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GAS KINEMATICS IN THE CENTRAL REGIONS OF SEYFERT GALAXIES. V. MRK 6 AND MCG 8-11-11

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The results of kinematical study of ionized gas and of imaging in the emission line [OIII]λ5007 and in the nearby continuum band for the central regions of Seyfert galaxies Mrk 6 and MCG 8-11-11 obtained with the 6-m telescope of the Special Astrophysical Observatory are presented. In Mrk 6 we have found a large-scale gaseous disk inclined by ~40° to the galaxy line of nodes; in the centre of the galaxy there are strong radial gas flows directed toward the nucleus. The central gaseous disk of MCG 8-11-11 rotates separately from the outer parts of the galaxy; its major axis is aligned with the central radio structure. In general, all the motions of ionized gas in the central regions of Mrk 6 and MCG 8-11-11 exclude the possibility of the formation of nuclear radio structure due to the collimated jet.

В настоящей статье представлены результаты исследования кинематики ионизованного газа и распределения поверхностной яркости в эмиссионной линии [OIII]λ5007 и в близлежащем участке континуума для центральных областей сейфертовских галактик Mrk 6 и MCG 8-11-11, полученные на 6-м телескопе САО АН СССР. В Mrk 6 обнаружен крупномасштабный газовый диск, наклоненный примерно под 40° к линии узлов галактики; в центре галактики присутствуют мощные радиальные течения газа, направленные к ядру. В MCG 8-11-11 центральный газовый диск вращается автономно от внешних частей галактики; ориентация его большой оси совпадает с ориентацией центральной радиоструктуры. В целом, характер движения газа в центральных областях Mrk 6 и MCG 8-11-11 исключает объяснение ядерной радиоструктуры коллимированными выбросами из ядра.

INTRODUCTION

Mrk 6 is SO galaxy with a bright Seyfert 1.5 nucleus. In the centre it has a double radiostructure elongated in the direction of P.A. 177°, by 50° to the major axis of the outer isophotes of the galaxy, with separation of the radio lobes of ~ 1″ (Ulvestad and Wilson, 1984). From the spectra obtained using

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a long slit in [OIII]λ5007 emission line range with the slit orientation similar to that of radio structure (P.A. 0°), Unger et al. (1987) have detected "extended narrow line region" (ENLR) in Mrk 6, i.e. they have found out that high excitation gas with a very small cloud velocity dispersion (FWHM ⩽ 50 km/s) is extended up to ~35″ from the centre. Recently a detailed study of ENLR in Mrk 6 was presented by Meaburn et al. (1989). They have obtained the galaxy image in [OIII]λ5007 emission line. It turned out that the high-excitation gas is distributed in the band elongated along the central radio structure direction (P.A. 0°), while the position angle of the major axis of the continuum isophotes in the outer regions is 130°, and that in the inner regions is probably 159°. Maximum gas extension to the north from the nucleus is greater than 10 kpc.The authors suppose this gas to be ionized by strongly collimated nuclear radiation.

MCG 8-11-11 has also Seyfert 1.5 nucleus. Nilson (1973) has classified this galaxy as a spiral, visible almost "face-on", with a large diffuse bar aligned along the north-south direction. However, it should be noted that in spite of great attention to MCG 8-11-11 nucleus (it has unique properties, that is, it is the brightest γ-source identified among the Seyfert nuclei) its outer regions were not practically studied. The galaxy nucleus was often observed in the radio band. In one of the latest works Ulvestad and Wilson (1986) have presented the maps of MCG 8-11-11 nucleus at 2 cm wavelengths with 0.1″ resolution and at 6 cm wavelengths with 0.4″ resolution. In the nucleus itself there is seen a triple radio source of 0.7″ in size, elongated at P.A. 127°. Orientation of more external radio isophotes is north-south, and at 1″ to the north from the nucleus there is one more radio lobe, weaker than the nucleus (Unger et al., 1986). Whittle et al. (1988) associate the north radio lobe with the line-of-sight velocity anomaly of approximately +100 km/s, which is shown by the narrow (FWHM ~ 160 km/s) component of [OIII]λ5007 emission line, visible in the spectra to the north from the nucleus. The common view is the following: a jet is driven away from the nucleus along the direction of P.A. 127° and is seen, first of all, as a triple radio source in the centre; at larger distances from the nucleus the gas flows along the bar make the relativistic electron beam to turn and thus outer radio structure is oriented in the north-south direction.

OBSERVATIONS

Observations of Mrk 6 and MCG 8-11-11 were carried out in 1986-1987 at the prime focus of the 6-m telescope using the long slit spectrograph. The spectra were registered by two-dimensional photon counting system (for the journal of observations - see Table 1). The slit length was 100″, its width was 1.5″ in 1986, and 2″ in 1987, the dispersion - 1.3-1.5 A/pix. For each of two galaxies we obtained 2 spectra in the red range (6300-6900 A), and 3 spectra in the green one (4700-5400) including H_β and [OIII] emission lines near the position angle of the nuclear radio structure. The line-of-sight velocities of ionized gas were determined from the H_β and [OIII]λ4959, 5007 emission lines in the green and from H_α and [NII]λ6583 in the red spectra by two methods. For the outer parts of galaxies (more far than 4″ from the centre) we used the standard reduction (Alyavdin et al., 1988), included the determination of V_r from the emission line peaks. Emission line profiles in the central regions (R⩽4″) of both Mrk 6 and MCG 8-11-11 are complicated, multicomponent; for these lines we distinguished different kinematical gas subsystems using the interactive Gaussian component analysis. For Mrk 6 four gas subsystems were distinguished which give rather narrow lines (FWHM ⩽ 500 km/s); radial distributions of line-of-sight velocities of ionized gas after the component separation are shown in Fig. 1. For MCG 8-11-11 with the help of Gaussian component analysis we divided emission line into three components; however, taking into account the strict boundary between the inner and outer gaseous disks at R=3-4″, we distinguish four kinematical gas subsystems in this galaxy; the radial distributions of their line-of-sight velocities are shown in Fig. 2.

Table 1. A journal of long-slit observations for the galaxies Mrk 6 and MCG 8-11-11

Spect. No.	Object	Date	Exp.	P.A. slit	Spectral range (A)	Seeing (″)	Scale (″/px)
M03002	Mrk 6	1/2.IV.86	60	18°	6250÷6900	1.5	0.50
M04705	Mrk 6	30/31.X.86	107	113	6250÷6900	3	0.52
M06432	Mrk 6	16/17.X.87	10	0	4700÷5400	1	0.37
M06433	Mrk 6	16/17.X.87	9	149	4700÷5400	1	0.37
M06434	Mrk 6	16/17.X.87	5	117	4700÷5400	1	0.37
M03604	MCG	8/9.X.86	60	176	6250÷6900	3	0.50
M04802	MCG	31/1.XI.86	35.5	175	6250÷6900	3	0.52
M06606	MCG	18/19.X.87	10	128	4700÷5400	2	0.37
M06607	MCG	18/19.X.87	10	97	4700÷5400	2	0.37
M06608	MCG	18/19.X.87	10	156	4700÷5400	2	0.37

In August 1989 we observed the central regions of Mrk 6 and MCG 8-11-11 at the 6-m telescope with the multipupil fiber spectrophotometer (MPFS, (Afanasiev et al., 1990). A journal of observations is presented in Table 2. The spectra for each element of the galaxy surface of 1.25″×1.25″ in size, from overall area 10″×12″, were obtained in the wavelength range 4700-5400 A with a dispersion of 1.3 A/pix. The seeing was ~1″. The spectra were registered with the two-dimensional photon counting system. After the spectrum reduction for different fiber transparency we constructed the maps of the surface brightness distribution in narrow spectrum bands for the central regions of galaxies. Observational results for Mrk 6 are presented in Fig. 3, and for MCG 8-11-11 - in Fig. 4. They include the maps of the surface brightness in continuum (the central wavelength is 5110 A, the spectral band is 40 A) and in [OIII]λ5007 emission line, continuum being subtracted.

Table 2. A journal of observations with MPFS for the galaxies Mrk 6 and MCG 8-11-11

Spect.	Object	Date	Exp.	P.A. vert.	Seeing
T00608	MCG 8-11-11	27/28.VIII.89	20^m	118°	1.5″
T00609	MCG 8-11-11	27/28.VIII.89	20	118	1.5
T00705	Mrk 6	28/29.VIII.89	30	69	1.5

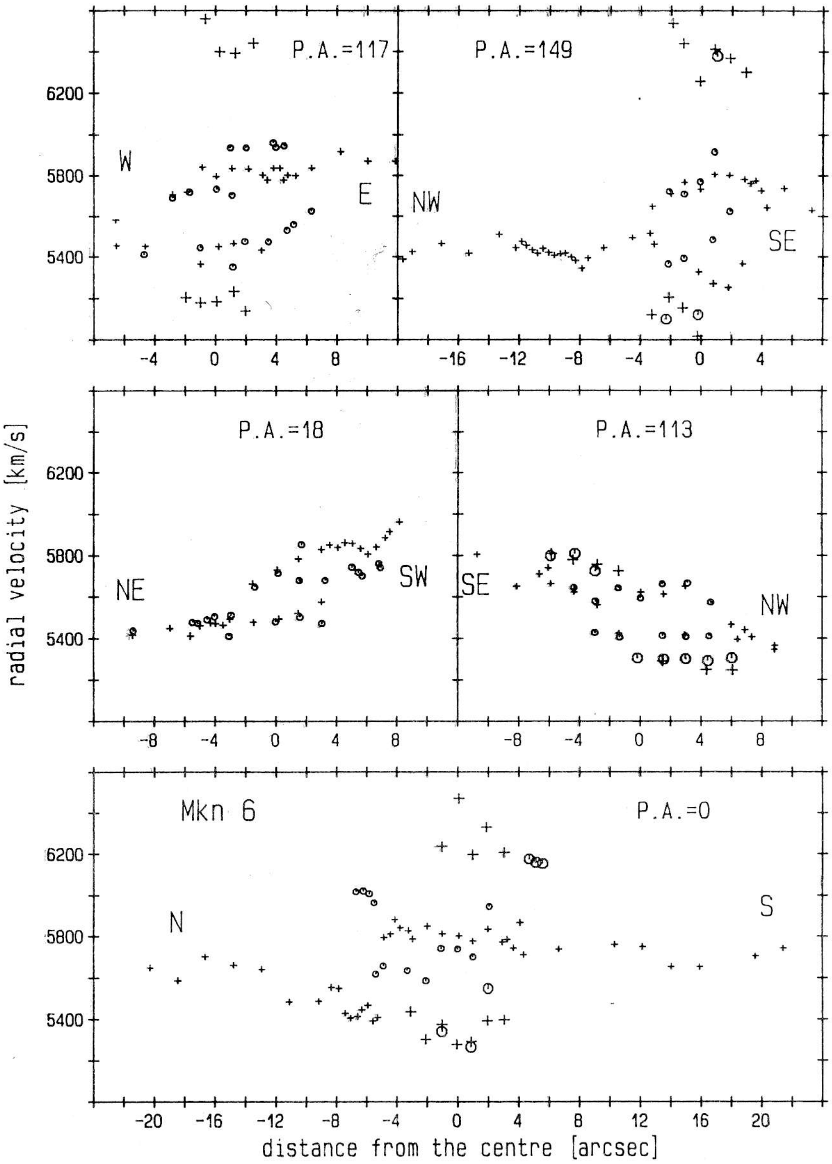

Fig.1. Radial distributions of the line-of-sight velocities of ionized gas in Mrk 6. Larger symbols sign high- and low-velocity components.

ROTATION OF Mrk 6

Meaburn et al. (1989) have noted the difference of line-of-sight velocities for the high-excitation gas to the north and to the south from the Mrk 6 nucleus; allowing for large distance from the centre, (several kiloparsecs), and small velocity dispersion of gaseous clouds (absence of turbulent motions) they have supposed that they see the gaseous disk rotation. But if the peculiar orientation of the visible large-scale distribution of the ionized gas is caused only by the anisotropy of ionized radiation, then the ionized gas in the outer parts (if this is usual gas of the galactic disk) should participate in the normal circular rotation, the dynamic major axis of which must coincide with the major axis of the outer isophotes of the galaxy disk. Comparing the outer parts (R>4″) of gas line-of-sight velocity distributions at M06432 (P.A. 0°) and M06433 (P.A. 149°), (spectra being numerated according to Table 1), we tried to obtain the galaxy rotation curve.

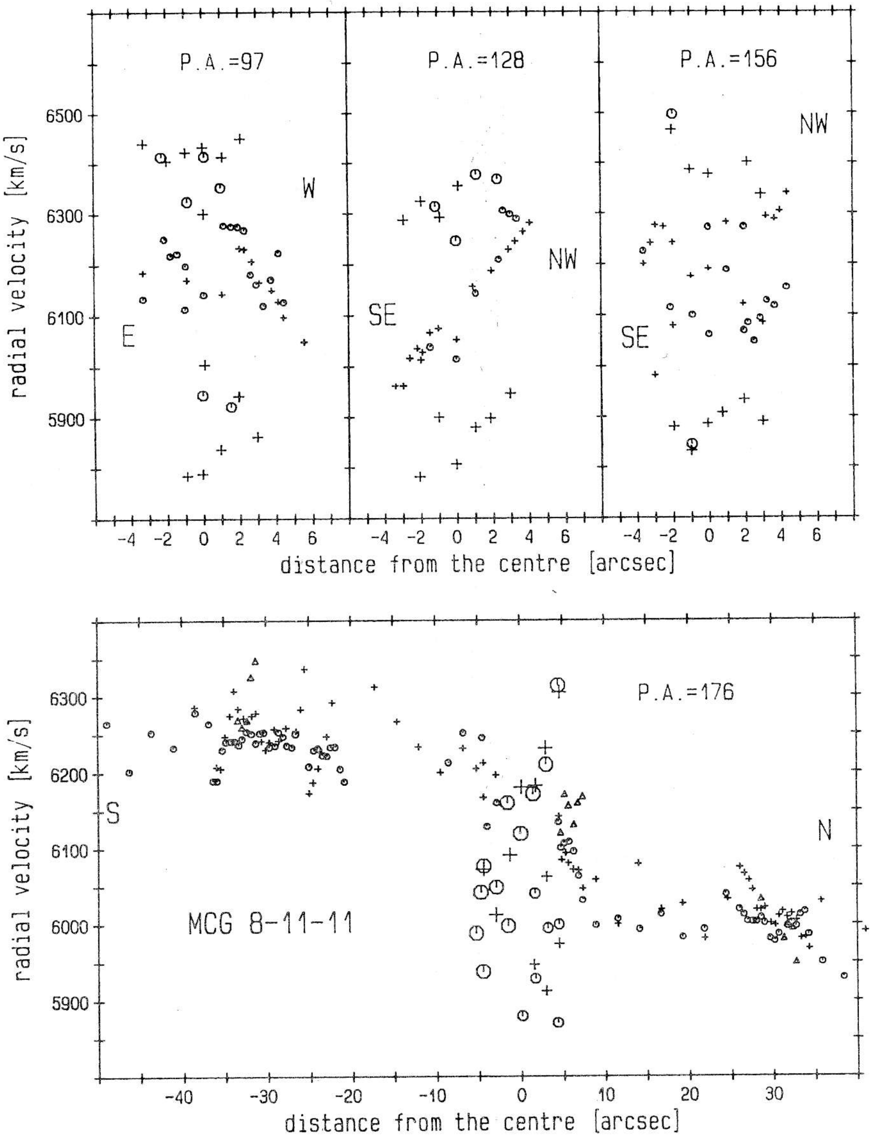

Fig.2. Radial distributions of the line-of-sight velocities of ionized gas in MCG 8-11-11. Larger symbols sign high- and low-velocity components.

First of all a question raises on systemic galaxy velocity: relative to what value should the difference of line-of-sight velocities at various dis-

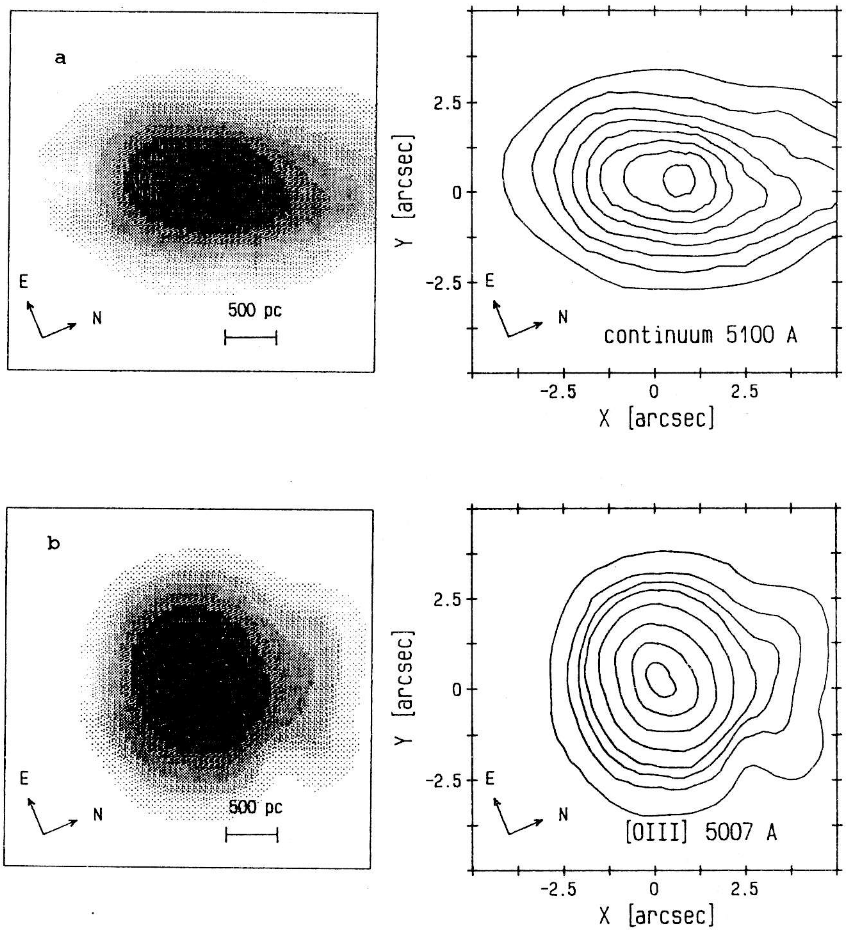

Fig.3. The maps of surface brightness distribution in the emission line [OIII]λ5007 (a), and nearby continuum band λ5110 (b) for the central region of Mrk 6, obtained with MPFS.

tances from the galaxy centre be taken? It is clear that the line-of-sight velocity, obtained from the emission line peak in Mrk 6 nucleus, differs greatly from the systemic one: all the measurements of V_r both to the north and to the south from the nucleus give points locating lower than V_r(nuclear). However, there is a paper of Vrtilek and Carleton (1985) where measurements of line-of-sight velocities from both [OIII]λ5007 emission lines and absorption lines are presented for a sample of Seyfert galaxies. For Mrk 6 the nuclear line-of-sight velocity from absorption lines appeared to be 215 km/s lower than that from the [OIII] peak (see their Fig. 2). Using our measurements of [OIII] in the nucleus we have established that by the day of observations the geocentric systemic velocity of Mrk 6 (or line-of-sight velocity of the stellar population of the nucleus) is equal to 5580 km/s.

Then we have taken the longest two "branches" of the line-of-sight velocity curves that is the south one for P.A. 0° and the north one for P.A. 149° and tried to combine them according to the formulae of circular rotation. These formulae include two parameters: inclination of the galaxy disk to the sky plane and line-of-nodes direction. After Unger et al. (1987) and Afanasiev (1981) we accepted the angle of the disk inclination, determined according to visible outer isophote ellipticity, to be cos i = 0.60. The position of the line of nodes ought to be P.A.$_0$ 130°, since this is just the value of P.A. of the major axis of the disk outer continuum isophotes (Meaburn et al., 1989).

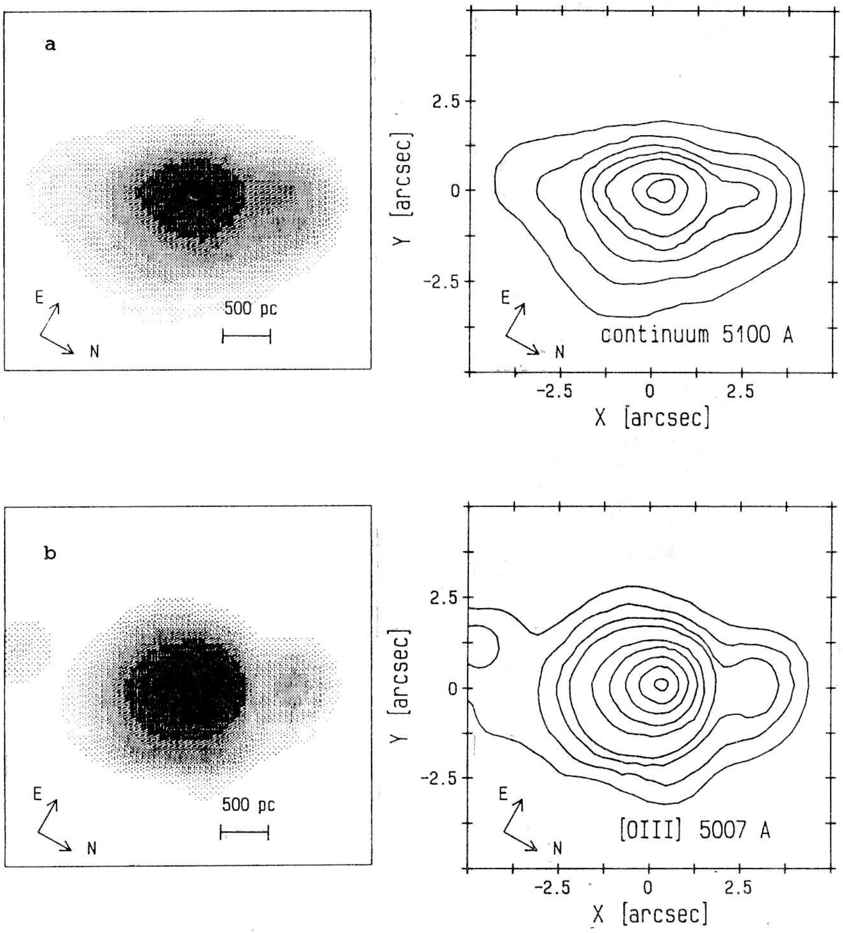

Fig. 4. The maps of surface brightness distribution in the emission line [OIII]λ5007 (a), and in nearby continuum band λ5110 (b) for the central region of MCG 8-11-11, obtained with MPFS.

However our two "pieces" of the circular rotation curve have coincided only at P.A.$_0$ 170°! This is the direction in which the structure of the high-excitation gas is elongated. Thus the phenomenon that Meaburn et al. (1989) thought to be biconic field of ionized radiation is in reality the gaseous disk visible almost edge-on and being inclined to the galaxy plane. Having determined from isophotes, obtained in [OIII]λ5007 emission line by Meaburn et al. (1989), a new inclination angle of the gaseous disk (cos i $\cong 0.5$) we have calculated the circular rotation velocities of the gaseous disk of Mrk 6 according to standard formulae. The rotation curve is presented in Fig. 5. It has a local maximum at a distance of 3.4 kpc from the centre, where V_{rot} reaches 250 km/s; then rapid velocity decrease follows, steeper than restricted by the Kepler law. It gives a rise for some doubts on the applicability of the circular rotation formulae at these distances from the centre. Nevertheless it is useful to present rough estimate of mass for the studied part of the galaxy ($R \leqslant 9$ kpc): in the framework of the regularly rotating thin disk model it is equal to $1.4 \cdot 10^{11} M_{\odot}$.

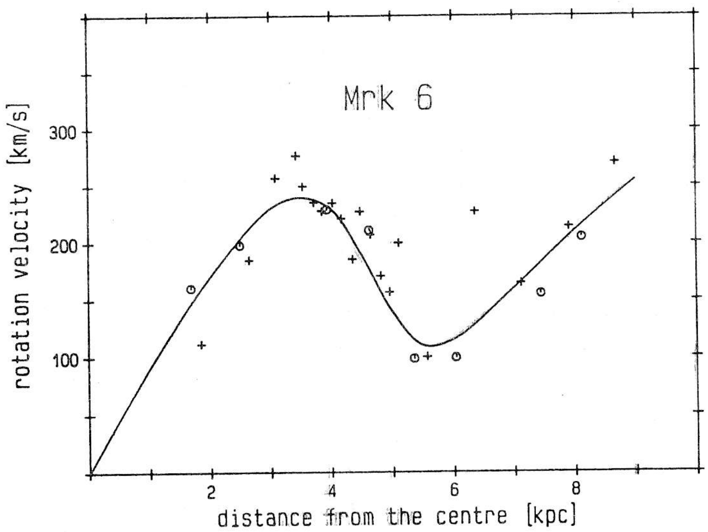

Fig.5. The rotation curve of Mrk 6 gaseous disk at the following accepted parameters of the disk orientation: cos i=0.5 and $P.A._0 = 169^{\circ}$.

RADIAL GAS FLOWS IN MRK 6

Meaburn et al. (1989) have noted that the most central isophotes in continuum have the position angle of the major axis $\cong 159^{\circ}$, i.e. are turned by 30° relative to the outer isophotes. Though due to instrumental difficulties they consider this result as uncertain, however in our measurements (see the continuum map of the central region of Mrk 6 at λ=5110 A, Fig. 3) isophotes on scales ~5″ from the centre are elongated at the position angle 150°. Thus, we confirm the turn of the inner continuum isophotes relative to the line of nodes. This fact evidences for the lack of axial symmetry in the distribution of stellar population in the centre of Mrk 6 and hence for the triaxial central potential. At these conditions there should inevitably appear shock wave regions and strong radial gas flows (see e.g. Roberts et al., 1979).

It seems to us that we see them really. Near the nucleus the emission lines are splitting almost symmetrically relative to the systemic velocity (Fig. 1); the red component being more intense than the blue one. This resembles the infall of spherical gaseous envelope onto the nucleus with a radial velocity of ~250 km/s. The envelope sizes are rather enormous: according to kinematics it is traced up to ~3″ (1 kpc) from the centre.

Besides this envelope there are faint wings of [OIII] λ4959, 5007 emission lines: the line-of-sight velocity of the blue one is ~5200 km/s (-400 km/s relative to the systemic velocity), and that of the red one is ~6400 km/s (+800 km/s). At the cross-sections near north-south direction the red component is localized mainly to the south from the nucleus, and the blue - to the north. Such locations do not contradict the identification of the flow toward us with the north radio lobe, and the flow from us with the south radio lobe (see radio map at λ=6 cm in Ulvestad and Wilson, 1984). In this sense Mrk 6 resembles other galaxies of our sample, since the association of radio lobes with kinematic anomalies of the high-excitation gas in many of them is noted first by Whittle et al. (1988), and the detailed identification of radial flows, seen as faint wings of [OIII] emission lines, with the radio continuum brightness centres has been performed by us for Mrk 573 in our Paper I. If suppose that the north radio lobe is smaller than the south one, since being observed through the stellar-gaseous ellipsoid elongated at P.A. 150°, then we get an indirect argument in favour of the fact that the south radio lobe is nearer to us than the nucleus, and we also observe the gas infall onto the centre.

One more curious fact may be noted in velocity radial distributions for the faint line wings at P.A. 0° and 149° (Fig. 1) Both high- and low-velocity components show line-of-sight velocity gradient which slope being opposite to the sense of the outer gaseous disk rotation. As we have seen from the examples of Mrk 573 (Paper I) and Mrk 3 (Paper II) the radial gas flows rotates usually with the central part of the gaseous disk and their velocity gradients are coincident with the central rotation angular velocity. If it is true also for Mrk 6, we can suspect that the central part of the galaxy gaseous disk, hidden from us by the contracting spherical envelope, rotates really in the opposite sense to that of the outer parts as it is observed in Mrk 3 (Paper II).

GAS ROTATION IN THE OUTER PARTS OF MCG 8-11-11

The spectral cross-section MO3604 (P.A. 176°, H_α region) reveals a notable gas rotation in MCG 8-11-11 up to the distance from the centre ~50″ (~20 kpc) (see Fig. 2). It is surprising, because according to Nilson (1973) the major axis of the outer isophotes has the P.A. 90° and hence the slit in the cross-section MO3604 was practically perpendicular to the line of nodes. Reducing MO3604 line-of-sight velocity curve to the galaxy plane following the circular rotation formulae (accepted according to Nilson P.A.$_0$=90° and cos i=0.89) we have obtained the rotation velocity of MCG 8-11-11 of some thousand kilometers per second! Since this cannot be real, it should be accepted that the galaxy disk orientation remains to be not clear yet.

If suppose that the large-scale diffuse structure elongated in the north-south direction, which was treated by Nilson as a bar, is in reality the galaxy disk visible almost edge-on (according to Keel, 1980; b/a=0.47), then the parameters under consideration appear to become reasonable: the rotation velocity of MCG 8-11-11 is equal to 140 km/s and remains approximately constant up to the distance ~20 kpc from the centre, the galaxy mass is $9\cdot10^{10}$ $M_{\odot}$, the central gradient of the rotation velocity is 37 km/s/kpc, the northern side of the galaxy is approaching us. The rotation curve calculated from the line-of-sight velocity radial distribution of M03604 cross-section in the assumption that P.A. = 0° and cos*i* = 0.47, is presented in Fig. 6. It is probably acceptable in the distance range from the centre R=2-20 kpc.

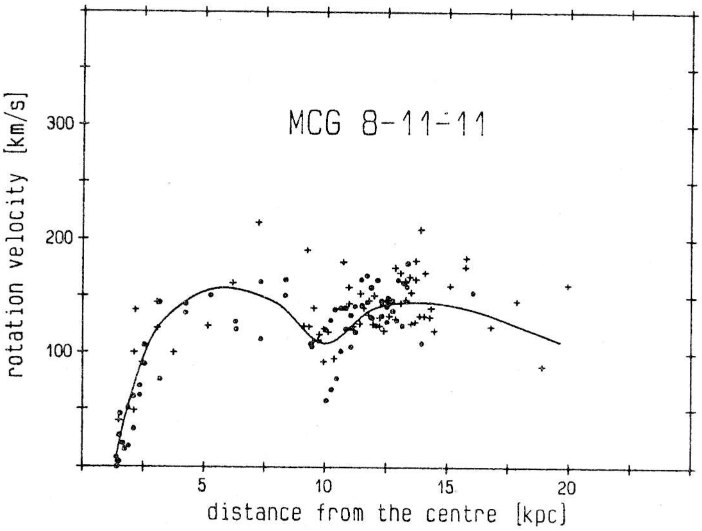

Fig.6. The rotation curve of MCG 8-11-11 gaseous disk at the following accepted parameters of the disk orientation: cos i=0.47 and $P.A._0=0°$.

GAS KINEMATICS IN THE INNER REGIONS OF MCG 8-11-11

The innermost regions of MCG 8-11-11 (R⩽1.6 kpc), as it is well seen from the line-of-sight velocity distribution in the M03604 cross-section (P.A. = 176°, Fig. 2), represent an independent gaseous disk rotating rapidly and rigid-body at the opposite sense to the general galaxy rotation.This kinematic subsystem is remarkably well seen at P.A. 128° (the cross-section M06606 in the green spectral range), where it dominates in the spectrum within the distance range from the nucleus ±4″ (1.6 kpc). Its more faint signs can be seen at P.A. 156°(the cross-section M06608 in the green spectral range). The NW-side of the disk moves away from us. Let us determine the location of the line of nodes for the inner gaseous disk of MCG 8-11-11 comparing the central line-of-sight velocity gradients at P.A. 176°, 156° and 128°. Using the relation

$$\Delta V_r/\Delta R \propto \cos\ (P.A. - P.A._0),$$

we obtain $P.A._0 = 138°\pm6°$. This gives rise to association with the central radio structure: as we have already noted in the centre of MCG 8-11-11 there exists the triple radio source, aligned at P.A. 127° (Ulvestad and Wilson, 1986). The angular rotation velocity of the central gaseous disk is equal to

110/sin*i* km/s/kpc, i.e. at least 3 times higher, than the angular rotation velocity of the outer disk within the distance range from the centre 1.6-2.7 kpc; the lower limit of the mass, concentrated in the region of the inner disk, is $1.1\cdot10^{10}$ $M_{\odot}$.

The map of the central region of MCG 8-11-11 in [OIII]λ5007 emission line, obtained with the two-dimensional multipupil spectrophotometer (Fig. 4) shows that the isophotes of the gas surface brightness are not elongated at P.A. 130°-140°, they are rather round. However if to take into account that the continuum isophotes are elongated in the north-south direction (in agreement with the large-scale structure, i.e. galaxy disk orientation?), then the distribution of the gas surface brightness has, nevertheless, some excess at the distances of 2″-3″ from the centre in the direction which is interesting to us. Probably we may think that the bright source of emission lines in the nucleus contaminates radiation of the inner gaseous disk.

Besides of regular rotation of the inner disk, in MCG 8-11-11, as in other galaxies of our sample, we observe radiation in the forbidden lines of high-velocity radial gas flows. In Fig. 2 they are marked as high- and low-velocity line components. The low-velocity component is well visible at all spectral cross-sections: it has the radial velocity gradient which traces exactly the rotation of the inner gaseous disk and at P.A. 128° asymmetry of the brightness distribution with a shift to the north-west from the nucleus, that allows to associate it with the north-west lobe of the triple radio structure (asymmetry is small, since the radio lobe is only 0.5″ from the nucleus). The high-velocity component (+200-+250 km/s) is best seen at P.A. 128°. From the fact that in projection onto the nucleus (R=0″) the high-velocity wing of the emission lines is brighter than the low-velocity one we may suppose that just in this case we observe the gass infall onto the centre.

On the MCG 8-11-11 map in the [OIII]λ5007 emission line there exists faint brightness condensation at 1″ to the north from the nucleus. It is coincident with the secondary radio centre (Unger et al., 1986), however no velocity anomalies were detected in this place.

CONCLUSION

Many authors (see e.g. the paper of Whittle et al., 1988) interpret the radio lobes locating symmetrically relative to the nucleus in Mrk 6 and MCG 8-11-11 as well as in other Seyfert galaxies of our sample as realization in miniature of what is happened in giant radio galaxies: that is outburst of plasmons out of the nucleus and their interaction with the surrounding gaseous medium. Mrk 6 and MCG 8-11-11 differ from other galaxies by the presence of the strong emitter of forbidden emission lines in the nucleus prevented to relate the ionized gas distribution in the galaxy central parts with their radio structures. However while investigating the gas kinematics the facts have been revealed which make us doubt whether we observe the outbursts from the nucleus. First, according to the shift of brighter wing of the emission line relative to systemic velocity in the spectrum of the nucleus we may conclude that here we observe the gas infall onto the centre rather than its motion outside. Second, the radio lobes in both galaxies appeared to be on the line of nodes detected by us from kinematics, that evidences for their belonging to the gaseous disk, while in the case of outbursts they ought to stay perpendicularly to the disk plane. In this sense only the north radio lobe locating at 1″ from the MCG 8-11-11 nucleus can play a role of jet).

What can cause the double or triple linear radio structure near the centres of Mrk 6 and MCG 8-11-11, except the jet? In both galaxies, in MCG 8-11-11 it is absolutely for certain, and in Mrk 6 is probable, the central regions of gaseous disks of 1-1.5 kpc in radius rotate in opposite sense relative to the rotation of the outer regions. In the region of the jump of the angular rotation velocity there should appear shift instabilities, and as consequence strong turbulent gas motions which will cause formation of shock waves and surface brightness spots in radio continuum and in forbidden emission lines. This region ought (in the case of circular gas rotation) to have the shape of torus and, being observed edge-on, will provide two brightness centres, locating symmetrically relative to the nucleus. Just in these shock wave regions strong radial gas flows should appear, which we observe as emission line wings.

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