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A Kinematic Study of M51-Type Galaxies

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Abstract—Spectroscopic observations of twelve M51-type binary galaxies with the 6-m Special Astrophysical Observatory telescope are presented. We constructed the rotation curves for the primary galaxies of each binary system and determined the line-of-sight velocities of their companions from the Hα and [N II] 6583 Å emission lines. © *2002 MAIK "Nauka/Interperiodica"*.

Key words: *galaxies, galaxy groups and clusters, intergalactic gas*

INTRODUCTION

Binary systems similar to the M51 galaxy constitute rather rare and very interesting types of objects. Vorontsov-Vel'yaminov (1957) and Arp (1966) were the first to point out M51 type systems as a special class of binary galaxies. These systems consist of a spiral primary and a relatively small companion that is seen projected onto the tip of one of the spiral arms of the primary.

Klimanov and Reshetnikov (2001) presented a new sample of M51-type galaxies. Objects of this type are very poorly studied and for many of them neither kinematic data for the primary galaxy nor even the line-of-sight velocities of their companions are available. The principal aim of this work was to obtain observational data about M51-type galaxies. We will use these data to study the origin and evolution of binary galaxies with very different component masses.

OBSERVATIONS

Our program list included 12 binary systems drawn from the sample described by Klimanov and Reshetnikov (2001) (see the table for the list of objects).

Observations were made in February, March, and November 2000 with a high focal ratio spectrograph operating in the primary focus of the 6-m telescope of the Special Astrophysical Observatory of the Russian Academy of Sciences (Afanas'ev *et al.* 1995). The observations used a 1024 × 1024 Photometrics CCD with a pixel size of 24 μm attached to the Schmidt–Cassegrain camera of the spectrograph ($F = 150$ mm). The spectra were obtained using a spectrograph with a $2'' \times 120''$ slit and a 1302 lines/mm grating operating in the wavelength interval 6000–7200 Å. The scale along the slit was $0\overset{''}{.}40$ per pixel and the reciprocal dispersion was equal to 1.21 Å pixel. The seeing during observations varied from $1''$ to $2''$. For each object we obtained several spectra with a characteristic exposure time of 10–20 min. ArNeHe comparison spectra were recorded between the spectra of program objects. The position angle of the spectrograph slit is given in the second column of the table.

We reduced the spectra using an ESO-MIDAS software package (LONG context). We constructed the rotation curves of galaxies from Hα (6562.8 Å) and [NII] (6583.4 Å) emission lines whose contours we fitted to Gaussian profiles. We did not measure the positions of other lines, because of their weakness. We estimated the accuracy of our reduction from the measurements of night-sky lines. The standard deviation of the wavelengths of the latter from the mean position never exceeded 0.33 Å which corresponds to $\sigma \leq 15$ km s^{-1} at the Hα wavelength. We estimated the internal errors of measurements from the dispersion of line-of-sight velocities measured at the center of the galaxy and in the neighboring pixels. Such a procedure is justified by the small separation between neighboring pixels ($0\overset{''}{.}40$), which is much smaller than the seeing. One must bear in mind, however, that the gradient of the rotation curve may increase the internal error estimate thus obtained and, consequently, our estimates characterize only the upper boundary of the real error. Internal errors given

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Parameters of galaxies

Name	*P.A*	V_{din}, km s^{-1}	V_{phot}, km s^{-1}	ΔV, km s^{-1}	R_V/R_{25}
MCG -01-01-70 a	175°	5991 ± 11	5971 ± 13	-76 ± 16	0.62
MCG -01-01-70 b	175	6067 ± 11	6071 ± 3	–	0.3
NGC 151 a	68	3732 ± 21	3745 ± 28	-277 ± 21	0.64
NGC 151 b	68	4009 ± 4	4008 ± 4	–	0.8
NGC 797 a	66	5664 ± 18	5662 ± 18	92 ± 39	0.71
NGC 797 b	66	–	5572 ± 35	–	0.4
NGC 2535	59	4079 ± 7	4082 ± 5	1 ± 21	0.47
NGC 2536	59	4078 ± 20	4071 ± 20	–	0.6
NGC 2535	163	4090 ± 8	4084 ± 10	15 ± 22	0.32
NGC 2536	163	4075 ± 20	4077 ± 20	–	0.4
UGC 6865 a	37	5930 ± 29	5882 ± 27	162 ± 29	0.94
UGC 6865 b	37	5768 ± 3	5768 ± 2	–	0.6
NGC 4088 a	55	775 ± 12	769 ± 9	159 ± 12	0.56
NGC 4088 b	55	616 ± 3	621 ± 3	–	0.9
NGC 4137 a	90	11171 ± 3	11172 ± 4	99 ± 8	1.06
NGC 4137 b	90	–	11072 ± 7	–	1.0
NGC 5278	68	7629 ± 17	7527 ± 12	58 ± 17	0.55
NGC 5279	68	7571 ± 4	7552 ± 4	–	0.6
UGC 10396 a	19	8680 ± 16	8652 ± 15	-154 ± 21	0.68
UGC 10396 b	19	8834 ± 14	8866 ± 3	–	0.7
UGC 11680 a	71	7806 ± 4	7807 ± 4	-89 ± 7	0.75
UGC 11680 b	71	7895 ± 6	7899 ± 5	–	0.5
NGC 7753	44	5142 ± 30	5112 ± 32	202 ± 34	0.52
NGC 7752	113	4940 ± 16	4940 ± 16	–	0.6
NGC 7757 a	110	2944 ± 12	2974 ± 5	-109 ± 30	0.76
NGC 7757 b	110	–	3053 ± 27	–	0.9

in the table do not exceed 35 km s^{-1} (their mean is 13 ± 9 km s^{-1}).

We used the rotation curves obtained as described above from Hα and [NII] lines to determine the positions of the centers of both components and their radial velocities. We computed the positions and velocities as the weighted means of the corresponding values inferred from Hα and [NII] lines with weights equal to the line intensities. To reveal an eventual relation between the dynamical and photometric parameters of the systems, we determined two centers—dynamical and photometric—for each galaxy. We found the position and velocity of the former from the condition of maximum symmetry of the rotation curve. The photometric center coincided with the maximum of the continuum spectrum. Note that the dynamical centers were determined only formally for a number of companion galaxies due to their small angular sizes and, consequently, small extent of their rotation curves.

RESULTS AND DISCUSSION

The figure shows the images of 12 M51-type systems taken from the DSS[1] with slit positions superimposed, and the rotation curves of these galaxies. North is at the top and West, on the right. The distances and velocities are given relative to the dynamical center of the primary galaxy.

[1] The Digitized Sky Surveys were produced at the Space Telescope Science Institute under U.S. Government grant NAG W-2166.

The main results are summarized in the columns of the table:

(1) Number of the galaxy according to NGC, UGC, or MCG catalogs. In the cases where the companion has no designation in the above catalogs the components of the system are indicated by letters a and b corresponding to the primary and its companion, respectively;

(2) Position angle of the slit during observations;

(3) Line-of-sight velocity of the dynamical center of the galaxy corrected for the Earth's orbital motion;

(4) Line-of-sight velocity of the photometric center of the galaxy corrected for the Earth's orbital motion;

(5) Difference of the radial velocities of the dynamical centers of the primary and its companion. In the cases where the small size of the companion made the determination of its dynamical center uncertain we used the velocity of its photometric center;

(6) Extent of the measured portion of the rotation curve expressed as a fraction of the radius of the galaxy (R_{25}) either reduced to the standard isophote of 25^m/sq. qrcsec (according to the RC3 catalog) or inferred from our measurements of DSS galaxy images.

The mean extent of our rotation curves is equal to $(0.66 \pm 0.20)R_{25}$ and $(0.64 \pm 0.22)R_{25}$ for the primary galaxies and their companions, respectively. Thus our rotation curves reach the region of maximum rotation velocity for the exponential disk of a typical bright spiral galaxy ($\sim 2h$, where h is the exponential disk scale length, or $\sim 2/3R_{25}$), and they can therefore be used for analyzing the global kinematics of these objects.

In this paper we briefly describe the main specific features of the spectra of the observed galaxies and their rotation curves, and compare our results with those published earlier. We adopted most of our comparison data from the NED database[2] where one can find the bibliographic references. Below we give references only to recent publications and to the detailed studies of objects. Hereafter all radial velocities are heliocentric line-of-sight velocities.

MCG-01-01-70. During observations the spectrograph slit passed almost along the minor axis of the galaxy. The Northern and Southern branches of the rotation curve exhibit local maxima at a galactocentric distance of 5″ where radial velocity of rotation reaches 50–60 km s^{-1}. So far, no rotation curves of this galaxy has been published. The radial velocity of the center of the primary—5985 ± 38 km s^{-1}—found by Huchra *et al.* (1993) agrees well with our result (see the table).

NGC 151. The slit passed through the major axis of the primary. The rotation curve is characterized by a nonmonotonic variation of velocity, which is most conspicuous on the companion side. The Hα line is almost invisible in the spectrum of the companion—its central intensity is lower than that of the [NII] line by a factor of 30. The Hα rotation curve of the primary was obtained by Mathewson and Ford (1996) (at a slit position angle of 75°). It reaches a plateau and exhibits smaller variations of rotation velocity. The velocity of the center of the primary computed by Mathewson and Ford—3738 ± 10 km s^{-1}—agrees well with our result.

NGC 2535–2536. We observed this system at two slit position angles and obtained separate spectra of the primary and companion (see the figure). When aligned along the position angle $P.A. = 59°$, the slit crosses the arms of the primary galaxy and the spectrum exhibits a characteristic clumpy pattern with several condensations in Hα and [NII] lines, which are likely to be associated with $\sim$100 km s^{-1}-amplitude waves on the rotation curve. The rotation curve of the companion also exhibits nonmonotonic variations of V_r with a slightly smaller amplitude. The spectrum taken at the slit position $P.A. = 163°$ shows much fewer bright condesations. The velocity variations in this case have much smaller amplitude. At the same time, this rotation curve is not quite symmetric: its southeastern part at a distance of 8″–10″ from the center of the primary reaches a plateau (the maximum velocity V_r reaches $\sim$100 km s^{-1}), whereas the northwestern part at about the same distance exhibits a sharp maximum beyond which the velocity also reaches a plateau. In addition, this part cannot be traced as far as the southeastern part (out to the galactocentric distances of 20″ and 30″, respectively). The rotation curve of the satellite is more symmetric than that of the main galaxy.

Amram *et al.* (1989) report a rotation curve for this system based on an analysis of a detailed velocity field of ionized gas obtained with a Fabry-Perot interferometer. The above authors also point out that the rotation curve of the primary reaches a plateau at a velocity of about 110 km s^{-1}, which remains approximately constant out to a galactocentric distance of 30″ and 20″ for the southeastern and northwestern sides of the central disk, respectively. Beyond this distance the rotation curve of Amram *et al.*, which is traced to greater galactocentric distances than our totation curve, exhibits a fast decrease of rotation velocity. The direction of rotation of NGC 2535 as determined from our data (southeastern part of the galaxy

[2]The NASA/IPAC Extragalactic Database (NED) is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

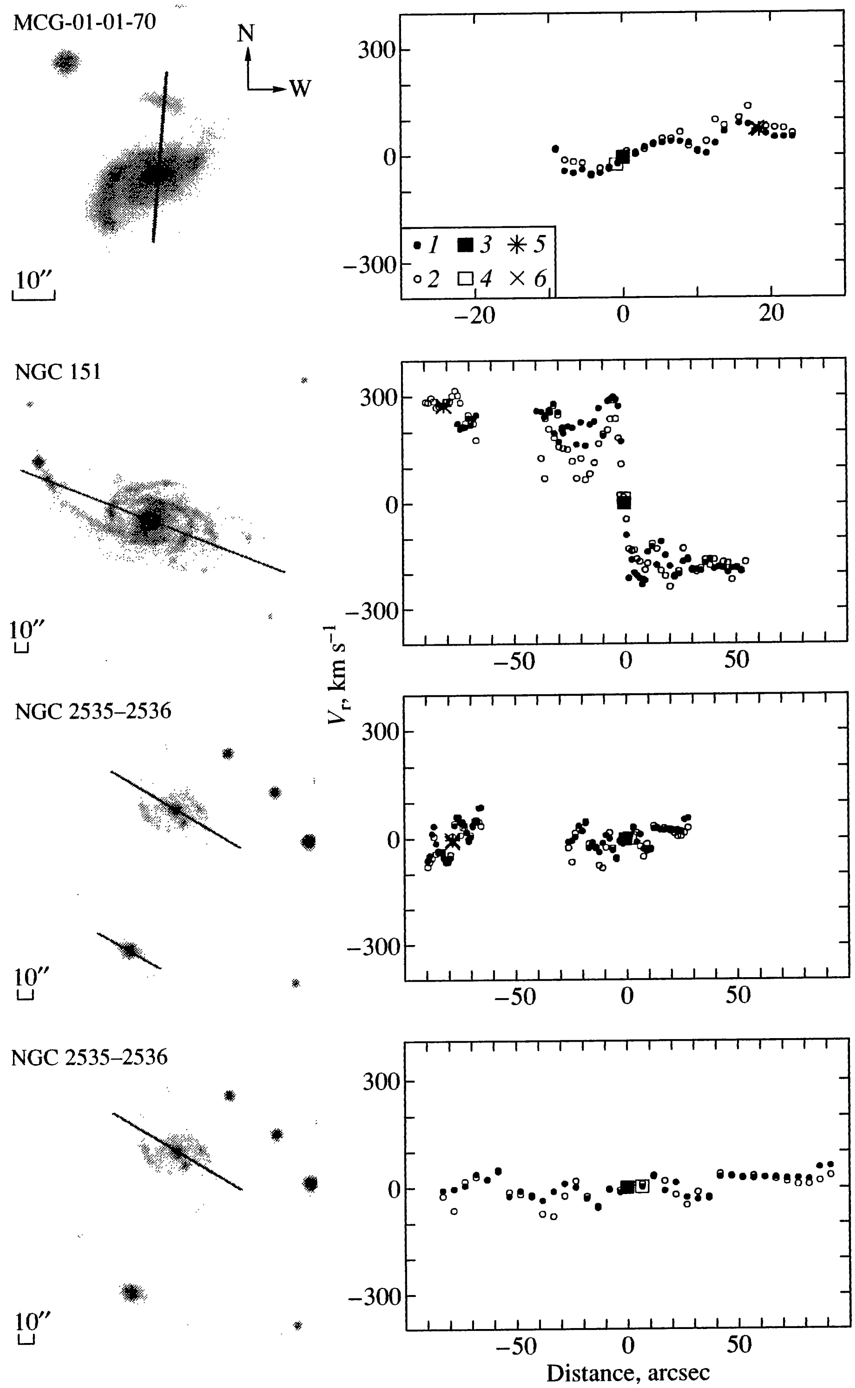
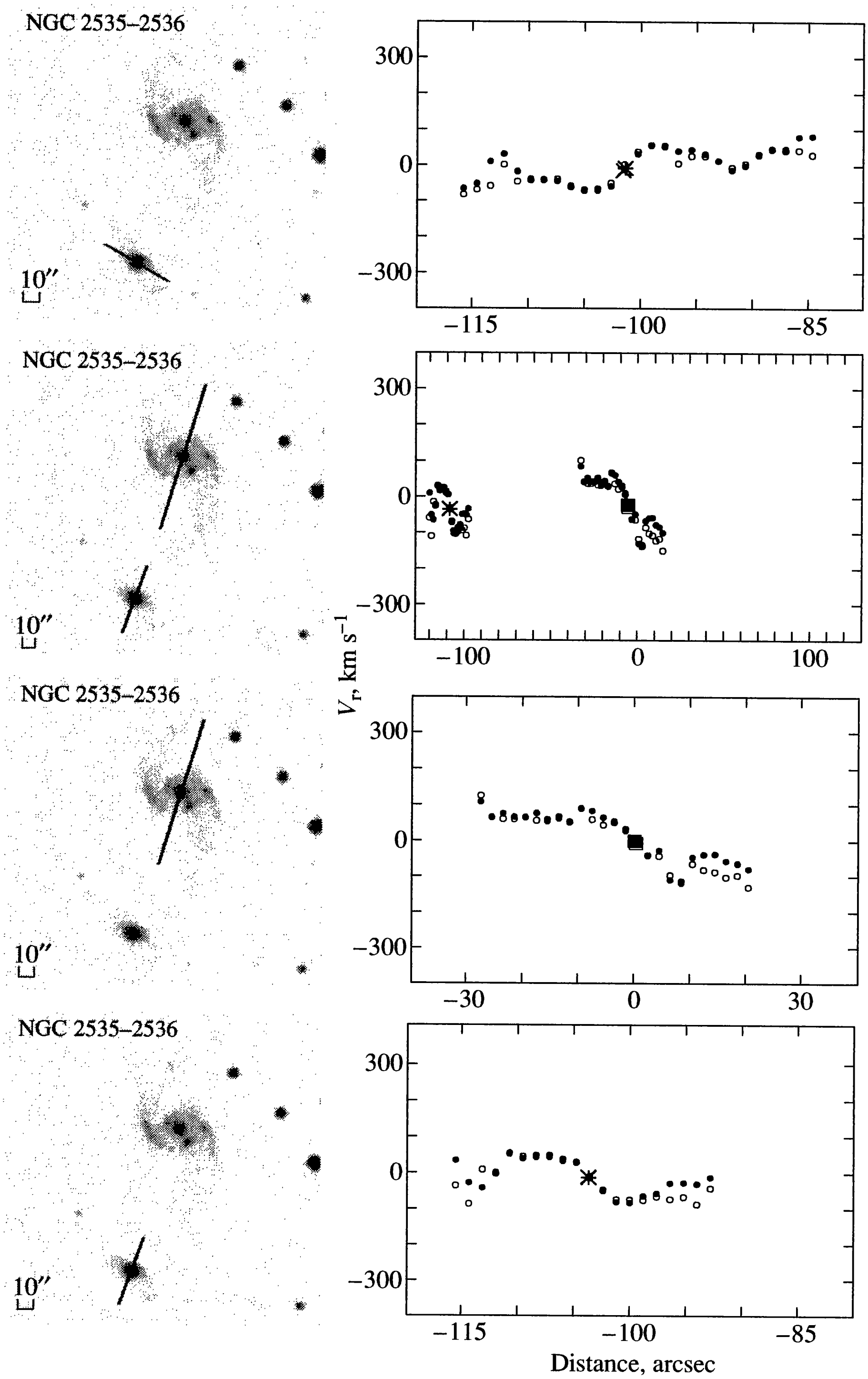


Figure. Images and rotation curves of M51-type galaxies. The lines indicate the positions of the slit during observations. Designations on the rotation curves: (*1*) velocity of rotation determined from Hα line; (*2*) velocity of rotation determined from [NII] line; (*3*) dynamical center of the primary galaxy; (*4*) photometric center of the primary galaxy; (*5*) dynamical center of the companion; and (*6*) photometric center of the companion. The distances and velocities are with respect to the dynamical center of the galaxy.

recedes and the northwestern part approaches) coincides with that indicated by Amram *et al.* (1989) (see Fig. 3 in the above paper). (Note, however, that Amram *et al.* give different rotation directions in their Figs. 3 and 4.)

As for the rotation curve of the satellite reported by Amram *et al.*, it exhibits the same main features as can be seen on our rotation curve: velocity decreases beyond 5″ from the center, and the curve flattens out. The radial velocities of the centers of the primary and



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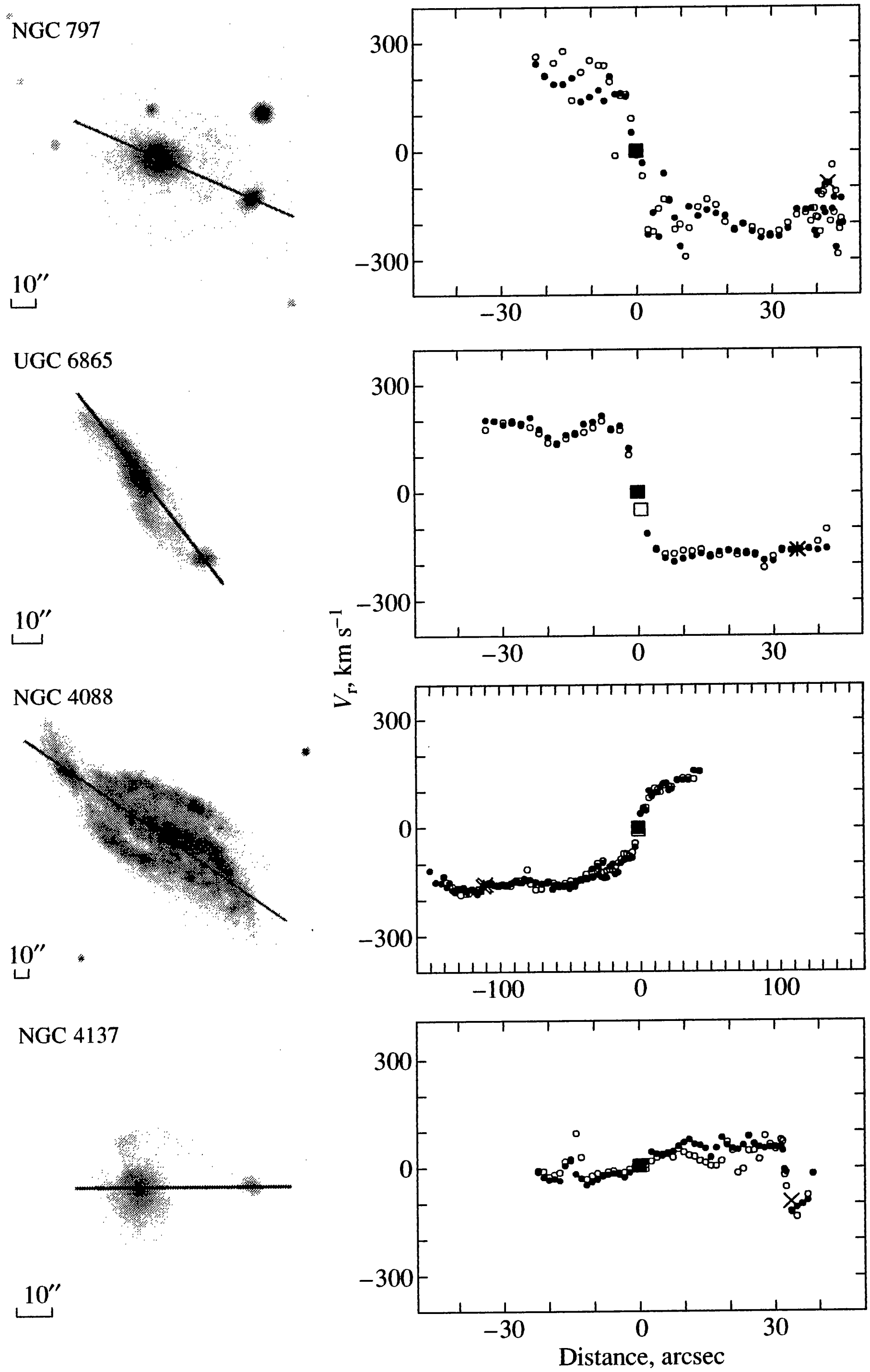
the satellite determined by Amram *et al.* agree well with our results: 4095 ± 10 and 4085 ± 10 km s^{-1}, respectively.

NGC 797. The spectrum of this system exhibits a powerful continuum in the nuclear regions of both components. A strong absorption feature develops closer to the center, which virtually engulfs the Hα and [NII] lines, thereby hindering significantly the measurements. The emission spectrum shows a discontinuous pattern outside the nuclei and line intensities are extremely low in these regions. Both rotation curves exhibit strong local variations of rotation velocity. Van Moorsel (1983) obtained a 21-cm HI



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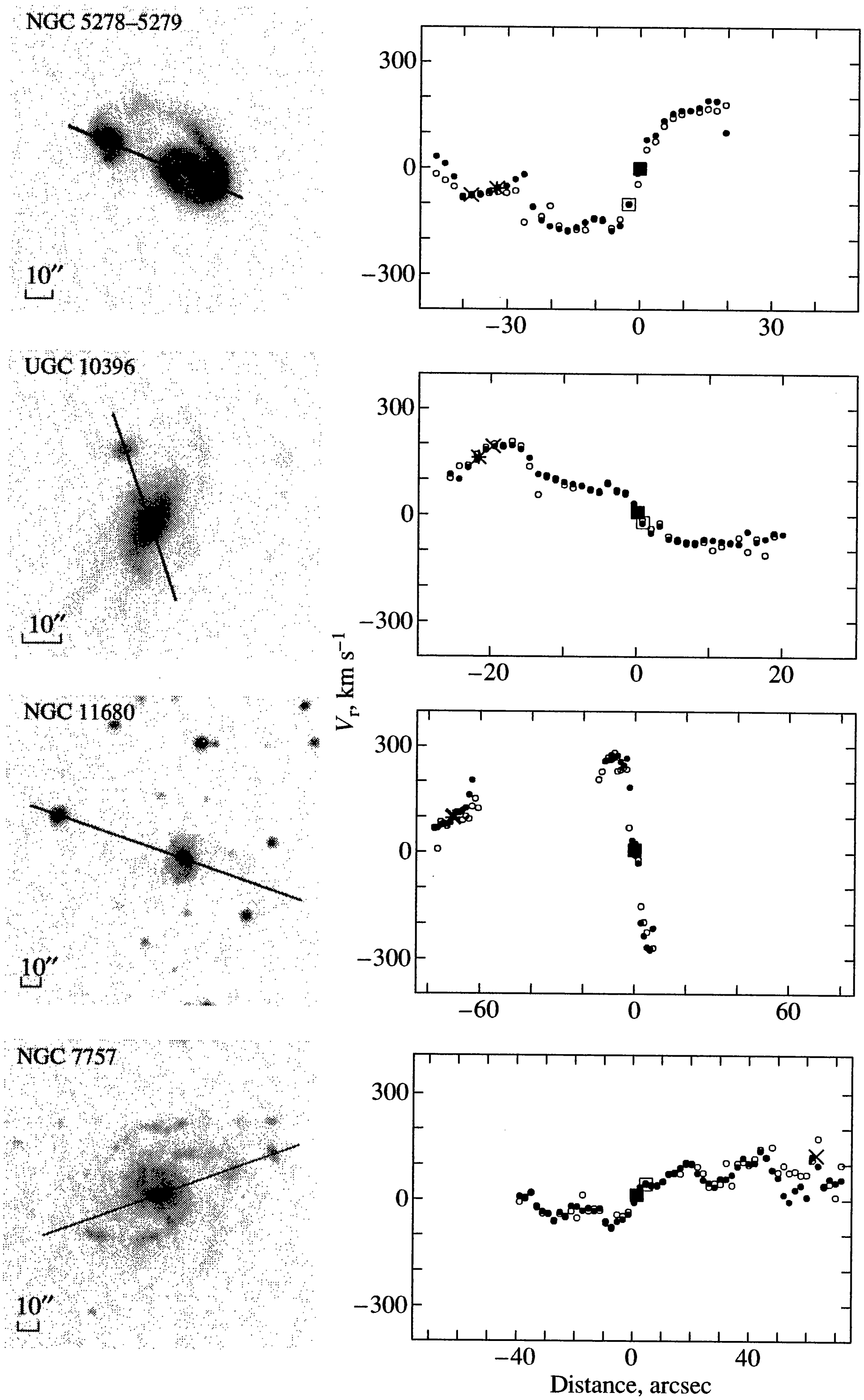
line rotation curve for NGC 797, which extends out to a distance of 1′ from the center of the primary. The maximum rotation velocity corrected for the tilt of the galaxy inferred from the same rotation curve is equal to 270 km s^{-1} (at a distance of 40″ from the nucleus). The Updated Zwicky Catalog (UZC) (Falco *et al.* 2000) reports for the optical center of the primary a radial velocity of 5654 ± 4 km s^{-1}, which is close to our result.

UGC 6865. This system is strongly tilted with respect to the line of sight. The rotation curve flattens out beyond 8″–10″ from the center of the primary galaxy. However, the northern branch exhibits a local



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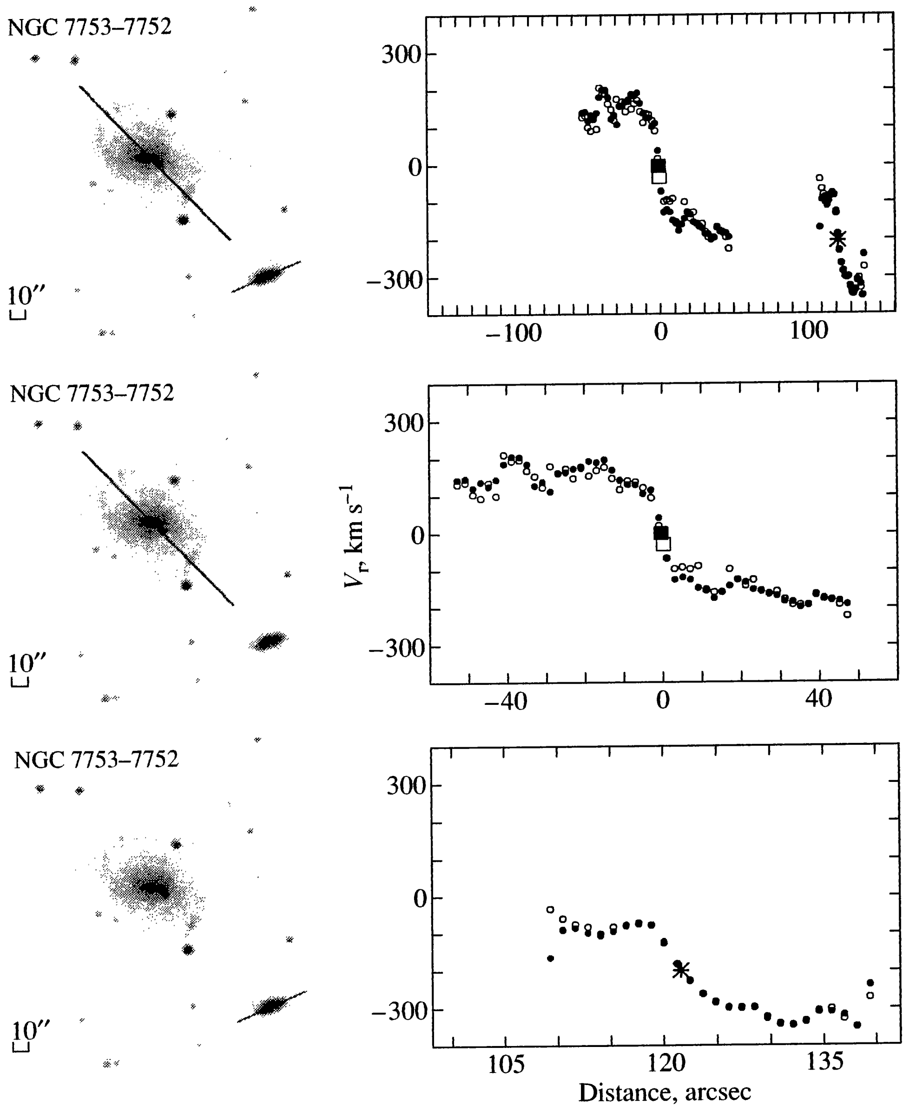
velocity decrease with an amplitude of 80 km s^{-1}. This may be due to inhomogeneous internal absorption. Because of the latter the rotation curve appears asymmetric and our systemic radial velocities determined for the photometric and dynamic centers of the main galaxy differ by 50 km s^{-1}. The central radial velocities reported by different authors scatter substantially. For example, the LEDA database gives for the primary galaxy a radial velocity of 5845 ± 83 km s^{-1}, whereas Bushouse (1986) reports velocities of 5900



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and 5650 km s^{-1} for the primary and the satellite, respectively. No rotation-curve data could be found in the literature.

NGC 4088. We observed this galaxy with a slit passing through the major axis. Both emission lines broaden strongly in the nucleus of the galaxy. The large angular size of the galaxy prevented us from tracing the rotation curve for the southwestern part at more than 50″ from the center. The northeastern part of the curve flattens out beyond 40″ at a level of ~150 km s^{-1}. Carozzi-Meysonnier (1978) obtained several spectra of this system at different position angles including $P.A. = 58°$. The northeastern branch of his rotation curve flattens out at ≈100 km s^{-1} at a galactocentric distance of ~10″, as determined by the author, whereas the velocity of the southwestern part continues to increase monotonically. The position of the center of the galaxy determined by Carozzi-Meysonnier appears to be shifted relative to our position by ~25″. The radial velocity of this center determined by the above author for the position angle considered is equal to 706 km s^{-1}. In addition, Carozzi-Meysonnier also points out the asymmetry of his rotation curve: the rotation velocity of the northeastern part of the curve is, on the whole, smaller by 100 km s^{-1} than that of the southwestern part. Our rotation curve appears much more symmetric. Carozzi-Meysonnier explains this asymmetry either by ejections from the active nucleus or by the influence of the neighboring galaxy NGC 4085. The velocities of the center of the primary galaxy reported by other authors scatter substantially. The UZG catalog (Falco *et al.* 2000) gives an optical velocity of 759 ± 4 km s^{-1}, which is close to our result.

NGC 4137. The satellite in this system has a very peculiar spectrum. It consists of two components separated by a small gap. The difference of the radial velocities of these components reaches 200 km s^{-1}. The rotation curve of the satellite consists of two branches, which correspond to these components. The rotation curve has a very large central gradient dV_r/dr. The rotation curve of the primary galaxy has velocity maxima of about $V_r = 70$ km s^{-1} and, on the whole, a symmetric shape. The UGC (Falco *et al.* 2000) gives a velocity of $11\,218 \pm 58$ km s^{-1} for the center of the primary galaxy, which is close enough to our result. No published rotation curves could be found in the literature.

NGC 5278–5279. This Markarian system (Mrk 271) exhibits a spectrum with very bright and broad emission lines in the nucleus. The spectral lines of both components are inclined in opposite directions, indicating that they rotate in opposite directions. The rotation curve of the primary galaxy flattens out, albeit with certain velocity variations. The main specific feature of this system are strongly noncoincident positions and radial velocities of the dynamic and photoimetric centers of both components (3″ and 100 km s^{-1} for NGC 5278 and 6″ and 20 km s^{-1} for NGC 5279, respectively). A detailed photometric analysis of the system performed by Mazzarella and Boroson (1993) revealed a number of regions or spots of enhanced brightness and the brightest of them is located in the satellite. The strong difference between the dynamic and photometric centers mentioned above may be explained by a similar inhomogeneity of the photometric properties of the two components. The latter may be due, in turn, to the interaction between the galaxies. Numerous determinarions of the radial velocities of the component centers yielded results that show a rather substantial scatter. The LEDA database gives the velocities of 7558 ± 79 and 7580 ± 46 km s^{-1} for the primary galaxy and the satellite, respectively. No published rotation curve could be found in the literature.

UGC 10396. The rotation curve of the primary galaxy flattens out beyond 5″ from the center, reaching a velocity of ~80 km s^{-1}. The system's components rotate in opposite directions. The dynamical and photometric centers of both components somewhat differ in position and radial velocity. The only determination of the central radial velocity found in the literature appears to come from Arkhipova and Esipov (1979). It is listed, e.g., in the UZC catalog (Falco *et al.* 2000) and is equal to 6185 ± 150 km s^{-1}. The causes of such a strong discrepancy between this value and our determination (~2500 km s^{-1}) are unclear.

UGC 11680. The satellite in this system is the Markarian galaxy Mrk 897. The spectra of both components in the vicinity of the nuclei exhibit strongly inclined broad emission lines superimposed on a strong continuum. The rotation curve of the primary galaxy can be confidently traced only at a small distance from the center—in fact only within the rigid-rotation portion in the broad emission-line region. The maximum observed velocity is equal to $V_r = 300$ km s^{-1}. The rotation curve of the system obtained by Keel (1996a) appears to show the same features as our rotation curve. The component radial velocities determined by Keel agree well with our results: 7791 ± 11 and 7894 ± 5 km s^{-1} for the primary and the satellite, respectively.

NGC 7757. The primary galaxy in this system has an asymmetric rotation curve: the observed rotation velocity of the eastern branch reaches a maximum of $V_r = 100$ km s^{-1} at a galactocentric distance of about 8″, and that of the western branch, at a distance of 18″. The rotation curve shows a specific behavior at its center: here velocity does not increase monotonically but the gradient dV/dr decreases locally to zero. No published rotation curves could be found for this galaxy. The UZC catalog (Falco *et al.* 2000) gives an optical radial velocity of 2960 ± 21 km s^{-1}, which agrees well with our results.

NGC 7753–7752. The primary galaxy and the satellite were observed separately and with different positions of the slit, which passed through the major axes of the components. The spectrum in the spiral-arm region appears discontinuous and clumpy and consists of several condensations. The rotation curve of the primary substantial velocity variations with an amplitude of ~100 km s^{-1}, which can be explained by inhomogeneous internal absorption when the slit crosses the spiral arms, or by the tidal interaction of the components. The same interaction can explain the different velocities of the photometric and dynamic centers (Marcelin *et al.* 1987). An analysis of the detailed velocity field allowed Marcelin et al. to obtain the rotation curves of both components. The rotation curve of the primary extends out to a distance of 100″ from the center (compared to 50″ for our rotation curve). The rotation velocity decreases beyond 50″. At smaller galactocentric distances the rotation curve of Marcelin *et al.* is, on the whole, similar to our rotation curve, and exhibits the same specific features. Thus Marcelin et al. point out velocity maxima exceeding 200 km s^{-1} at a galactocentric distance of 40″, and this feature agrees well with our results. In addition, Marcelin *et al.* traced their rotation curve somewhat farther from the center than we did in the case of our satellite's rotation curve, and it exhibits the same characteristic features. The component radial velocities obtained by the above authors agree rather well with our data: 5160 ± 10 and 4940 ± 10 km s^{-1} for the primary and the satellite, respectively. Note that other radial-velocity determinations in this system are characterized by a large scatter of the results obtained.

To reveal the possible systematic errors in the velocities of galaxies, we compared our results with the those published in the NED database. The mean difference in the sense of the radial velocity of the dynamic center minus the NED velocity is -5 km s^{-1} with a dispersion of 55 km s^{-1} (averaged over 15 objects including some satellites). The same comparison for the photometric centers yielded -18 ± 44 km s^{-1} (15 objects). These results imply that our data are free of important systematic errors.

The mean difference of our velocities of dynamic and photometric centers averaged over 23 objects (including satellites) is equal to 16 km s^{-1} with a dispersion of 23 km s^{-1}. The corresponding difference for 36 binary galaxies from the catalog of Karachentsev (1972) with radial-velocity estimates given by Keel (1996b) is equal to 9 ± 37 km s^{-1}.

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