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Dynamics, mass and physical characteristics of the spiral galaxies NGC 1084, 6503, 7339 and 7537

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1. Introduction

Mass is one of the basics in the system of fundamental parameters characterizing the galaxies. Several methods are known for determination of the mass of a galaxy:

1. Statistics method — based on observations of double galaxies. A thorough description of the details of this method is given by Page (1961). As a whole, four major investigations of double galaxies are well known: the works of Page (1961, 1962), Turner (1976a, b), Peterson (1979a, b), and Karachentsev (1981a, b, c, d).

It is interesting that the works of Karachentsev include many close pairs, while those of Peterson include many wide pairs. The objects studied by Turner are of intermediate position.

2. Determination of the mass of spheroidal systems (e. g. E and SO galaxies). Three basic methods are known for the determination of the mass of such systems. For non-rotating spheroidal galaxies with known velocity dispersion we can apply the virial theorem. The method has been described thoroughly by Poveda (1958). The results are not very reliable which is due above all to the inclusion of the outermost parts of the galaxies and they have not been studied thoroughly. That is why King (1966) proposed a solution to the equation of stellar hydrodynamics by assuming that the distribution of the velocities in the nucleus is Gaussian and isotropic. Later, Young, Sargent and others worked out a similar formalism, also applicable to the regions outside of the nucleus. The third method is based on the study of the circular motion of a test "particle" around the spheroid component (Knapp et al., 1978).

3. Use of the rotation curves — applicable mainly to flat systems (spiral and irregular galaxies). The theory of this method has been worked out by Babcock, Osort, Weiss and Mayall, Perec and others. We shall deal more with this subject below.

2. Determination of the mass of spiral galaxies

The most general view of a rotation curve is shown in Fig. 1. The analysis of the rotation curve gives the following data: the slope of the rectilinear sector gives the density of the central region, the length of the flat part points to the

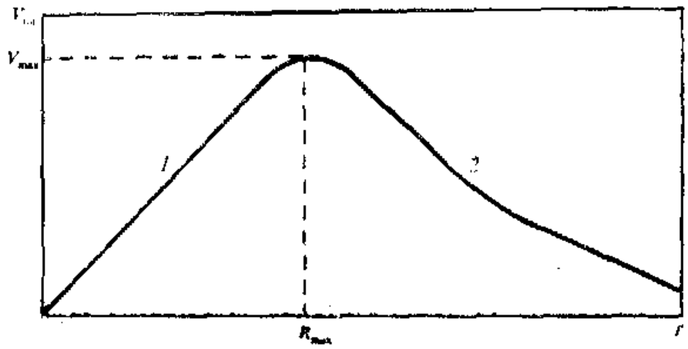

Fig. 1. General view of the rotation curve of a spiral galaxy. Distance r from the centre of the galaxy is plotted along the abscissa, and rotation velocity V_{rot} in km/s is plotted along the ordinate.
1 — rectilinear part of the curve — ω=const, solid body rotation
2 — "Keplerian" part, $V_{rot} \sim r^{-1/2}$, the motion is in agreement with Kepler's third law

quantity of matter in the disk, and velocity in each point R of the Keplerian curve determines the total mass in a sphere with radius R

$$M_R = \frac{RV_R^2}{G}.$$

It should be noted that the assumption of the spherical distribution of mass adopted above has some theoretical prerequisites but has not been universally adopted. If a heavily oblate spheroid is used as a model, its mass would decrease by $\sim$35% (Faber, Gallagher, 1979). Other simplifications have been also worked out. Wide is the application of the method of Weiss and Mayall by which the galaxy is viewed as a thin flat disk. In one of its modifications, the case of the exponential distribution of density $\sigma \sim e^{-d}$, it is also applied in Section 4 of this paper. A relatively simple approximation is the one proposed by Brandt (1960) where the rotation curve is presented in the form of

$$V_{rot(R)} = \frac{V_{max}\frac{R}{R_{max}}}{\left[\frac{1}{3} + \frac{2}{3}\left(\frac{R}{R_{max}}\right)^n\right]^{2/3}}, \tag{1}$$

where V_{max} is the maximum rotation velocity, and R_{max} is the radius at which the velocity is observed, n is a parameter corresponding to the velocity gradient at the point of "breaking", i. e. it shows how fast the rotation curve turns into a Keplerian one. In this case, the total mass of the system is determined by

(2) $$M_{tot}=\left(\frac{3}{2}\right)^{\frac{3}{n}} V^2_{max}\frac{R_{max}}{G}.$$

Some problems, connected with the determination of the total mass, will be discussed in Section 4.

3. Determination of the physical characteristics of the emitting gas

The observing data, the spectrum of the galaxy in particular, permit us not only to plot the rotation curve and hence estimate the mass of the system, but also to determine other fundamental characteristics: flux, luminosity, mass of the gas, ion abundance, etc.

By using the spectra to determine the redshift of the galaxies, the equivalent widths and the relative intensities of the emission lines, we can carry out an analysis of the spectrum, similar to the one applied by Dibay and Pronik (1965) to the investigation of NGC 1068, or by Osmer et al. (1974) in the research of a sample of galaxies with emission lines.

Using the ratios of the intensities of the forbidden lines by the method of Seaton (1954) with its various modifications and corrections, we can determine the electron density n_e and the electron temperature T_e of the emitting gas.

During these calculations the following dependencies are discussed:

(3) $$[OI]:\frac{I_\lambda 5577}{I_\lambda 6300+I_\lambda 6363}=f(T_e)=0{,}113t^{0,06}\,10^{-1,12t};\quad t=10^{-4}T_e;$$

(4) $$[NII]:\frac{I_\lambda 6548+I_\lambda 6584}{I_\lambda 5755}=f(n_e,\ T_e)=\frac{6{,}92\,.\,10^{\frac{10800}{T_e}}}{1+0{,}31x},\quad x=10^{-2}\frac{n_e}{T_e};$$

(5) $$[OIII]:\frac{I_\lambda 4959+I_\lambda 5007}{I_\lambda 5755}=f(n_e,\ T_e)=\frac{7{,}2\,.\,10^{\frac{14300}{T_e}}}{1+0{,}063x};$$

(6) $$[NeIII]:\frac{I_\lambda 3869+I_\lambda 3968}{I_\lambda 3342}=f(n_e,\ T_e)=\frac{13{,}5\,.\,10^{\frac{18700}{T_e}}}{1+0{,}0027x};$$

and other similar ones (see e. g. Kaler et al., 1976).

In the case of spectra poorer in emission lines, like the ones we study, the possibilities of unequivocal determination of n_e and T_e are limited. This question has been discussed by and large by Allain et al. (1979).

In such cases, an estimate of the electron density n can be obtained from the forbidden lines of ionized sulphur $I_\lambda 6717$ and $I_\lambda 6731$. Nosov (1980) presents a tabulation of the above-mentioned ratio for $T_e=5.10^3$, 10^4 and 2.10^4K which covers the most important and most frequent cases.

The flux in the $H\alpha$ line could be determined from the observed magnitude of the galactic nucleus and the equivalent width of the line:

(7) $$F^{obs}_{H_\alpha}=W_{H_\alpha}\frac{F^{*st}_{H_\alpha}}{10^{0,4(m^{nucl}-m^{*}_{st})}}\ [erg/cm^2s]\,.$$

For a standard star we have chosen a star of spectral class AO whose flux is $F_{\lambda 5840} = 3,64.10^{-9}$ erg/cm^{2}s A for stellar magnitude $V=0,00$ (O k e, S c h i l d, 1970). Luminosity in the same line is determined by

$$L_{H_\alpha} = \frac{4\pi c^2 z^2}{H^2}(1+z^2)\ F_{H_\alpha}[\mathrm{erg/s}]. \tag{8}$$

If we know the volume coefficient of radiation ε_{H_α} of this line from the ratio

$$L_{H_\alpha} = \varepsilon_{H_\alpha} V_{\mathrm{eff}}, \tag{9}$$

then we can determine the effective volume V_{eff} occupied by the emitting gas. However, without additional information about the real distribution of the gas we cannot estimate the real volume. In the general case the filling factor is taken as $0,01 \div 0,0001$.

Knowing the volume of the gas and its electron density, we can estimate its mass. We make the natural assumption that the number of electrons is nearly equal to the number of protons, since the emitting gas is mostly hydrogen. Then

$$M_{\mathrm{gas}} = V_{\mathrm{eff}} n_e m_H, \tag{10}$$

where m_H is the mass of the proton.

The estimate of the power of the source of ionization E could give us a clue about its nature, too. It is clear from general considerations that

$$E = N_{\mathrm{ion}}(E_0 + E_{\mathrm{ion}}), \tag{11}$$

where N_{ion} is the number of ionizations, E_0 is the initial energy of the free electron and E_{ion} is the energy necessary for the ionization of the hydrogen atom. If the medium is optically thick, the number of ionizations can be estimated from the number of the Balmer quants which have left the galaxy, i.e.

$$N_{\mathrm{ion}} \geq N_{\mathrm{Bal}} = 11,2 \frac{L_{H\alpha}}{h\nu_{H\alpha}}\,. \tag{12}$$

The energy necessary for the ionization is $E_{\mathrm{ion}} = h\nu_{\mathrm{ion}} = 2,18.10^{-1}$ erg/s, and the initial energy of the free electron, according to K a p l a n and P i k e l ' n e r (1977), equals

$$E_0 = \left[0,2\left(\frac{10^4}{T}\right)^{\frac{1}{3}} \frac{\Sigma I_{\lambda_i}}{I_{H_\beta}} + 1,2\frac{T}{10^4}\right][eV]. \tag{13}$$

The ion abundance and the chemical composition of the gas can be estimated by the method of P e i m b e r t (1975). For the most abundant ions the ratios are of the following type:

$$\frac{O^0}{H^+} = 0,141\ \frac{n_{e(\mathrm{HII})}}{n_e(\mathrm{HI})}\ \frac{I_\lambda 6300}{I_{H_\alpha}}\,; \tag{14}$$

$$\frac{N^+}{H^+} = 1,65\,.\,10^{-4}(1+0,14x)T_e^{-0.375}\ \frac{I_\alpha 6584}{I_{H_\alpha}}\ e^{\frac{2,2\,.\,10^4}{T_e}}\,; \tag{15}$$

$$\frac{N^+}{S^+} = 3,43e^{\frac{500}{T_e}} \frac{I_\alpha 6584}{I_\alpha 6717 + I_\lambda 6731} (1+0,14x)\, f\,(x,\ T_e), \tag{16}$$

where $f\,(x,\ T_e) \approx 1$ for $T_e \sim 10^4$ and

$$x = 10^2 \frac{n_e}{\sqrt{T_e}}\,. \tag{17}$$

In order to estimate the chemical composition, more observations of the elements in the other stages of ionization are needed.

4. Results

Using the methods presented in Sections 2 and 3, we have determined the basic dynamic and physical parameters of four spiral galaxies. The rotation curves of the four objects are smooth which enables us to estimate their mass within the frame of the one-component model. We discuss a thin flat disk, as in the method of Wiess and Mayall. B a l l a b h (1973) proposes the assumption that the density distribution follows the law

$$\sigma = \sigma_0 \exp\,(-\alpha r), \tag{18}$$

where σ_0 is the central surface density, and α^{-1} is the effective radius. The estimates given in Table 2 have been made on the basis of this model. The nature of the source of ionization has been investigated for the simplest suggestion — photoionization from hot stars. As the estimate of the number of ionizing stars of type 07V (average weighting of the stars 05-BO according to the luminosity function of Schmidt, 1963) is of the order of 10^2-10^3, no other explanation has been looked for.

The spectrophotometric data on the objects are given in Table 1 which contain the equivalent widths and the relative intensities of the emission lines [OI] λ6300, [NII]λλ6548 and 6584, $H\alpha$ λ6563 and [SII]λλ6717 and 6731. PA° de-

Table 1

Spectrophotometric data on the galaxies NGC 1084, 6503, 7339 and 7537

NGC	PA°	[OI]6300 W_λ I_λ/I_{H_α}	[NII]6548 W_λ I_λ/I_{H_α}	H_α6563 W_λ I_λ/I_{H_α}	[NII]6584 W_λ I_λ/I_{H_α}	[SII]6717 W_λ I_λ/I_{H_α}	[SII]6731 W_λ I_λ/I_{H_α}	$\frac{6717}{6731}$	$\frac{6717+31}{6384}$
1084	25°	2,5	5,0	20,0	8,5	5,5	4,5	—	—
$m_p = 11,2$		0,09	0,27	1,0	0,47	0,20	0,15	1,37	0,81
$V_r - 1413$		70,09	223,99	754,27	312,34	151,31	109,30		
Stauffer				15,1	8,3	6,2			0,75
6503	125°		3	16	5	2,5	2	—	—
			0,18	1	0,31	0,10	0,08	1,25	0,37
7339	90°	+	2,5	12,5	6,5	3	3	—	—
			178,74	598,10	208,55	65,37	57,13		
			0,12	1	0,35	0,11	0,095	1,14	0,59
7537	75°	1	4,5	25	14	4	5	—	—
		0,03	0,15	1	0,6	0,1	0,13	0,77	0,4

T a b l e 2

Integral physical parameters of the galaxies NGC 1084, 6503, 7339 and 7537 (H=75 km/s Mpc)

Basic parameters	NGC 1084	NGC 6503	NGC 7339	NGC 7537	Unit
Stellar magnitude m_p	11,2	10,9	13,1	13,8	—
Stellar magnitude of nucleus m_{nucl}	15,2	15,1	15,3	15,7	—
Redshift z	0,005	0,001	0,005	0,0096	—
Equivalent width of H_α	20	16	12,5	25	[Å]
Flux in H_α line F_{H_α}	$1,6.10^{-14}$	$4,1.10^{-14}$	$3,6.10^{-14}$	$7,98.10^{-16}$	[erg/cm² s]
Luminosity in the H_α line L_{H_α}	$6,80.10^{38}$	$7,8.10^{37}$	$5,8.10^{38}$	$5,9.10^{39}$	[erg/s]
Effective volume of the gas V_{eff}	$1,91.10^{59}$	$1,09.10^{56}$	$1,8.10^{58}$	4.10^{57}	[cm³]
Electron density n_e	100	400	300	2000	[cm⁻³]
Mass of the gas in nucleus M_{gas}	$3,17.10^{37}$	$7,2.10^{34}$	1.10^{37}	$1,33.10^{37}$	[g]
Power of source of ionization E	$1,42.10^{40}$	$1,32.10^{39}$	$1,2.10^{40}$	$1,2.10^{41}$	[erg/s]
Number of n^* ionizing stars	80	10	80	670	–
Relative number of ions ($\lg H$=12.00)					
$\lg N^+$	7,35	7,17	7,22	7,46	—
$\lg S^+$	6,66	6,38	6,43	6,48	—
$\lg O^0$	7,56	7,50	—	—	—
Central surface density σ_0	1144	1560	1200:	1400	[$M_\odot/ne^2$]
Effective radius α^{-1}	1,47	0,45	1,22:	1,30	[kpc]
Integral mass M	$1,55.10^{10}$	$2,1.10^{9}$	$1,95.10^{10}$	$5,73.10^{10}$	[$M_\odot$]
Mass-to-luminosity ratio M/L	0,49	1	2,3	4,2	[$M_\odot/L_\odot$]
V_{rot} max (for $i=\alpha_0$)	135 (i=65°)	90 (i=75°)	155 (i=7°)	150 (i=15°)	[km/s]
R_{max}	2,2	0,75	2	2	[kpc]
$r_{max\ obs}$	6	2	6	9	[kpc]

signates the position angle to which the data relate. The observing material has been obtained on the 125 cm ZTE telescope at the Crimean Station of the Sternberg Astronomical Institute, using the A-spectrograph of the station and a one-cascade image tube system. The spectra have been obtained on presensitized Kodak 103aO emulsion. They have been calibrated by printing of a nine-step wedge through blue filter. The rotation curves have been obtained on an Ascorecord coordinate measurer, and the records on a G-II microphotometer. The processing method has been presented throughly in K y a z u m o v (1982) and P e t r o v (1980).

Fig. 2 shows the rotation curves in uniform scale. Along the abscissa the distance from the centre of the galaxy has been given in arc seconds, and along the ordinate the angular velocity has been given in km/s (the scale has been pointed out).

Table 2 gives the basic characteristics of the galaxies: flux and luminosity in the $H\alpha$ line, volume and mass of the gas, electron density, relative num-

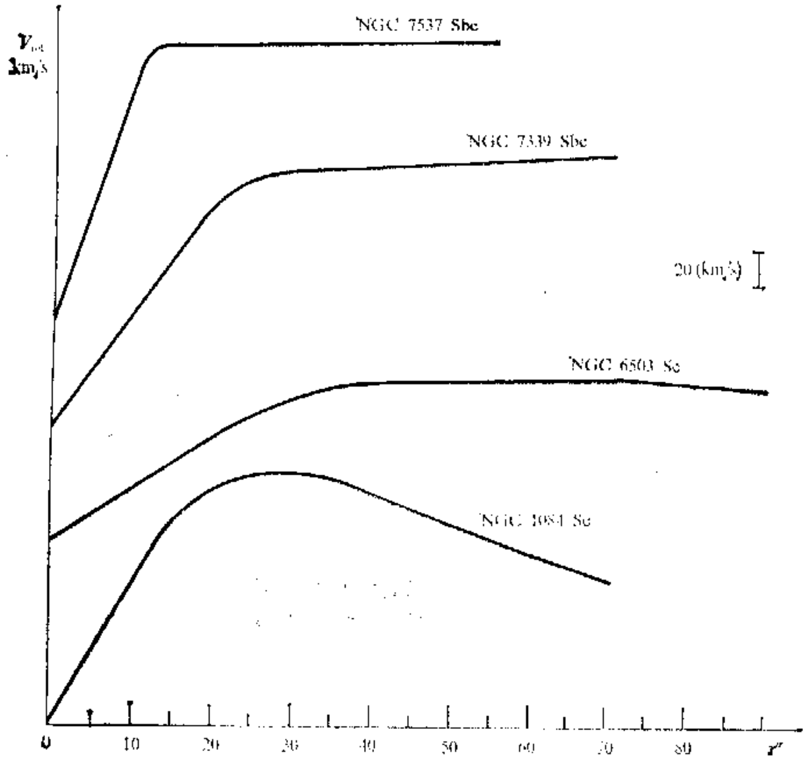

Fig. 2. Rotation curves of the galaxies NGC 1084, 6503, 7339 and 7537. Distance r from the centre of the galaxy is plotted along the abscissa, and rotation velocity V_{rot} in km/s is plotted along the ordinate. The scale is conventional. For details see the text

ber of ions ($\lg H = 12{,}00$), power of the source of ionization, integral mass and mass-to-luminosity ratio. Estimates have been given of the effective radius α^{-1} and of the central surface density σ_0.

5. Discussion of the results

The rotation curves of the four galaxies are smooth. According to our data, there is no evidence of considerable non-circular motion in the galaxies. No velocity gradient along the minor axis is observed in any of the four galaxies. Although three of the galaxies (NGC 1084, 7339 and 7537) are members of pairs or groups, their rotation curves are symmetrical, which is the reason why we show only half of them in Fig. 2. The four galaxies are included in *A General Catalogue of HI Observations of External Galaxies* by Huchtmeier et al. (1983).

It is worth pointing out the disagreement (of an order and more) between various authors concerning the determined masses. To a great extent this is due to the following: as a matter of fact, only the rotation curve of NGC 1084 approximates a Keplerian curve after reaching the maximum. That is why, having in mind what we said before, the mass of this galaxy must have been determined with greater accuracy. On the other hand, it is well known (see, for example, B o s m a, 1978) by radio observations in the 21 cm band that for the vast majority of galaxies the rotation curves remain flat after the "breaking" up to the outermost parts of the galaxy (sometimes up to 50 kpc and more from the centre). The other galaxies in our case must probably have curves of this type (at least NGC 7339 and 7537) which hampers their interpretation within the framework of this model.

Let us elaborate on the peculiarities of the separate galaxies.

NGC 1084 (MCG-1-8-7). It has been investigated ever since B u r b i d g e et al. (1963) who also noted the mass-to-luminosity ratio $M/L<1$. No increase of the M/L ratio towards the periphery of the galaxy has been observed. H u c h t m e i e r et al. (1983) give estimates of the mass by different methods ranging from $4{,}51.10^{10}\ M_\odot$ to $2{,}79.10^{11} M_\odot$ (our estimate is $1{,}55.10^{10} M_\odot$). The mass of the neutral hydrogen was estimated at $M_{H_{tot}}=2{,}39.10^{9} M_\odot$, i.e. the gas in the galaxy is from 1 to 10%. Part of the differences in the estimation of the mass is probably due to the fact that we have assumed that the inclination angle is $i=65°$ after N i l s o n (1973), and the above-mentioned maximum estimate assumes it to be $i=58°$.

NGC 6503. The previous investigation of the mass of the galaxy based on optical data has been carried out by B u r b i d g e et al. (1964) but they reach only up to 50″ from the nucleus. Our rotation curve covers 90″ of the nucleus in which the mass is $1{,}82.10^{9}\ M_\odot$. H u c h t m e i e r et al. (1983) give estimates ranging from $7{,}6.10^{9} M_\odot$ to $2{,}9.10^{10}\ M_\odot$. The mass of the neutral hydrogen is $M_{H_I}=1{,}1.10^{9}\ M_\odot$, i.e. in all cases the galaxy is rich in gas.

NGC 7339 (Karachentsev 570b; see K a r a c h e n t s e v, 1972). H u c h t m e i e r et al. (1983) give $3{,}36.10^{10} M_\odot$ and $9{,}5.10^{10} M_\odot$ as estimates of the galactic mass. Our estimate is $1{,}95.10^{10}$ which is in good agreement with the estimates given above. The mass of the neutral hydrogen is from $6{,}4.10^{8}\ M_\odot$ to $<1{,}2.10^{9} M_\odot$, i. e. $<5\%$. The mass-to-luminosity ratio $M/L=2{,}3$ is lower than the average ($<7>$) for this subtype. After the coordination of the rotation curves at PA=80° and PA=90°, the slope angle was determined to be $i=7°$.

NGC 7537 (Karachentsev 578a, Holmberg 805, UGC 12443). With the slope angle assumed to be $i=15°$, $V_{max}=150$ km/s at 2 kpc from the centre. Within a radius of 9 kpc, mass of $5{,}73.10^{10}\ M_\odot$ is enclosed. H u c h t m e i e r et al. (1983) estimate it at $1{,}02.10^{10}\ M_\odot$ to $3{,}43.10^{11}\ M_\odot$. In these cases, however, the slope angle has been assumed to be $i=74\div82°$. To the estimate of $M=5{,}8.10^{10}\ M_\odot$ corresponds the mass of the neutral hydrogen $M_{H_I}=5{,}85.10^{9}\ M_\odot$, i. e. the probable gas content of the galaxy is $\sim 10\%$.

6. Conclusion

Using spectra of mean resolution and dispersion ~ 100 Å/mm around the H_α line, with the help of unified methods we have determined the basic parameters of four spiral galaxies: two of the Sc type (NGC 1084 and 6503) and two of the Sbc type. Although one of them (NGC 6503) is an isolated galaxy included in the list of K a r a c h e n t s e v a (1973), NGC 1084 is a member of a group of galaxies, and NGC 7339 and 7537 are double galaxies (K a r a c h e n t s e v, 1972), the general feature is the presence of strong emission lines in their spectra and smooth rotation curves, which enables us to study them within the framework of the one-component model with exponential distribution of the density in the disk. The luminosities in the H_α line are of the order of 10^{38}-10^{40} erg/s, the electron densities are from 10^2 to 2.10^3 cm^{-3}, and the integral mass is from 2.10^9 to 6.10^{10} $M_\odot$. All galaxies contain a lot of neutral gas in the disk, while the gas in the nucleus is not much $\sim 10^4 M_\odot$. The only exception is NGC 6503 where the gas in the nucleus is very scarce — 30-40 $M_\odot$. The sources of ionization in all cases are young hot stars — from 10 to 700 07V stars with mass of ~ 30 $M_\odot$. In the galaxies NGC 1084 and 6503 (Sc type) there is a great quantity of neutral oxygen which in the general case indicates a lower degree of gas ionization in the nucleus.

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Динамика, масса и физические характеристики спиральных галактик NGC 1084, 6503, 7339 и 7537

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(Р е з ю м е)

Используя спектры с дисперсией 100 A/mm, полученные 125 cm телескопом ЗТЕ Крымской станции ГАИШ, определены динамические и физические характеристики четырех спиральных галактик. Распределение масс исследовано методом Баллаба в рамках однокомпонентной модели. Приведены оценки светимостей в линиях H_α и масс газа в ядрах галактик. Электронные плотности находятся в границах 100—2000 cm^{-3}. Содержание ионов близко к нормальному.

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