in Table 3 while their locations are shown in Fig. 7b. The size-histogram shown in Fig. 3 peaks around 90 pc (the average is 178 pc, the standard deviation 156 pc) and – again – few large YSGs ($D > 200$ pc) are present. The more numerous population of small YSGs in this galaxy with respect to those in NGC 7217 is the result of the joint effects of the lower surface brightness of UGC 12732 and of its slightly shorter distance. The dimensions of the YSGs of this galaxy are similar to those of YSGs in local group galaxies.

The B-band luminosity function of YSGs in UGC 12732 is shown in Fig. 4 and has a best-fit power law exponent

$\alpha = -1.52 \pm 0.25$. The radial YSG B-band luminosity surface density in Fig. 5 peaks at about 2 kpc radius and falls off smoothly with radius by one and a half orders of magnitude at a radius of 12 kpc.

5. Discussion and conclusions

This paper presents the first results of an ongoing project whose main aim is to collect homogeneous data suited to the study of regions of recent star formation in a variety of galaxies. We apply a cluster analysis algorithm to obtain, in a semi-automatic way, an objective identification of young star groupings (YSGs) in UBVR_I frames of NGC 7217, NGC 1058 and UGC 12732.

These are the first spirals we observed from a sample (selected from the RC3) of nearly face-on galaxies, with radial velocities less than 1200 km s^{-1} and small enough to fit in just one CCD frame of the Apache Point Observatory Spicam. This sample will allow us to check in a statistically significant way whether correlations among properties of YSGs and their parent galaxies exist. Such correlations are useful to understand better how star formation in galaxies proceeds (see e.g. Elmegreen 1994, 1996).

We have identified 149, 69 and 108 YSGs in NGC 7217, NGC 1058 and UGC 12732, respectively. These numbers correspond to specific frequencies $S_N \equiv N_t \cdot 10^{0.4(M_B^0 + 15)}$ equal to 1.0, 3.9, 19.7. If we consider just YSG brighter than the likely completeness limit ($L_B = 10^5 L_{B\odot}$), specific frequencies reduce to 1.0, 3.1 and 12.9 for NGC 7217, NGC 1058 and UGC 12732, respectively. In any case, the high S_N value for UGC 12732 indicates an overabundance of YSGs in this galaxy; however, since distances are from radial velocities, peculiar motions may significantly affect the total luminosity and consequently the S_N value. For instance, a variation of 50% in the UGC 12732 distance makes its S_N value comparable to those of the other two galaxies.

As explained in Sect. 3, determining an accurate background for the YSGs is an inherently difficult problem since they usually lie in areas with a lot of structure. This makes the colours of the YSGs unreliable but the luminosities can still be used to determine a statistically reliable luminosity function. We found that the slope of the bright tails of the YSG luminosity functions in these three galaxies are similar, within the errors, and lie in the range -1.33 to -1.52 . In Sect. 4 we also present the size distribution and surface density of the YSGs versus galactocentric radius: no significant variation is found. From the radial distribution of our identified YSGs and their integrated luminosities we

could extract information about differences in star formation rate within each galaxy and between galaxies. We found a steeper radial slope for the SFR in NGC 1058 while in both NGC 7217 and UGC 12732 the variation of the SFR between the inner and outer galactic regions is up to a factor of about 10. The YSG size distributions (which are of course affected by the poorly known galactic distances) are similar in NGC 7217 and UGC 12732 (peaks around 100 pc), while NGC 1058 shows smaller YSGs (the peak is at 50 pc). Since the latter galaxy is much closer than NGC 7217 and UGC 12732, one could believe the smaller sizes of YSGs as an artifact of the intrinsic better spatial resolution (pc/pixels) of the images. A simple test we performed clearly proves this is not the case: the identification of YSGs on images of NGC 1058 artificially re-binned to simulate larger distances shows that the peak of the size distribution is almost insensitive on a variation up to 40% of the distance. More specifically, increasing the distance implies a loss of just the smallest objects (those smeared out by the image re-binning).

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