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SURVEY OF GALAXIES IN THE LOCAL VOLUME IN Hα: FAINT COMPANIONS OF M31

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Observations on the 6-m telescope in the Hα line and in the continuum are reported for 10 dwarf companions of the galaxy M31: And I, And II, And III, And V, And IX, And X, Cass dSph, Peg DSph, NGC147, NGC221, and one irregular dwarf galaxy in the background, And IV. All the observed companions of M31 have current star formation rates (SFR) on the order of or less than 10^{-6} $M_\odot$/yr. On a "star formation rate-neutral hydrogen mass" diagram for galaxies in the local volume, the dwarf spheroidal companions of Andromeda lie in the region of extremely low values for these parameters.

Keywords: *Galaxies: dwarf- galaxies: spheroidal- galaxies- ISM*

1. Introduction

In order to understand the evolution of the stellar and gaseous subsystems of galaxies over their entire range of sizes and luminosities, it is necessary to have systematic data on the fluxes radiated by the galaxies in the emission Hα line. These fluxes provide a direct characterization of the current rates of star formation in galaxies. Measurements of the Hα fluxes for all the galaxies, without exception, within a fixed nearby volume can be used to compare the rates of star formation for galaxies of different types and to estimate the relative contributions of dwarf and giant galaxies, while avoiding the complicated process of taking selection effects into account.

The catalog of nearby galaxies of Karachentsev et al. [1], which contains 450 galaxies within a volume of (radius) 10 Mpc surrounding the Milky Way, is most suitable for carrying out such a program. Another 30 new objects have been added to this catalog within the last 2 years. For most of the galaxies in the Milky Way the individual distances have been measured with an accuracy of better than 10% based on the luminosity of the red giant branch. Almost 75% of the galaxies in the Milky Way have been detected in the 21 cm line of neutral hydrogen. Over this distance, masses

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of neutral hydrogen of up to 10^4-$10^6\,M_\odot$ can be measured in the galaxies, so that it is possible to compare the current rate of star formation with the initial amount of gas even for the dwarf galaxies.

Unfortunately, by 2000 only a small fraction of the galaxies in the Local Volume had been studied in the Hα line. Later surveys [2-6] have substantially improved the situation in this region. We have set ourselves the task of obtaining Hα images for all the galaxies in the Local Volume that had not been observed previously in order to obtain a complete set of data on the Hα fluxes for the members of the Local Volume.

In the first article of the present series [7], we presented the measured Hα fluxes for all the galaxies in the near group surrounding the giant spiral NGC6946. In this article we present the results of Hα observations on 10 dwarf galaxies located in the closest neighboring group surrounding the galaxy M31.

2. Observations and data processing

According to Karachentsev [8], the group M31 contains 19 galaxies, to which yet another dwarf system, And X, has been added in the past year [25]. Half of the brightest companions of Andromeda have already been observed in the Hα line. We obtained CCD images in the Hα line and in the continuum for the remaining 10 galaxies with low surface brightnesses during November 2004 and during October and November 2005. All the observations were made on the 6-m telescope at the Special Astrophysical Observatory (SAO) of the Russian Academy of Sciences using the SCORPIO detector [9] with a 2048×2048 pixel matrix and a scale of 0.18"/pixel, which yields a full image field of 6'.1×6'.1. Images in Hα+[NII] and in the continuum with an average image quality of 1".9-2".0 were obtained by observing each galaxy through a narrow band interference filter at Hα ($\Delta\lambda$ = 75 Å) with an effective wavelength λ = 6567 Å, and a broad band SED607 filter for the continuum with $\Delta\lambda$ = 167 Å and λ = 6063 Å. The typical exposure times were 2×300 s in the continuum and 2×600 s in Hα. Since the range of radial velocities in our sample is small, we have used the same Ha filter for all the observed objects.

The data processing procedure is the standard one for direct photographs obtained with CCDs. The bias was first subtracted for all the data and then all the images were mapped onto a flat field, after which space particles were removed and the sky background was subtracted for all the images. Then all the images in the continuum were normalized to the Hα images using 5-15 stars in the field and subtracted. In Fig. 1 (at the end of this article) we show (left to right) images of Hα plus the continuum and Hα minus the continuum for the 10 observed galaxies. The Hα fluxes were determined from the Hα images with the continuum subtracted using spectrophotometric images of standard stars observed on the same nights as the objects.

The resulting Ha fluxes were subsequently corrected for the galactic absorption, the magnitude of which was taken to be $A(\mathrm{H}\alpha)=2.32E(B-V)$, where $E(B-V)$ is the color excess obtained from the data of Ref. 10. A study of the measurement errors showed that they are typically ~15%.

3. Results

Some of the basic parameters of the 10 galaxies which we observed are listed in Table 1. Columns 1 and 2 give

TABLE 1. Some Parameters of the Observed Galaxies.

Galaxy	RA (2000.0) Dec		D, Mpc	$\log(L_B)$, $L_\odot$	$\log(M_{HI})$, $M_\odot$	$\log(F_{H\alpha})$, erg/s·cm^2	log[SFR], $M_\odot$/year
NGC147	$00^h33^m11^s.6$	+48°30'28"	0.76	8.08	<3.5	-14.93	-6.07
And III	00 35 33 .8	+36 29 52	0.76	5.88	<4.5	-14.92	-6.06
And IV	00 42 30 .1	+40 34 33	6.11	7.20	8.29	-13.83	-3.15
NGC221	00 42 42 .1	+40 51 59	0.77	8.54	<4.0	-14.66	-5.79
And I	00 45 40 .0	+38 02 14	0.81	6.51	<4.5	<-15.32	<-6.40
And IX	00 52 52 .8	+43 12 00	0.79	5.01	<4.5	<-15.70	<-6.80
And X	01 06 33 .7	+44 48 16	0.70	5.04	<4.5	-14.06	-5.27
And V	01 10 17 .1	+47 37 41	0.81	5.52	<4.5	<-15.52	<-6.60
And II	01 16 29 .8	+33 25 09	0.68	5.89	<4.5	<-15.30	<-6.53
Cass dSph	23 26 31 .8	+50 40 32	0.79	6.83	<4.8	<-15.10	<-6.20
Peg dSph	23 51 46 .4	+24 35 10	0.82	6.48	<4.8	<-15.30	<-6.44

the name and coordinates of the objects; columns 3 and 4, the distances to the galaxy and the luminosities; column 5, the estimated masses of neutral hydrogen HI according to the observational data of Refs. 11 and 12; column 6, the total observed fluxes in the Hα+[NII] line after correction for the galactic absorption; and, the last column gives the rates of star formation,

$$\mathrm{SFR}\left(M_\odot/\mathrm{year}\right)=1.27\times10^{9}\,F\left(\mathrm{H}\alpha\right)D^{2}\,,$$

where D is the distance in Mpc and F(Hα) is the flux in units of erg/s·cm^2.

In the following we briefly describe some of the individual properties of the galaxies.

NGC 147. This galaxy, as is the neighboring NGC 185, has a luminosity and surface brightness that is intermediate between dwarf elliptical (dE) and dwarf spheroidal (dSph) galaxies. According to Ref. 13, NGC 147 does not emit in the neutral hydrogen HI line and an upper estimate for its hydrogen mass is $3\times10^3\,M_\odot$. Our observations of NGC 147 reveal a faint emission compact object to the north of its center with a star formation rate $\mathrm{SFR}\sim10^{-6}\,M_\odot$/year. Further spectral observations will be needed to establish whether it is a compact HII region or a planetary nebula.

And III. This faint galaxy with a very low surface brightness (LSB), along with three of the other galaxies, And I, And II, and And IV, was discovered by van den Bergh [14]. The stellar population of And III has been studied [15,16] and the galaxy has been classified as a dwarf spheroidal companion of M31 which contains no young stars. One unexpected feature of our deep Hα image was the presence of 4 emission nodes lying inside the optical boundaries of the galaxy (indicated by circles in Fig. 1). We hope that spectral observations of these objects will allow us to establish whether they belong to And III.

And IV. This LSB object lying in the southern border of M31 is a background irregular galaxy. According to Ferguson et al. [17], And IV has a heliocentric velocity of +256 ± 9 km/s and a distance of 6.11 Mpc. They also obtained an image of And IV in Hα and discovered several compact emission sources with a total flux

$F(\mathrm{H}\alpha) = 0.17\times10^{-13}$ erg/s·cm^2, corrected for galactic absorption. The total Hα flux obtained by us for 5 bunches (indicated by circles in Fig. 1) agrees with the data of Ref. 17 to within the measurement error of ~15%. Observations of And IV in the HI line have been made on a 100-m radio telescope by *W*. Huchtmeier. His measurements show that this galaxy has a radial velocity $V_h = +234 \pm 2$ km/s, a linewidth $W_{50} = 78$ km/s, and a flux $F(\mathrm{HI}) = 22.2$ Jy.

NGC 221=M32. The first image of M32 in the Hα line was obtained by Ford and Zenner [18] who found an annular emission region with an extent of ~30" and several other compact regions to the west. Given the radial velocities of these emission features, only part of them (indicated in our image by circles) belong to the galaxy M32, as such, while the rest are projected onto M32 from the disk of M31. Our measured Hα flux for these densifications is given in Table 1. According to Ref. 19, the mass of neutral hydrogen in M32 is no more than $10^4 M_\odot$.

And I. The color-luminosity diagram for this dwarf LSB galaxy has been studied previously [20,21] and the distance to it was determined and the age of the main stellar population was found to be ~10 billion years. Our Hα observations did not reveal any compact or diffuse emission sources in this dSph galaxy, with an upper sensitivity limit of 0.5×10^{-15} erg/s·cm^2.

And IX. This extreme LSB galaxy was discovered by Zucker et al. [22] and has been classified as a dwarf spheroidal companion of M31 with a low (-2dex) metallicity [23]. Chapman et al. [24] have measured its radial velocity V_h = -216 km/s, as well as the dispersion in the velocities of the stars ~5 km/s, and found a very high ratio of mass to luminosity for this galaxy, $M/L_V \sim 90\, M_\odot/L_\odot$. Our observations revealed neither diffuse nor compact Hα sources with fluxes greater than 0.2×10^{-15} erg/s·cm^2. Note that we were not able to subtract the stellar images in the photographs of And IX, And I, and And V entirely successfully. The residual images of reddish stars are not associated with the galaxies themselves.

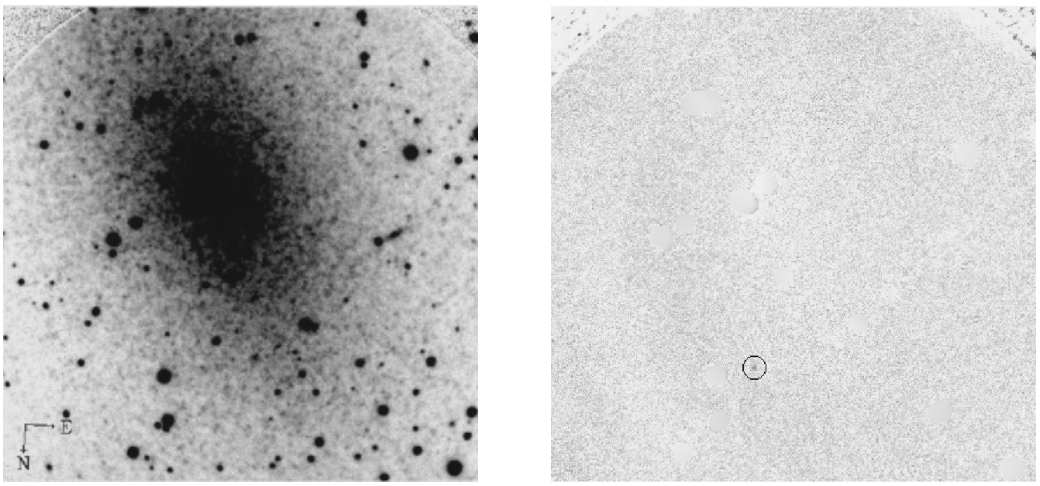
And X. This dwarf spheroidal galaxy with an extremely low luminosity and surface brightness was discovered by Zucker et al. [25] as a bunch of red (RGB) stars during photometry of data from the Sloan Digital Sky Survey. We obtained a picture of this galaxy in Hα with an image size of 2".9. Within the optical boundaries of And X, one can see one emission densification (or a planetary nebula?), which is indicated by a circle in the figure. The Hα flux for this detail is indicated in Table 1.

And V. This new dwarf companion of M31 was discovered by Armandroff et al. [26] According to them, And V has no young stars and Hα no diffuse emission in Hα or compact HII regions. We estimated that the total Hα flux of this galaxy is no more than 0.3×10^{-15} erg/s·cm^2.

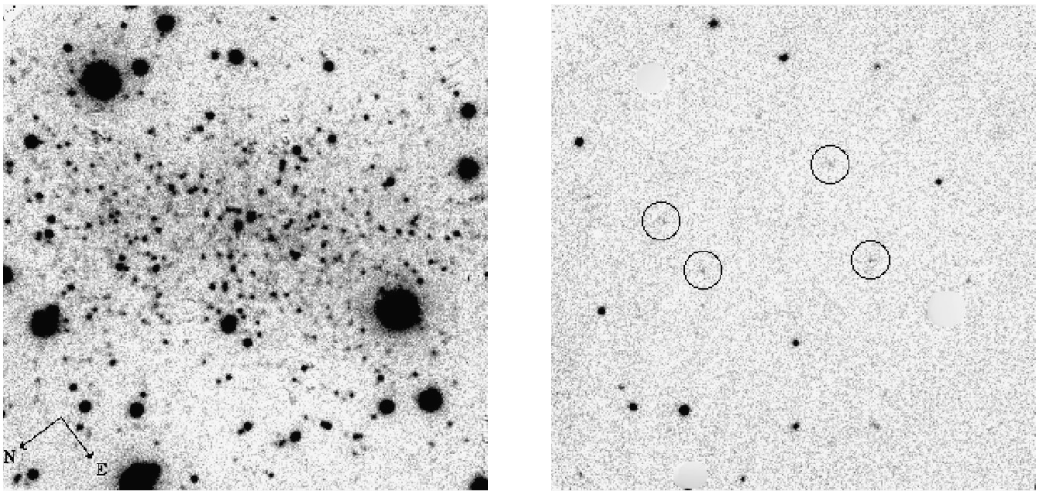
And II. The stellar population of this dSph companion of M31 has been studied previously [27,28]. Cote et al. [29] have measured the dispersion in the velocities of RGB stars in And II (~9 km/s) and estimated the mass to luminosity ratio, $M/L_V \sim 20\, M_\odot/L_\odot$. Our observations show that we did not detect any HII regions or any diffuse emission in And II.

Cass dSph. This distant dwarf companion of M31 was observed by Karachentsev and Karachentseva [30]. Its stellar population has been studies by others [31]. Our Hα data for Cass dSph revealed no HII regions or diffuse sources, which confirms the classification of this galaxy as dSph.

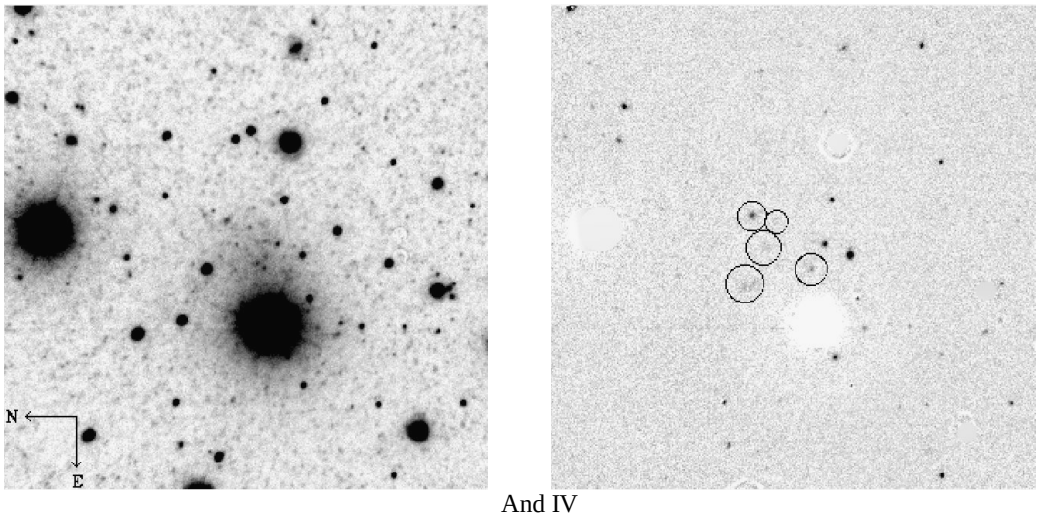
Peg dSph= And VI. This dwarf spheroidal galaxy was discovered independently by Karachentsev and Karachentseva [30] and Armandroff et al. [32] The latter obtained an Hα image of this galaxy, but did not find any emission, in accord with our observations.



NGC147

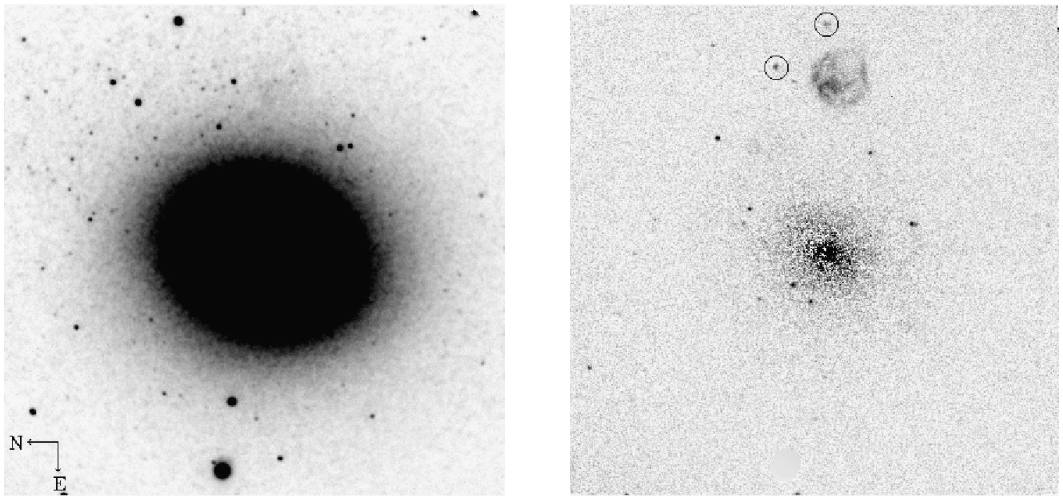


And III

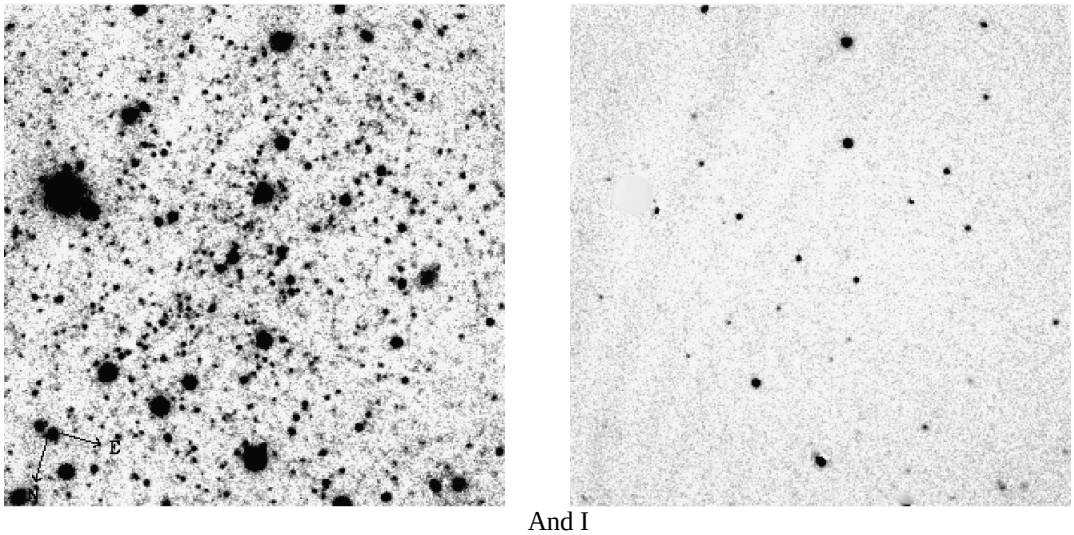


And IV

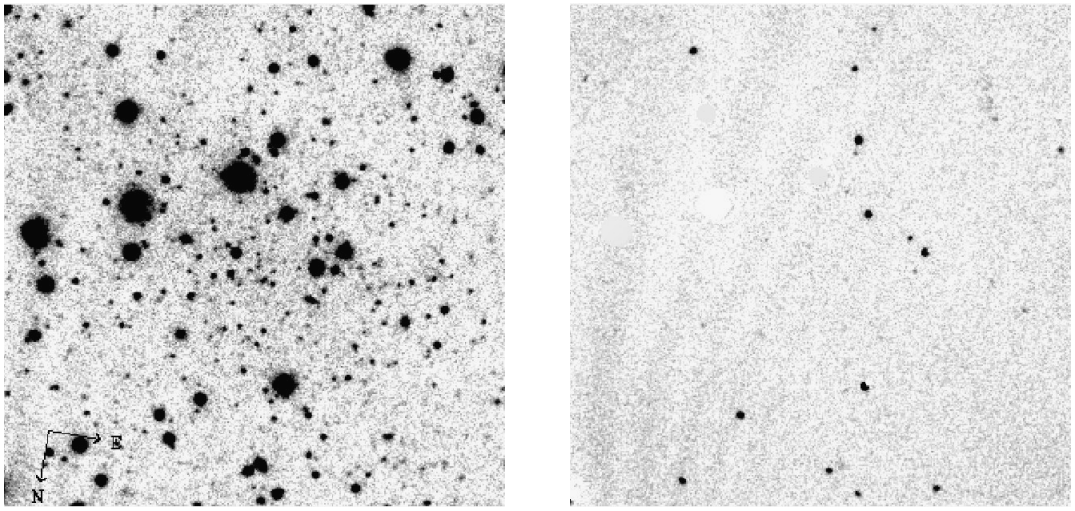
Fig. 1. Images of the observed galaxies in the neighborhood of M31: Hα plus continuum (left) and Hα minus continuum (right). The north-east direction is indicated by the arrows. The image sizes are 4’×4' except for NGC147 and NGC221, for which the image size is 5’×5'.



NGC221

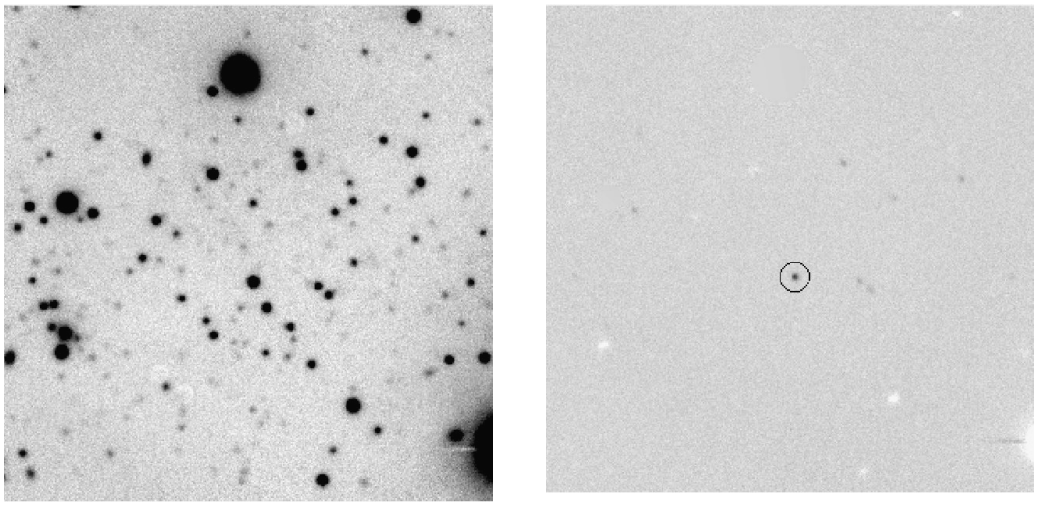


And I

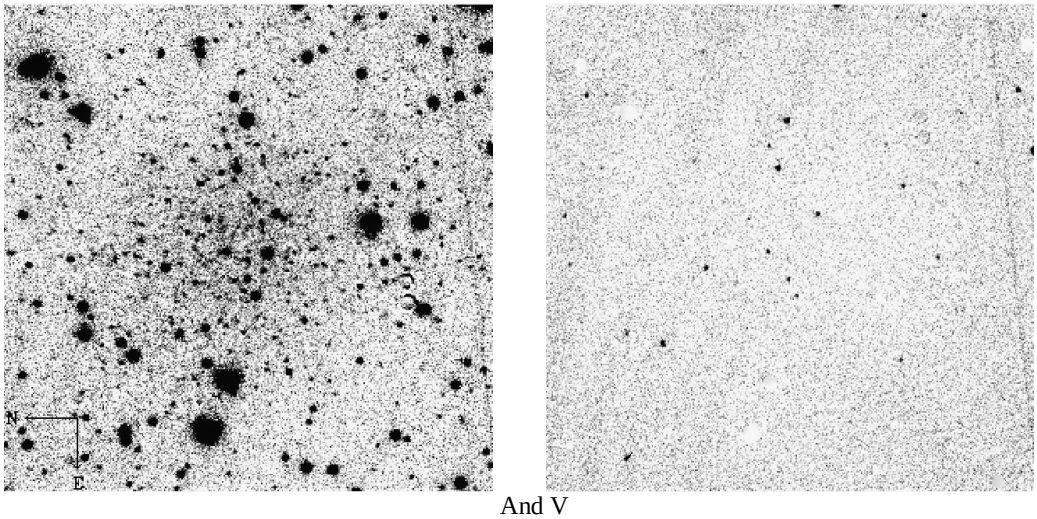


And IX

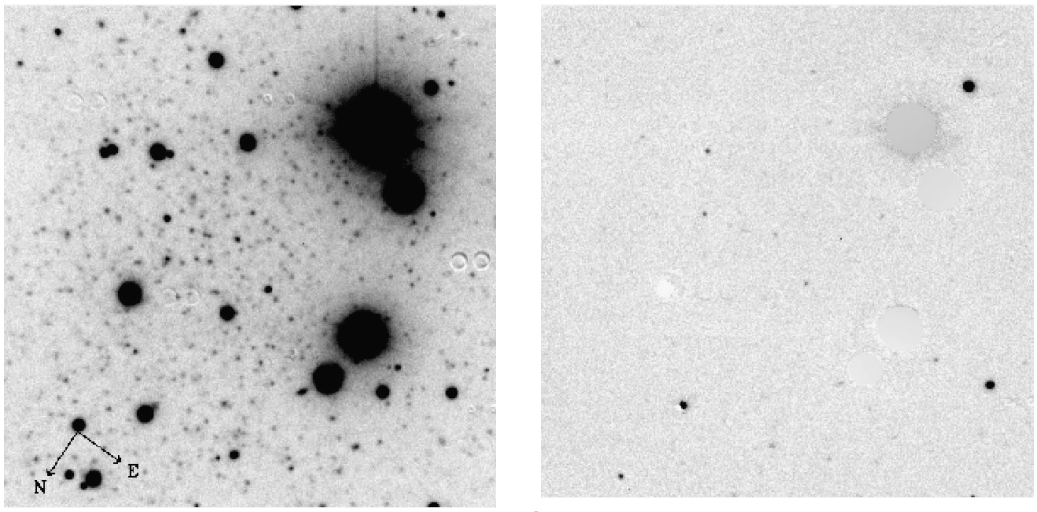
Fig. 1. (continued)



And X

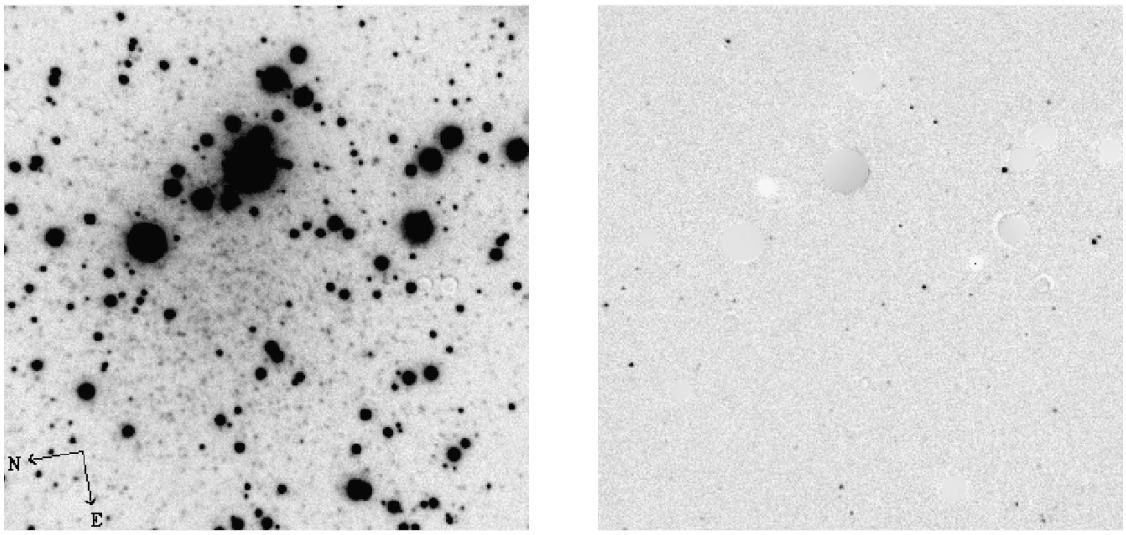


And V

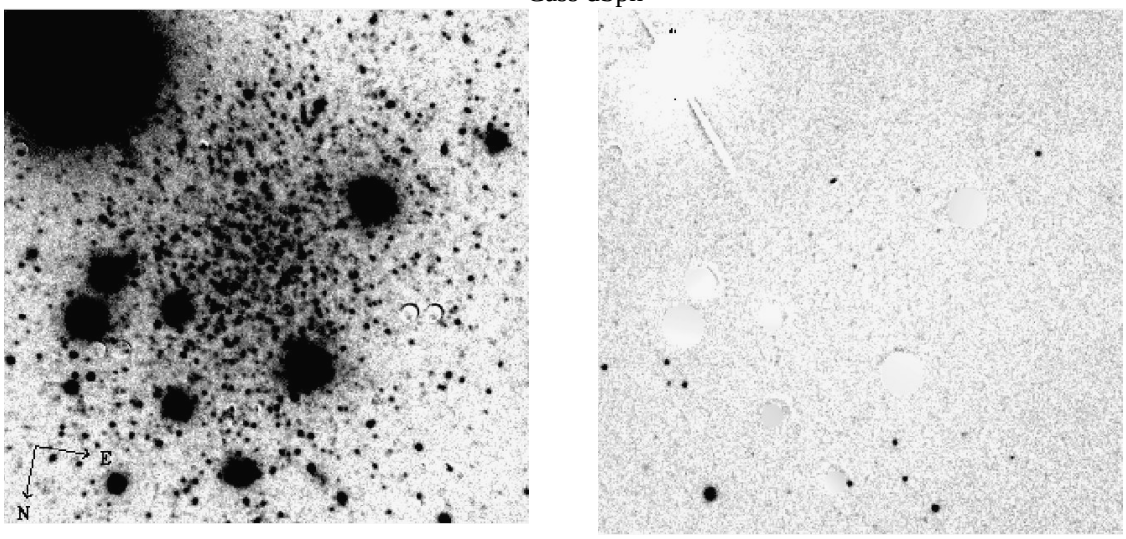


And II

Fig. 1. (continued)



Cass dSph



Peg dSph

Fig. 1. (conclusion)

4. Discussion

Dwarf spheroidal and elliptical galaxies with a very shallow potential well and internal motions at ~10 km/s are easily separated from their gaseous component under the influence of external forces. This is considered to be the reason for the higher excess of dSphs companions in the immediate neighborhoods of giant galaxies compared to dIrs. According to the summary by Mateo [33], the Hα fluxes from all 9 dSph companions in the Milky Way lie below the detection threshold, and a noticeable mass of neutral hydrogen ($2.6\times10^4 M_\odot$) was observed in only one of them (Sculptor). However, in Refs. 34 and 35 it is assumed that only half of the dSphs galaxies in the Local Group are associated with HI clouds lying near to, but outside the optical contours of the galaxies. Detailed observations [13] of the dE galaxies NGC 147, NGC 185, and NGC 205 showed that these objects differ significantly in terms of the amounts of neutral and ionized hydrogen contained in them. Johnson et al. [42] have discovered a compact HII region in the galaxy KDG 61 which

TABLE 2. Parameters of Other Galaxies in the M31 Group.

Galaxy	D, Mpc	$\log(L_B)$, $L_\odot$	$\log(M_{HI})$, $M_\odot$	log[SFR], $M_\odot$/year	Refs.
WLM	0.92	7.74	7.60	-2.98	[40]
IC10	0.66	8.39	7.99	-1.15	[33]
N185	0.62	8.06	5.18	-4.67	[13]
N205	0.83	8.62	5.55	<-7.60	[13]
M31	0.77	10.79	9.67	-0.26	[41]
LGS-3	0.62	5.34	5.39	<-7.22	[33]
IC1613	0.73	7.96	7.81	-2.52	[33]
M33	0.85	9.71	9.32	-0.44	[41]
DDO210	0.94	6.60	6.46	-5.42	[33]
Pegasus	0.76	6.75	6.41	-5.08	[4]

was previously regarded as spheroidal. HI flows have recently been measured [36] in several dwarfs of the Sculptor group which had previously been classified as dSphs. These cases show that observations in the HI and Hα lines are much to be desired for a reliable classification of dwarf galaxies as dSph or dSph/Irr.

It is well known that the more massive irregular and spiral galaxies manifest a fairly distinct correlation between the Hα luminosity (or SFR) and the mass of hydrogen. According to Refs. 37-39, the HII regions in the galaxies, like the galaxies themselves as a whole, obey the relationship

$$\log[\mathrm{SFR}] \propto 1.4\log(M_{HI}).$$

We have collected published observational data on the hydrogen mass and SFR for 154 galaxies in the Local Volume and reduced them to the most accurate estimates of the distances of the galaxies contained in the Karachentsev catalog [1]. A summary of these data for M31 and its bright companions is given in Table 2.

Figure 2 is a $\log[\mathrm{SFR}] \propto \log(M_{HI})$ plot for the galaxies in the Local Volume. Here we only show the upper limits for SFR and M_{HI} for And I and some of the other objects. The three lines correspond to the time in units of the Hubble $T_0=H_0^{-1}$ over which the available reserves of gas in the galaxy are depleted at the observed star formation rate. This diagram shows that, on the average, the giant spiral galaxies have a shorter time scale for depletion of the gas reserves ($\langle tH_0 \rangle \sim 0.5$) than the dwarf galaxies with the masses of the Magellanic clouds ($\langle tH_0 \rangle \sim 1.0$). The dispersion in the depletion time tH_0 increases substantially for those objects with the lowest luminosity. This behavior has been pointed out previously [6]. However, a more precise proof of this point requires measurements of the Hα fluxes for all the galaxies in the Local Volume in order to reduce the effect of observational selection to a minimum.

The spheroidal companions of Andromeda which we have measured, as well as M31 and its other companions, are indicated in Fig. 2 by their names. As might be expected, the dSph and dE companions of M31 lie in the lower left corner of the diagram where the values are minimal. The two spiral galaxies in the M31 group (M31 itself and M33) and its three irregular members (IC10, IC1614, and WLM) show up as typical objects in the Local Volume in accordance

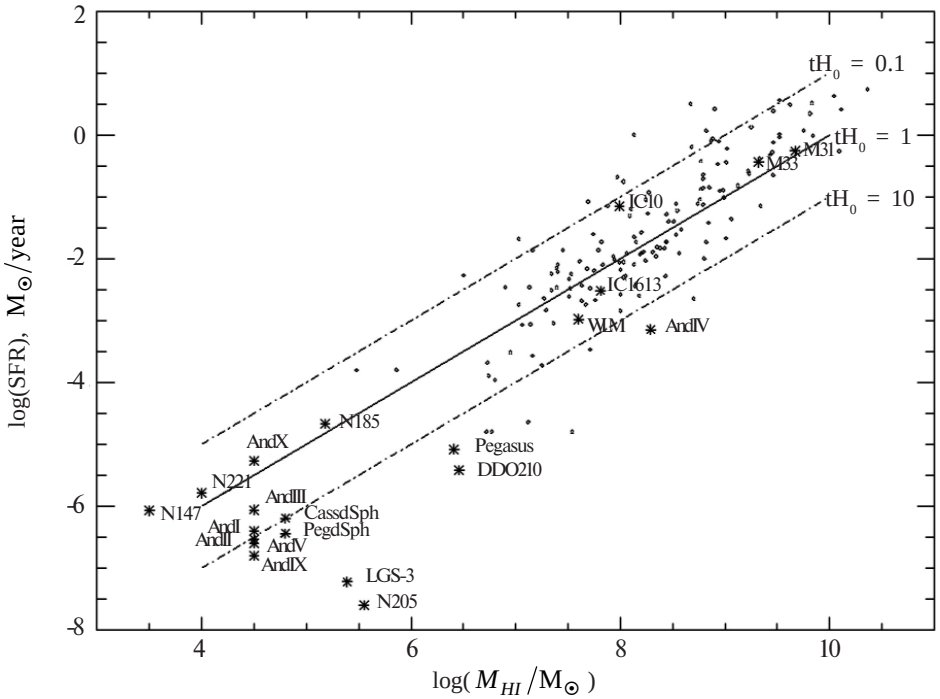


Fig. 2. The star formation rate SFR as a function of neutral hydrogen HI mass for 154 galaxies in the Local Volume with a radius of 10 Mpc. Members of the M31 group are indicated by their names. The three lines correspond to depletion times for the gas contained in the galaxies of tH_0 = 0.1, 1, and 10 at their current rates of star formation.

with their rates of star formation and neutral hydrogen HI masses.

Because of its closeness to us, the system of companions of M31 is a unique laboratory for determining their neutral and ionized hydrogen contents at a level which has thus far not been attainable for the members of other, more distant groups. The data in Tables 1 and 2 yield the following conclusions:

(a) The ratio of the detected mass of neutral hydrogen to the luminosity for 10 companions lies within a range of 1 to 10^{-3} in units of the sun's mass and luminosity. For the other companions that have not been detected in HI (NGC147 and NGC221), this ratio may be even lower than $3\times10^{-5}\,M_\odot/L_\odot$. It is curious that the only galaxy in the distant background, And IV, has an unusually high ratio $M(\mathrm{HI})/L_B = 12\,M_\odot/L_\odot$.

(b) All the galaxies of the M31 group (except IC10) have current rates of star formation that are so low that, for a typical mass to luminosity ratio of $\sim 1 M_\odot/L_\odot$, they cannot "use up" their mass (stellar luminosity) over the cosmological time scale T_0 = 13.7 billion years. For the companions of M31 [SFR] T_0/L_B is typically only 10^{-2} and for the galaxy NGC205, it is less than 10^{-6}. Thus, the epoch of rapid star formation for these galaxies lies in the distant past.

(c) For the 8 companions of M31 for which both *M*(HI) and SFR have been measured, the available reserve of gas is sufficient to ensure the observed rate of star formation for 10^{-1} (IC10) to ~50 (DD0210) Hubble times. For the companions LGS-3 and NGC205, this time, *M*(HI)/[SFR], is even longer than $10^2\,T_0$. These estimates of the HI and HII contents, along with ever more detailed data on the metallicity of the companions of Andromeda, will make it possible to clarify some features of their evolution.

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