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Flat rotation curves of galaxies are left in the past

A. V. Zasov

Sternberg Astronomical Institute of Moscow State University, Universitetskij prospect, 13, 119899, Moscow

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Abstract. A study of rotation of spiral galaxies, which was carried out in the last decade, has led to a conclusion that their rotation curves usually have a complex shape and rarely contain a long "plateau". A possible physical nature of local maxima on the rotation curves is briefly discussed.

Key words: galaxies: spiral – galaxies: fundamental parameters – galaxies: rotation

A gradual change-over from comparison of galaxies by morphological properties or integral parameters to comparison of the distribution of different physical quantities inside galaxies is under way now. It has become apparent, for instance, that many properties of spiral galaxies, such as proportion of flat and spherical components, star formation rates, gas content, excitation and maintenance of the wave spiral pattern are related to radial distribution of rotational velocity of the cool component (gas, young stars).

The first extended rotational curves derived in the 1960s–1970s from both radio observations and optical lines were not highly reliable. Observations in the radio line HI were of low angular resolution, which resulted in the fact that the rotational velocity gradients in the inner regions turned out to be largely underestimated, and the details of the rotational curves "blurred". On the other hand, optical observations used to be restricted to the uprising part of the rotational curves within several kiloparsecs from the centre and determined with rather large errors. It followed from general assumptions that the rotational curve must gradually fall off at the outskirts of galaxies in accordance with the observed brightness distribution in the stellar disk. By irony of fate, such a drop was indeed found in nearby galaxies having, as it seemed, the most reliable gas velocity estimates: in M31 (Rubin, Ford, 1971), in NGC 300 (Shobbrook, Robinson, 1967) and M81 (Rots, Shane, 1975). However it appeared later that the M31 rotational curve was considerably "smoother" than it had been suggested by Rubin and Ford (1971) and nearly flat at the periphery (see Tenjes et al. (1994) and references therein). In NGC 300 the rotational velocity gradient disappeared after taking account of the disk inclination angle variation in the outer regions of the galaxy (Rougstad, 1979). It is only in M81 that the rotational velocity is likely to decrease with radius.

Later on, both radio and optical observations using image tubes showed that the rotation curves look, with a few exceptions, rather alike: they come rapidly on the plateau and at large R the rotation velocity does not markedly tend to decrease. This is a convincing point for the existence of dark matter in galaxies. The rotational velocity of galaxies averaged in azimuth and strongly smoothed along the radius is well fitted by the quasisolid-body part of the curve in the inner regions and by a long smooth plateau. However, the more accurately the measurements were performed, the more obvious it became that such an approximation was tentative. In some galaxies individual details on the rotational curves rendering their shape not so "standard" were reliably revealed. Local extrema or wave-like velocity variations with an amplitude of 10–20% of the mean value are generally observed (see e.g. Rubin et al., 1985). The nature of these details may be different: the local decrease or increase in the velocity of rotation either represent the character of variation of the potential in the disk plane, that is, they are associated with the mass distribution peculiarities, or point out to non-circular motions in the local regions of the disk. The latter is of particular interest since it allows to investigate the mechanisms of gas motion perturbation. The departures from circular motions in galaxies (in the absence of a bar) may be due to both the regular disturbance of the velocity field in spiral arms and the existence of intense star formation, where the peculiar velocities of gas are affected by the influence of massive stars. In the circumnuclear regions the nuclear activity may also be effective. At last, there is one more reason, which is unfortunately badly understood but worth mentioning: accretion of gas clouds and their interaction with the main gaseous layer of a galaxy.

For velocities of gas to be studied in more detail, high spatial and spectral resolution observations e needed. Note that although the radio observations ·ovide the most reliable estimates of gas rotation vecity at the periphery of the optical disk and beyond , their angular resolution is insufficient (with the ex:ption of the closest galaxies) to determine the local :culiarities of gas motion. This is why, the examina- on of non-circular motions on scales of several kilo- ırsecs in most cases requires optical measurements.

Unfortunately, most rotational curves measured , the present time have been derived from one or :veral spectral cuts, which is apparent to be insuf- :ient for detailed study of gas motion in the disk. he shapes of the rotation curves for the same galaxy :rived by different researchers from spectral cross- :ctions are often dramatically different from one an- :her. At best, analysis of the total gas velocity field ıd more careful determination of such parameters as ıe angle of inclination of the disk to the line of sight ıd the orientation of the galaxy dynamical axis are :eded. A special problem is presented by measure- ıents of gas velocities in the central regions of galax- s (1–2 kpc from the centre), where the emission lines :e often weak, while the stellar continuous spectrum the brightest, which requires a linear detector and a articularly high spectral and spatial resolution. This why the detailed study of gas rotation is a task to e performed with large telescopes.

On putting the 6 m telescope into operation, one f the long-term observational programmes was a ›int (SAO–SAI) programme of investigation of kine- ıatics of close interacting system carried out under ıe supervision of B. A. Vorontsov-Vel'yaminov. At ıat time, analysis of the shapes of rotational curves 'as naturally out of question, for the radial velocity stimates were not quite accurate and in many cases nly the radial velocity gradient along the slit and ıe extent of the "solid-body" rotating region could e determined reliably. Moreover, drastic non-circular ıotions were present in a number of objects. Never- ıeless, using the radial velocities obtained for many bjects for the first time, it was managed not only to stimate the distances and integral luminosities, but lso to give a rough value of mass of many interacting alaxies, to see that there is no clear evidence of in- tability of the systems, as well as to show that quite few close systems, which had been considered as ıteracting galaxies, represented galaxies of low lu- ıinosity with two or more powerful centres of star ›rmation (see Arkhipova et al., 1987).

After a certain break, a long-term programme was esumed at the SAO to study rotational curves of the ıner regions of normal (i.e. non-interacting and non- eyfert) galaxies with an ordered spiral structure, sing the long-slit spectrograph UAGS. The spec- ra were first recorded on photographic film (through n image tube), then with the aid of the TV sys- em, when the technique of digital detection was properly developed. The first paper of this series appeared in 1987 (Zasov, Sil'chenko, 1987), the last one (Afanasiev et al., 1992) in 1992. The galaxies, which were the most attractive for studying rotational curves, were observed with several orientations of the slit, which enabled to obtain reliable measurements of the azimuth averaged rotational curves. The observational programme was largely stimulated by theoretical predictions of the existence of regions with rapid variation of the gas angular velocity, or local minima on the rotation curves. Such kinematic peculiarities of the gaseous disk may be responsible for the development of hydrodynamical instabilities resulting in the appearance of long-lived spirals (see discussion of the point in the review of Fridman, 1990). The first observations gave ground to believe that the galaxies with smooth rotational curves are rather an exception than a rule. Measurements often reveal the existence of local velocity minima at distances of 0.5–3 kpc from the centre (for our Galaxy and the Andromeda nebula these features have been well known before). In many cases their explanation is quite trivial: as it has been shown by Zasov and Zotov (1989), if one proceeds from the distributions of mass in bulges and disks of "typical" spiral galaxies, the local minima may then be expected in a considerable part of galaxies in the region of transition between the inner zone of a galaxy, where the rotational velocity is defined by the bulge, and the outer zone, where the disk dominates. The most intriguing discovery was the detection of the local circumnuclear maxima of the rotational curve inside the bulges at a characteristic distance of 0.3–1 kpc from the nucleus. It was shown that in many (but obviously not in all) galaxies there exist dynamically isolated nuclei with a typical mass of about 10^9 solar masses, which are responsible for a high angular velocity of rotation. An example is the nuclear region of NGC 7331 for which it has been found from BTA observations that the fast rotation embraces a region by an order of magnitude smaller than the size of the bulge (Afanasiev et al., 1989). Later on, Sil'chenko (1993) has shown that a "jump" in the colour indices, pointing out to an enhanced abundance of heavy elements of stellar population within the nucleus, is characteristic of such high angular velocity nuclei. Thus it is not only in kinematics, but also in chemical evolution that these dense nuclei represent decoupled systems.

Another important inference, which has so far not been duly attended to, is that the distribution of mass in the bulge of galaxies (not to be confused with a nucleus) is inconsistent with Vaucouleur's law describing its photometric profile. With the increasing of distance from the centre the volume density decreases slower than the volume luminosity, which suggests that the mass-to-luminosity ratio of the bulge increases outwards (preliminary results appeared in the paper by Zasov and Sil'chenko (1993); later we obtained a similar result from observations of NGC 7217.

Owing to the development of novel techniques (CCD detectors, multipupil spectrograph, scanning Fabry–Perot interferometer) and the elaboration of packages of programmes for data reduction at the SAO RAS (Laboratory for Spectroscopy and Photometry of Extragalactic Objects), a possibility sprang up of studying the gas velocity field in more detail with the BTA. Over the last few years two-dimensional velocity fields have been studied for a number of spiral galaxies. Galaxies within a few hundred parsecs from the centre have been confirmed to rotate faster than it could be expected from extrapolation to the centre of the rotational curve at large radii. Another conclusion is that in approximately half of the cases the dynamical axis at a distance of a few arcseconds (hundreds of parsecs) from the centre deflects from the major axis of the galaxy elliptical isophotes and/or from the dynamical major axis (line of nodes) of the disk rotating sometimes up to tens of degrees (Zasov, Sil'chenko, 1995).

The first inference confirms the existence of dense nuclei, whereas the second one points to the deviation from the axial symmetry in the gravitation potential distribution, which may be due to the presence of a central minibar of 0.2–1kpc in size inside the galactic bulge. Such small structural elements are not detectable on photographic images and therefore there is little knowledge about them. Since in the inner regions of galaxies the potential is basically defined by the spherical (inner part of the bulge, stellar nucleus) but not the disk component, the mechanism forming the bar can not be the "classical" bar-mode, developing in the dynamically cool disk. Some other machine forming the elongated structure, which is connected with precession and joining of elongated star orbits in the dynamically "hot" component of the galaxy is likely to be operative here (see Polyachenko and Polyachenko, 1994, and references therein). For some galaxies, though, one cannot exclude an alternative explanation of the dynamical axis deflection: it may be expected if the gas forms a circumnuclear disk whose plane is different from that of the main disk of the galaxy.

A few years ago the possibility of using the scanning Fabry–Perot interferometer allowed another problem to be defined: making analysis by the 3D spectroscopy techniques of the systematic departures of velocities of gas motions from circular ones, connected, first of all, with the spiral arms (the work was done in collaboration with the Institute of Astronomy of RAS and the Marseile Observatoire). To accomplish the programme, galaxies with a moderate inclination angle were selected, which possessed clearly defined spiral arms and disks bright enough in emission lines. Preference was given to objects for which the preliminary long-slit observations showed complex gas motion allowing strong non-circular motions to be assumed. To reveal gas oscillations related to spiral density waves, a method of Fourier analysis of the azimuthal distribution of radial velocities at different distances from the galaxy centre (modified Canzian's method) was developed at the Institute of Astronomy. This technique makes it possible to isolate both the axially symmetric gas rotation and the higher harmonics caused by the gas oscillations in the R, ϕ and z coordinates (Lyakhovich et al., 1997). One of the objectives of this programme was to determine corotation radii and the discovery of anticyclonic structures in the velocity field predicted theoretically and by experiment. These closed streamlines develop simultaneously with spiral arms and their position must be different for the case of gravitational and hydrodynamical nature of spiral density waves (see Lyakhovich et al., 1996 and references therein). Similar structures were found earlier from the gas motion in a single galaxy, NGC 931 (Afanasiev, Fridman, 1996), however this galaxy is anomalous in a number of features: it has a companion, apparently interacting with it, possesses a Seyfert nucleus and demonstrates an unusual shape rotation curve containing a region of very sharp and deep drop of rotational velocity.

The programme observations of the first two morphologically normal galaxies, NGC 6181 and NGC 157, gave interesting and quite unexpected results. Great systematic velocity departures from circular motions (up to some tens of km/s) clearly identified with the wave spiral structure were found in these galaxies. Not only the radial and azimuthal, but also the z component of the perturbed velocity turned out to be essential. The most out-of-ordinary seems the behaviour of gas in a ring (in the galaxy plane) zone 2 kpc in diameter in NGC 6181. The zone shows clearly, without any Fourier analysis, strong radial motions with opposite signs on both sides from the centre up to nearly 100 km/s, if the motion occurs in the disk plane (expanding ring of gas or resonance effects?) (Sil'chenko et al., 1997).

We managed to make reliable velocity estimates for NGC 6181 mainly in the region of spiral arms, whereas in NGC 157 velocities were measured in about 11 thousand points, which made it possible to fully restore the character of gas motion, the perturbed velocity component, related to the spirals, and to estimate parameters of density waves, including the radial velocity of the wave pattern. Anticyclonic streamlines between the spiral arms predicted by theory were really discovered in the region of corotation of the galaxies. The observations have demonstrated new possibilities provided by the available high spatial and spectral resolution facilities.

In conclusion in Table 1 we present a list of spiral galaxies investigated previously in the frames of the programmes mentioned above, whose data reduction was completed or nearing completion in late 1996. The table columns represent certain peculiarities of rotational curves revealed through analysing gas velocities without taking into account the systematic departures from circular velocity related to the spiral-wave structure.

In the first column the "+" sign marks the galaxies having kinematic distinctions within several arcseconds from the nucleus, including also the galaxies with dynamically isolated nuclei, galaxies with a mini-bar or a compact nuclear disk non-complanar with the main disk. The second column indicates the galaxies whose rotational curve has a local minimum (minima) beyond the nuclear region. This feature reflects the character of distribution of mass in the galaxy, or points to ordered non-circular motions in a sufficiently large interval along the radius. In the third column are marked the cases with the rotation curve falling off at the optical disk periphery, which are most rarely revealed from optical measurements in non-interacting galaxies. The galaxies with strong (tens of km/s) non-circular motions of local character are marked in the fourth column. In the fifth column the "+" sign is placed against the galaxies in which the features listed above have not been found. Their small number shows obviously how rare are the "typical" rotational curves, where the velocity growing monotonically with radius changes into a more or less flat plateau.

Table 1

NGC	Type	(1)	(2)	(3)	(4)	(5)
23	Sa	+				
157	Sbc	+		+		
497	Sbc	+	+			
615	Sb	+				
834	Sc	(?)				(?)
895	Sc	+				
972	I0	+			+	
1024	Sab	+				
1084	Sc	(?)			+	
1134	Spec		+	+		
1637	Sc					+
1964	Sb					+
3646	Sc	+				
3810	Sc					+
4100	Sbc	+	+		+	
4357	Sbc					+
4536	Sbc	+		+	+	
4814	Sb				+	
5351	Sb					+
5371	Sbc					+
6181	Sc	+	+		+	
6643	Sc	+				
7013	Sa	+				
7171	Sb	+	+		+	
7217		+	+	(?)		
7331	Sbc	+	+			
7721	Sc		(?)			(?)
U 11973	Sbc	+				

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