NGC 7331: the galaxy with the multicomponent central region

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Partly based on observations collected with the 6m telescope at the Special Astrophysical Observatory (SAO) of the Russian Academy of Sciences (RAS).

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ABSTRACT

We present the results of the spectral investigation of the regular Sb galaxy NGC 7331 with the Multi-Pupil Field Spectrograph of the 6m telescope. The absorption-line indices \( \text{H}\beta \), Mg\( b \), and \( <\text{Fe}> \) are mapped to analyse the properties of the stellar populations in the circumnuclear region of the galaxy. The central part of the disk inside \( \sim 3'' \) (200 pc) – or a separate circumnuclear stellar-gaseous disk as it is distinguished by decoupled fast rotation of the ionized gas – is very metal-rich, rather young, \( \sim 2 \) billion years old, and its solar magnesium-to-iron ratio evidences for a very long duration of the last episode of star formation there. However the gas excitation mechanism now in this disk is shock-like. The star-like nucleus had probably experienced a secondary star formation burst too: its age is 5 billion years, much younger than the age of the circumnuclear bulge. But \([\text{Mg/Fe}]=+0.3\) and only solar global metallicity imply that the nuclear star formation burst has been much shorter than that in the circumnuclear disk. The surrounding bulge is rather old, 9–14 billion years old, and moderately metal-poor. The rotation of the stars and gas within the circumnuclear disk is axisymmetric though its rotation plane may be slightly inclined to the global plane of the galaxy. Outside the circumnuclear disk the gas may experience non-circular motions, and we argue that the low-contrast extended bulge of NGC 7331 may be triaxial.

Subject headings: galaxies: nuclei — galaxies: individual (NGC 7331) — galaxies: evolution — galaxies: structure
1. Introduction

The nearby spiral galaxy NGC 7331, the main parameters of which are given in Table 1, represents a challenge for the observers interested in structure and dynamics of disk galaxies. It has been observed many times, both photometrically and spectroscopically; but results of each new approach contradicted often to results of previous ones. Many years ago Bosma (1981) trying to give a general description of NGC 7331 noted that according to Sandage (1961) who saw spiral arms as close to the center as at \( r \approx 6'' \) NGC 7331 is a disk-dominated galaxy; however the deep photograph reported by Arp and Kormendy (1972) revealed a presence of prominent extended bulge. The problem of the bulge role in NGC 7331 is not solved yet despite numerous photometric studies. Boroson (1981) estimated a bulge-to-disk ratio as 1.10 by analysing a major-axis surface brightness profile. Kent (1987) analysed two-dimensional CCD images and proposed a method of bulge-disk decomposition based on different ellipticities of the bulge and disk isophotes; but he noted that this method is inapplicable to NGC 7331 because in this galaxy the isophotes of the bulge and of the disk demonstrate the same (1) ellipticity. As a result, he decomposed only the major-axis profile and derived \( B/D = 0.66 \) and the disk with a central hole. Among recent studies, von Linden et al. (1996) have published a surface brightness profile in the \( I \)-band extended up to \( R \approx 100'' \) and have concluded that a de Vaucouleurs’ bulge dominates over the whole radius range under consideration, whereas Prada et al. (1996) analysing together \( I \)- and \( K \)-images have reached the best fit with the compact bulge, having effective radius of \( \sim 10'' \), and two exponential disk components with different characteristic scales which meet at \( R \approx 100'' \). So the situation with the morphological characteristics of the bulge in NGC 7331 remains to be uncertain. A similar uncertainty exists relating to a dynamical status of the bulge in this galaxy: Prada et al. (1996) have found the bulge to counter-rotate with respect to the stellar disk basing on the long-slit observations in the Ca IIIR triplet spectral range, but Mediavilla et al. (1997) who observed
the central part of NGC 7331 with a panoramic fiber spectrograph in two spectral ranges, near Mgb and near Ca II IR, do not agree stating that the bulge in NGC 7331 corotates the stellar and gaseous disks.

Another question which is an object of discussion for several years: is there a ”dead quasar”, or supermassive black hole, in the center of NGC 7331? We have begun this discussion ten years ago. Afanasiev et al. (1989) examining the major-axis profile of line-of-sight velocities of the ionized gas have found that central ±2″ (the scale which is comparable to our spatial resolution) are kinematically decoupled by fast solid-body rotation. We have checked the axisymmetric character of the gas rotation and have concluded that this fast rotation is caused by a compact mass concentration of order of $5 \cdot 10^8 M_\odot$. To see if a ”dead quasar” may be in the center of NGC 7331, Bower et al. (1993) have studied major-axis and minor-axis profiles of stellar velocities. Though the angular rotation velocity of stars in the center of NGC 7331 has been found to be as high as that of the ionized gas, namely, about of 500 km/s/kpc, the very central part of the stellar rotation curve has not appeared to be so distinct. Moreover, the stellar velocity dispersion has not a sharp maximum in the center, as it is the case, for example, in M 31 where the presence of the supermassive black hole in the center is proved (Dressler & Richstone 1988, Kormendy 1988). On the contrary, in NGC 7331 $\sigma(r)$ along the minor axis seems to demonstrate a local minimum at $r \approx 0''$. So Bower et al. (1993) have concluded that the mass of the central black hole, if exists, must be less than $5 \cdot 10^8 M_\odot$. However, the problem of the black hole presence in the nucleus of NGC 7331 has not been closed: Cowan et al. (1994) have reported a detection of unresolved nuclear radio source in this galaxy which has appeared to be more luminous by a factor of 3–4 than the famous Sgr A in the center of our Galaxy, and recently Stockdale et al. (1998) have claimed an existence of the nuclear X-ray source in NGC 7331 – they treat it as a massive black hole. If it really exists, its dynamical implications must be re-looked for more carefully.
When Afanasiev et al. (1989) have detected a compact mass concentration in the center of NGC 7331, we have not made a definitive choice between the supermassive black hole and a compact dense stellar subsystem, such as a central star supercluster or circumnuclear stellar disk. Moreover, later we have undertaken a two-dimensional spectrophotometry of the central region of NGC 7331 and have found that its unresolved nucleus is chemically distinct: its magnesium index is much higher than that of the nearest bulge (Sil’chenko et al. 1992). As the kinematically decoupled nucleus in NGC 7331 has been found to be also chemically distinct, we would like to think it to be a separate stellar subsystem. So a more careful investigation of stellar population properties in the nucleus and in the circumnuclear region of NGC 7331 must help to clarify the structure and evolution of its center and of the entire galaxy. We report our observations and other data which we use in Section 2. The brief description of the ionized-gas morphology in the center of NGC 7331 is given in Section 3. Radial variations of the stellar population age and metal abundances are analysed in Section 4, and the kinematics of ionized gas and stars in the region under consideration is discussed in Section 5. Section 6 presents our conclusions and a brief discussion of our results.

2. Observations

The observations of NGC 7331 which results are presented in this paper have been undertaken with the Multi-Pupil Field Spectrograph (MPFS, Afanasiev et al. 1990) of the 6m telescope of the Special Astrophysical Observatory of the Russian Academy of Sciences in 1996.

The red spectral range, 6300–6900 Å, has been exposed on August 19, 1996, during 55 minutes, under the seeing $FWHM \approx 2''4$. The MPFS was equipped with CCD 520 × 580; we registered simultaneously 95 spectra from an area of 19'' × 12''6, each
spectrum corresponding to a spatial element of 1′′.58 × 1′′.58. The strongest emission line in the circumnuclear region, [NII]λ6583, has been measured to construct two-dimensional velocity field of the ionized gas; we fitted its profile by a single Gaussian.

The blue-green spectral range, 4100–5600 Å, has been exposed on October 9, 1996, during 40 minutes, under the seeing FWHM = 1′′.6. The sky has been exposed separately during 20 minutes, properly normalized and subtracted from the galaxy frame. The MPFS was equipped with CCD 1040 × 1160; we registered simultaneously 128 spectra from an area of 11″ × 21″, each spectrum corresponding to a spatial element of 1″.33 × 1″.33. This spectral range includes a lot of strong absorption lines, so we have used this exposure to calculate absorption-line indices Hβ, Mgb, Fe5270, and Fe5335 in the well-known Lick system (Worthey et al. 1994). We have checked our consistency with the Lick measurements by observing stars from their list (Worthey et al. 1994) and by calculating the absorption-line indices for the stars in the same manner as for the galaxies. The indices calculated for 9 stars are coincident with the data tabulated in (Worthey et al. 1994) in average within 0.05 Å. The exposure for the galaxy has been taken long enough to provide a signal-to-noise ratios of ~ 60 in the nucleus and ~ 10–15 near the edge of the frame; the corresponding random error estimations made in the manner of Cardiel et al. (1998) range from 0.2 Å in the center to 0.6–0.7 Å for the individual spatial elements at the outermost points. To keep a constant level of accuracy along the radius, we summed the spectra for the galaxies in concentric rings centered onto the nuclei and studied the radial dependencies of the luminosity-weighted properties of stars by comparing the observational index values to those from the synthetic models of old stellar populations of Worthey (1994) and Tantalo et al. (1998). We estimate the mean accuracy of our azimuthally-averaged indices as 0.1–0.2 Å. Besides, we have cross-correlated each elementary spectrum with the spectrum of the late-type star ADS 15470 (the brighter component) and have obtained two-dimensional velocity field for the stellar component of the central region of NGC 7331.
The reciprocal dispersion during these observations was 1.6 Å per pix, and the spectral resolution varied slightly over the field of view from 3.5 Å to 5 Å. As a result, we estimate our accuracy of the elementary line-of-sight velocities as 20–25 km/s. However, our spectral resolution allowed to obtain only luminosity-weighted mean line-of-sight velocities; we were not able to separate kinematical components similar to the counterrotating bulge reported by Prada et al. (1996).

To refine kinematical analysis, we have involved high-resolution long-slit data from the La Palma Archive. The galaxy has been observed on July 19, 1996, with the ISIS (red arm) equipped with CCD TEK 1024 × 1024 at the William Herschel Telescope. The near-infrared spectral range, 8360–8750 Å, containing the strong CaII absorption-line triplet, has been exposed: 60 min in the P.A. = 172° (major axis) and 30 min in the P.A. = 262° (minor axis). The slit width was 0.95″; the reciprocal dispersion of 0.39 Å per pix provided spectral resolution of 1.0 Å. A star HR 8656 (K0III) was observed during the same night; we have cross-correlated the galaxy spectra row-by-row with the spectrum of this star after binning by three pixels (with the final spatial step of 1″), sky subtracting and transforming into velocity scale. The subsequent Gauss analysis of obviously multi-component LOSVDs (line-of-sight velocity distributions) has allowed to extract several kinematical components along the slit aligned with the major axis of the galaxy.

The basic reduction steps – bias subtraction, flatfielding, cosmic ray hit removing, extraction of one-dimensional spectra, wavelength calibration, construction of surface brightness maps – have been fulfilled by using the software developed in the Special Astrophysical Observatory (Vlasyuk 1993). To calculate the absorption-line indices and to map them we have used our own programs as well as the FORTRAN program of Dr. Vazdekis.
3. Morphology of the Ionized Gas Distribution in the Center of NGC 7331

Fig. 1 shows raw observational data – so called ”data cube” – in the red spectral range. One can see immediately that a characteristic ratio of emission lines, $H\alpha$-to-$[\text{NII}]\lambda6583$, indicates a LINER-like excitation inside the central region, roughly $16'' \times 10''$, but a rather strong present star formation already in $11''$ to the east (along the minor axis) from the nucleus. This fact contradicts to the claims of Keel (1983) who observed the spectra in $10''$ to the north, south, and east (!) from the nucleus and everywhere had found the dominance of $[\text{NII}]\lambda6583$ over $H\alpha$. But his aperture, $8''1$, was perhaps too large to distinguish between the central shock-excited gaseous disk and nearby star-forming sites which are concentrated in a ring with a deprojected radius of $45''$ (or $15''$ on the sky plane along the minor axis). This ring is presented best of all in the recent paper of Smith (1998). It looks quite identical at different wavelengths: on the $H\alpha+[\text{NII}]$ map from Pogge (1989), on the $15\mu\text{m}$ map from Smith (1998), on the Nobeyama CO (1-0) map from Tosaki and Shioya (1997), and on the $20\text{ cm}$ radio continuum map from Cowan et al. (1994). Obviously, this multiple coincidence together with $H\alpha/[\text{NII}]\lambda6583 > 2$ in our Fig. 1 proves that this ring contains sites of intense present star formation, including formation of massive stars. If we accept the surface-brightness profile decomposition from Boroson (1981) or from Baggett et al. (1998), this star-forming ring is located well inside the bulge-dominated area.

The nature of the very central region is not so obvious. Fig. 2 presents isophotes of the $[\text{NII}]$ emission-line surface brightness distribution obtained with the MPFS. They are elongated and repeat approximately the shape of continuum isophotes. The consistent results are obtained by Mediavilla et al. (1997) (see their Fig. 9); even an asymmetry ”north-south” is the same. Keel (1983) also mentioned a gaseous disk with the radius of $2''$ having the diffuse extension up to $10''$ aligned in the $P.A. = 165^\circ$, close to the line-of-nodes orientation. Interestingly, the similar elongated structure, with the major-axis diameter
of $7'' - 9''$, is present on the 15$\mu$m map of Smith (1998), but the sense of the north-south asymmetry is opposite with respect to the [NII] map. Probably, the explanation of this asymmetry by the dust concentration to the south from the nucleus given by Mediavilla et al. (1997) is correct. There are no either HI (Begeman 1987) nor CO (Tosaki & Shioya 1997) inside this circumnuclear structure; also it is undetected in radio (Cowan et al. 1994). Therefore, there is no detectable present star formation there; but the gas is probably shock-excited, and the dust is warm. As the structure is aligned with the line of nodes, we would like to treat it preliminarily as a circumnuclear gaseous disk.

4. Stellar Population Properties in the Circumnuclear Region of NGC 7331

Figure 3 presents isolines of the surface distributions in the central $9'' \times 10''$ area for the green (5100 Å) continuum and three absorption-line indices, Mgb, $< \text{Fe}> \equiv (\text{Fe}5270+\text{Fe}5335)/2$, and H$\beta$. The continuum isophotes show a strange asymmetry: within $3''$ from the center eastern halves of them seem to be more tightly packed than their western halves. It looks like a some extracomponent of light to the west from the nucleus. Interestingly, on larger scales the sense of isophote crowding is opposite due to global dust concentration on the western side of the galaxy (Boroson 1981, Smith 1998). The magnesium-index isolines are rather roundish; the distribution is strongly peaked on the nucleus of the galaxy (NGC 7331 has a chemically distinct nucleus, as we noted earlier, Sil’chenko et al. 1992). But the surface distribution of another metal-line index, $< \text{Fe}>$, is quite different from that of Mgb and can partly explain an asymmetry of the continuum isophotes. In Fig. 3c we clearly see a compact Fe-rich disk shifted to the west from the nucleus (or do we see only its western half?). A strong north-south asymmetry is present too. If we assume that we see only south-western quarter of the disk, its radius may be as large as 3.5. This size agrees with the size of the central mid-infrared structure (Smith
But what is the most interesting thing, it is the similar surface distribution of the hydrogen-line index H$\beta$ (Fig. 3d): the circumnuclear Fe-rich disk is also distinguished by the very prominent Balmer absorption line. Since iron and hydrogen absorption lines in integrated spectra are unmatched being produced by different groups of stars, the similarity of the Fig. 3c and Fig. 3d may signify that the circumnuclear Fe-rich stellar disk is rather young. Let us look at what state-of-art diagnostics of the stellar population properties can tell us.

To compare our measurements to the stellar population models based on summation (with some weights) of spectra of stars, we must make corrections for the stellar velocity dispersion in galaxies which broadens absorption lines and "degrades" a spectral resolution in such way. We have calculated the correction by smoothing the spectra of K0-K3 III giants from the list of (Worthey et al. 1994) which we have observed and by measuring the absorption-line indices of the smoothed spectra. We have found that the index H$\beta$ is quite insensitive to the velocity dispersion when $\sigma_v$ remains to be less than 230 km/s; as for the metal-line indices, we have found the correction to be 0.1 $\AA$ for $\sigma_v$=130 km/s which is typical for the central part of NGC 7331 (Bower et al. 1993). Figures 4 and 5 contain the corrected indices.

The most popular models of Worthey (1994) allow to disentangle age and metallicity of old stellar populations by confronting some metal-line indices (e. g. Mgb, $<Fe>$, or $[MgFe] \equiv (Mgb < Fe>)^{1/2}$) with the Balmer-line index H$\beta$; but these models have been calculated for the solar magnesium-to-iron ratio. To use the Worthey’s (1994) models, we must be sure that the stellar population has solar magnesium-to-iron ratio. Figure 4 presents the diagram (Fe5270, Mgb) where we compare azimuthally-averaged (in circular rings centered onto the nucleus) index measurements in NGC 7331 with the models of Worthey (1994) for the solar magnesium-to-iron ratio. Since the circumnuclear Fe-rich disk
seen in Figs. 3c and 3d is located asymmetrically with respect to the nucleus and contributes only partially to the ring-integrated estimates at $r = 1''3$ and $r = 2''6$, we have also plotted individual-element measurements related to this disk though they are less accurate than azimuthally-averaged ones. One can see from Fig. 4 that the nucleus of NGC 7331 is surely magnesium-overabundant. The Mg/Fe ratio for the azimuthally-averaged measurements at $r = 1''3$ and $r = 2''6$ is obviously lower than that for the nucleus, but is it solar or not, depends on the stellar population age. Farther from the nucleus, at $r \geq 4$, the moderate magnesium overabundance can also be seen. Interestingly, the proper measurements of the circumnuclear Fe-rich disk lie much higher that the azimuthally-averaged points: the disk has the solar Mg-to-Fe ratio if it is as young as 2 billion years old and is iron-overabundant if it is older.

Taking in mind all said above, let us try to determine mean ages of stars in the nucleus and at different distances from the center. Figures 5a, 5b, and 5c present various diagrams which may be useful for this purpose. As the nucleus is magnesium-overabundant, the models of Worthey (1994) are inapplicable for it; in Fig. 5a we have plotted the calculations of Tantalo et al. (1998) for $[\text{Mg/Fe}]=+0.3$. From comparison with these models on the diagram ($\text{H}$$\beta$, $<\text{Fe}>$) one can see that the mean age of the nuclear stellar population in NGC 7331 is 5 billion years, and its global metal content, $Z$, is close to the solar value. Fig. 5b shows also the models from Tantalo et al. (1998), but for the solar magnesium-to-iron ratio; the locations of the azimuthally-averaged points at the $r = 1''3$ and $r = 2''6$ imply similarly a rather young age for the nearest neighborhood of the nucleus. The elementary measurements related to the circumnuclear Fe-rich disk, though well scattered, nevertheless all lie above the model sequence with the age of 5 billion years. The next Fig. 5c presenting the diagram ($\text{H}$$\beta$, $[\text{Mg Fe}]$) with the models of Worthey (1994) calculated under $[\text{Mg/Fe}]=0$ confirms that four individual points for the circumnuclear Fe-rich disk agree with the age estimate of 2 billion years and the overall metallicity at least
twice the solar one. If we return now to Fig. 4, we should conclude that the circumnuclear "Fe-rich" disk has indeed [Mg/Fe]=0 under the assumption of $T = 2$ billion years.

The work of Tantalo et al. (1998) proposes also a possibility to quantify differences of stellar population properties basing on the index differences. A set of three linear equations, connecting $\Delta[\text{Mg/Fe}]$, $\Delta \log Z$, and $\Delta \log T$ to the $\Delta \text{Mg}_2$, $\Delta <\text{Fe}>$, and $\Delta \text{H}\beta$, is written. We apply these equations to the differences between the nucleus and the bulge; the bulge is safely taken at the following values of radius, at $r = 4''$, $5.3''$, $6.7''$, and $8''$, namely, outside the circumnuclear "Fe-rich" disk but well inside the star-forming ring. Solely, one must take in mind that the index measurements at $r > 6''$ are twice less precise than the more inner ones so they can be used mostly as a check. Having performed the set of calculations, we have obtained the parameter differences listed in Table 2. They mean that the bulge is twice older and more metal-poor by a factor of 2.5–4 than the nucleus. Surprisingly, the Mg/Fe ratios are almost equal in the nucleus and in the bulge. When we compare the absolute values of nuclear indices, Mg$_2 = 0.229 \pm 0.005$, $<\text{Fe}> = 2.66 \pm 0.22$, and H\beta = 1.83 $\pm 0.19$, to the direct model calculations of Tantalo et al. (1998), we see that the model with $Z = 0.02$ (solar value), [Mg/Fe]=+0.3, and $T = 5$ billion years has consistent index values. Then the bulge stellar population parameters are $Z = 0.005 - 0.008$, [Mg/Fe]=+0.2, and $T = 9 - 12$ billion years. The latter age estimate agrees also with the positions of bulge points in Fig. 5a.

The analysis undertaken in this Section has allowed to identify three quite different stellar structures within 8\" ($\sim 600$ pc) from the center. The unresolved star-like nucleus is rather young, $5 \cdot 10^9$ years old, strongly magnesium-overabundant and has solar global metallicity. Farther out, the circumnuclear disk with a radius of $\sim 3''$ is even younger, $\sim 2$ billion years old, has the solar Mg-to-Fe ratio, and the global metallicity higher than the solar one. The surrounding bulge is older than the nucleus and the circumnuclear disk,
Table 1: Global parameters of NGC 7331

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type (NED)</td>
<td>SA(s)b</td>
</tr>
<tr>
<td>$R_{25}$, kpc (LEDA)</td>
<td>22.5</td>
</tr>
<tr>
<td>$B_0^1$ (LEDA)</td>
<td>9.27</td>
</tr>
<tr>
<td>$M_B$ (LEDA)</td>
<td>-21.41</td>
</tr>
<tr>
<td>$V_r(radio)$ (LED)</td>
<td>821 km·s$^{-1}$</td>
</tr>
<tr>
<td>Distance, Mpc (Hughes et al. 1998)</td>
<td>15.1</td>
</tr>
<tr>
<td>Inclination (LEDA)</td>
<td>70°</td>
</tr>
<tr>
<td>$PA_{phot}$ (LED)</td>
<td>171°</td>
</tr>
</tbody>
</table>

Table 2: Stellar population parameter differences "bulge-nucleus"

<table>
<thead>
<tr>
<th>Radius, $''$</th>
<th>$\Delta$[Mg/Fe]</th>
<th>$\Delta$ log $Z$</th>
<th>$\Delta$ log $T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>-0.09</td>
<td>-0.39</td>
<td>+0.26</td>
</tr>
<tr>
<td>5.3</td>
<td>-0.17</td>
<td>-0.41</td>
<td>+0.29</td>
</tr>
<tr>
<td>6.7</td>
<td>-0.16</td>
<td>-0.62</td>
<td>+0.46</td>
</tr>
<tr>
<td>8</td>
<td>-0.07</td>
<td>-0.58</td>
<td>+0.27</td>
</tr>
</tbody>
</table>
namely, is 9–12 billion years old, magnesium-overabundant and moderately metal-poor.

5. Kinematics of Gas and Stars

Two-dimensional line-of-sight velocity fields for stars and ionized gas obtained with the MPFS are presented in Fig. 6. Both fields look rather regular and show clear signs of rotation. However there are some differences between velocity fields of stars and gas. As we noted earlier (Afanasiev et al. 1989), the gas rotation curve has a sharp local maximum at $R \approx 2''$, and we see a consequent feature to the north-west from the center in Fig. 6b (it is somewhat farther than it must be due to a seeing quality worse with respect to that of our long-slit observations). Meantime the rotation velocity of stars rises continuously with radius – rapidly up to $R \approx 5''$ and more slowly farther from the center (Bower et al. 1993, Prada et al. 1996), and consistently, Fig. 6a has no closed isovelocities.

Two-dimensional velocity fields can allow to check an axisymmetric character of rotation. If we have an axisymmetric mass distribution and rotation on circular orbits, the direction of maximum central line-of-sight velocity gradient (we shall call it ”dynamical major axis”) should coincide with the line of nodes as well as the photometric major axis; whereas in a case of triaxial potential the isovelocities align with the principal axis of the ellipsoid, and generally the dynamical and photometrical major axes diverge showing turns with respect to the line of nodes in opposite senses (e. g. Monnet et al. 1992). In a simple case of cylindric (disk-like) rotation we have a convenient analytical expression for the azimuthal dependence of central line-of-sight velocity gradient within the area of solid-body rotation:

$$\frac{dv_r}{dr} = \omega \sin i \cos (P.A. - P.A_{-0}),$$
where $\omega$ is a deprojected central angular rotation velocity, $i$ is an inclination of the rotation plane, and $P.A._0$ is an orientation of the line of nodes.

We have fitted the data presented in Fig. 6a by this formula and have obtained for the gradients taken within $r \leq 2''$:

$$\frac{dv_r}{dr} = [33 \cos(P.A. - 183^\circ) - 2.5] \text{ km s}^{-1} \text{ arcsec}^{-1}.$$  

The amplitude of the cosine curve, $\omega \sin i = 33 \text{ km s}^{-1} \text{ arcsec}^{-1}$, agrees rather well with the central slopes of the major axis long-slit cross-sections obtained for the stellar component of NGC 7331 by Bower et al. (1993) and by Prada et al. (1996). Moreover, it agrees rather well with the rotation velocity of ionized gas within the kinematically decoupled region: in Afanasiev et al. (1989) we reported an azimuthal dependence of the central line-of-sight velocity gradients based on the long-slit [$\text{NII}$$\lambda$6583 emission line measurements in four different position angles, the best-fitted cosine curve formula for which was:

$$\frac{dv_r}{dr} = [38.4 \cos(P.A. - 175^\circ) + 1.3] \text{ km s}^{-1} \text{ arcsec}^{-1}.$$  

The phases of these two cosine curves are close too; but together they evidence for a marginal turn of the dynamical major axis with respect to the line of nodes which has $P.A. = 166^\circ - 167^\circ$ (Prieto et al. 1992, von Linden et al. 1996). It would be a signature of a triaxial potential, if the photometric major axis turns in opposite sense, to lesser $P.A.$.

But indeed it turns in the same sense! Numerous photometric studies detected a turn of the photometric major axis in NGC 7331 to $P.A. \approx 175^\circ - 183^\circ$ inside $R = 6'' - 8''$
(somewhat different in different works). It is also known that this turn is stronger at shorter wavelengths. For example, Prieto et al. (1992) have measured the following orientations of the isophote major axis at $R \approx 4''$: $P.A. \approx 182^\circ$ in the $B$-band, $P.A. \approx 179^\circ$ in the $V$-band, and only $P.A. \approx 176^\circ$ in the $I$-band; the asymptotic $P.A.$ value at larger radii given by them is $166^\circ$. Up to now the common point of view is that it is a dust effect which must be wavelength-dependent. But in the center of NGC 7331 the dust is still visible in the $I$-band, however, the measurements of $P.A.$ in the $I$- and in the $K$-bands agree well (Prada et al. 1996). There may be another explanation: if there is a blue (young) misaligned stellar disk inside the red (older) bulge, the measurements of combined isophotes should show a stronger turn through the bluer filter. The coincidence of the dynamical and photometrical major axes at $P.A. \approx 180^\circ$ reveals a presence of inclined circumnuclear stellar disk, rather rapidly rotating.

The long-slit observations made under higher spectral resolution may help to clarify a dynamical structure of the central region of NGC 7331. The similar observational data taken along the major axis of the galaxy in 1992 August have allowed Prada et al. (1996) to claim a presence of counterrotating bulge in NGC 7331. Here we present the later results for the major-axis and minor-axis cross-sections. Fig. 7 shows a direct view of the LOSVD calculated along the major axis, and Figs. 8a and 8b – the results of multi-component Gauss analysis of the LOSVDs.

One can immediately see a difference between our Fig. 7 and the analogous Fig. 3 of Prada et al. (1996). The description of the latter included only two kinematical components: fast-rotating disk and retrograde bulge rotating more slowly and seen only in the radius range of $5'' - 15''$. Prada et al. (1996) claimed an absence of prograde bulge. Meantime even a single glance at our Fig. 7 reveals two quite noticeable prograde structures: a fast-rotating disk and a slower rotating prograde bulge seen up to $\sim 35''$ from
the center. The retrograde component is seen too, but it is not so prominent as it seemed to be in Fig. 3 of Prada et al. (1996). Since our long-slit data were obtained with the same equipment – the ISIS, red arm, of the WHT, – and the template star is of the same spectral type as that of Prada et al. (1996), we can only refer to our better spectral resolution – 35 km/s (their spectral resolution was reported as 52 km/s).

Fig. 8a displays the results of Gauss analysis of the LOSVD along the major axis P.A. = 172° together with stellar velocity profiles derived without component separation, namely, together with the recent data of Heraudeau & Simien (1998) obtained under seeing of 2.5′′ and with the simulated one-dimensional profile calculated from our MPFS two-dimensional velocity field shown in Fig. 6a. By analysing the long-slit data, we have extracted three kinematical components. The first, fast-rotating component dominates over the full range of radii. Since according to Prada et al. (1996) at $R \geq 5''$ its stellar velocity dispersion does not exceed 70 km/s, we would treat it as a disk. The second component, corotating with the first one and seen at $R \geq 5''$, rotates much slower than the first one, so we would conclude that it is an ordinary bulge; but it dominates nowhere, and that is very strange for the early-type spiral galaxy with extended photometric bulge. Interestingly, its nearly solid-body slow rotation up to $R \approx 45''$ matches perfectly the rotation of the ionized gas at $R > 2''$ (see Fig. 1 in our work, Afanasiev et al. 1989, or the lower resolution Hα data in Marcelin et al. 1994) while the rotation curve of the dominant stellar component, disk, diverges strongly with the gas rotation curve. Finally, the third component counter-rotates with respect to the main stellar and gaseous rotation; it is just the same component which was reported by Prada et al. (1996) as a "retrograde bulge". But there is some ambiguity with this diagnosis: in their Conclusions Prada et al. (1996) stated that "the inner parts of the galaxy consists of a boxy component, dominating the inner 5''. It shows position angle twisting, rotates retrograde to the rest of the galaxy, and is rounder"; meantime the retrograde component is seen only in the narrow radius range $5'' < R < 20''$ according both
to the data of Prada et al. (1996) and ours! Besides, its velocity dispersion is as low as that of the disk (Prada et al. 1996), and it rotates faster than the prograde bulge though slower than the disk. So it does not resemble a bulge; it must be a rather flat structure.

The central 5″ contains only one inseparable component; but at $R \approx 5″$ it meets perfectly the disk component. As it looks like a straight solid-body rotation curve, we would identify it with a central part of the disk rotation profile. An increased velocity dispersion inside $R \approx 5″$ which has been reported by Prada et al. (1996) is probably a result of adding slower rotating, weaker components. However, we can conclude that from a dynamical point of view the disk dominates over the whole central region of NGC 7331.

6. Discussion

We can summarize our conclusions as follows. In the Sb galaxy NGC 7331 the stellar disk is a kinematical component dominating over the full radius range. The bulge is less prominent though it can be traced up to $R \approx 45″$ (3.3 kpc); its slow solid-body rotation is very similar to the main rotation of the ionized gas. We confirm also an existence of the counter-rotating stellar component in the radius range of $5″ – 20″$ (400 – 1500 pc). The central part of the disk inside $\sim 3″$ (200 pc) – or a separate circumnuclear stellar-gaseous disk as it is distinguished by decoupled fast rotation of the ionized gas – is very metal-rich, rather young, $\sim 2$ billion years old, and its solar magnesium-to-iron ratio evidences for a very long duration of the last episode of star formation there. However the gas excitation mechanism in this disk now is shock-like. The star-like nucleus had probably experienced a secondary star formation burst too: its age is 5 billion years, much younger than the age of the circumnuclear bulge. But $\text{[Mg/Fe]}=+0.3$ and only solar global metallicity imply that the nuclear star formation burst has been much shorter than that in the circumnuclear disk.
Up to now two-dimensional mapping of the absorption-line equivalent widths (or indices) is rarely used to investigate stellar population properties in galaxies. Practically unique examples of such approach are a long-slit combined study of the center of M 31 by Davidge (1997) and a detailed TIGER investigation of NGC 4594 by Emsellem et al. (1996). The latter case appears to be something similar to the case of NGC 7331: the magnesium-index map of the center of NGC 4594 demonstrates a point-like peak in the nucleus of the galaxy, and the iron indices are roughly constant along the major axis up to the border of the area investigated, $R \approx 5''$ (Emsellem et al. 1996). So the isolines of the iron indices in NGC 4594 present something like the Fe-rich circumnuclear stellar disk found by us in NGC 7331. Though the measurements of Mgb index in NGC 4594 are complicated by a presence of the rather strong emission line [NI]λ5199 (Emsellem et al. 1996) and though two examples are not a statistics yet, perhaps, there exists some evolutionary sense in different morphologies of magnesium- and iron-index surface distributions.

An interesting problem is an origin of the counter-rotating component. Usually counter-rotating stellar substructures are considered as a result of merger. Some merger event could also provoke a secondary star formation burst in the center of the galaxy in this way producing the chemically distinct nucleus and, if the merger was dissipative, the inclined circumnuclear disk. However, the circumnuclear Fe-rich disk in NGC 7331 rotates in the same sense as the rest of the galaxy and so cannot be genetically related to the counter-rotating component. Recently we have found a counter-rotating stellar component in the nearby spiral galaxy NGC 2841 (Afanasiev & Sil’chenko 1999). NGC 2841 and NGC 7331 look almost twins: the same morphological type, Sb, the same size and luminosity, the same inclination. They were the first galaxies where a global ring-like distribution of CO has been detected (Young & Scoville 1982). Analysing the major-axis long-slit cross-section of NGC 2841, we have found two kinematical components in the bulge: strong prograde one which dominates up to $R \approx 25''$ and weak retrograde one
A set of other phenomena allow us to suggest an existence of extended triaxial bulge almost aligned with the line of nodes of the global disk in this galaxy, and we have thought the counter-rotating stellar component to be an intrinsic property of a slightly tumbling triaxial potential. Perhaps the similar situation takes place in NGC 7331; the only difference is that in NGC 7331 the disk dominates over the full radius range whereas in NGC 2841 the bulge is more prominent. A hypothesis of the bar presence in the center of NGC 7331 has already been proposed by von Linden et al. (1996) to explain a central depletion of molecular gas in this galaxy. Besides, the French team (Marcelin et al. 1994) have constructed a global two-dimensional velocity field of the ionized gas in NGC 7331 from their observations of Hα emission line with a scanning Fabry-Perot interferometer and have found a strong large-scale turn of the isovelocities which is usually treated as a signature of bar presence. Now we can add another argument in favor of a triaxial potential aligned with the line of nodes: inside \( R \approx 40'' \) the gas in NGC 7331 rotates more slowly than the stellar disk, and it is valid both for the ionized gas (Rubin et al. 1965, Afanasiev et al. 1989, Marcelin et al. 1994) and for the molecular gas (von Linden et al. 1996). Since the emission lines are narrow (below the spectral resolution) and the gas seems to be well-settled to the global plane of the galaxy (Bosma 1981, von Linden et al. 1996), the only explanation can be non-circular rotation of the gas caused by the triaxial potential of the bulge. The stronger response of the gaseous disk to the triaxial potential of the bulge when compared to the response of the stellar disk may be explained by a viscous nature of the gas and by a significant self-gravitation of the massive stellar disk of NGC 7331 which is a dominant dynamical component in this galaxy. Interestingly, the solid-body part of the gas rotation curve, or a zone of non-circular motions as we think, ends at \( R = 40'' - 45'' \) – exactly at the ring of molecular gas, warm dust, and intense star formation which we have discussed in Section 3. The configuration looks like an HII ring around a bar which is often observed in classic barred galaxies. Probably, the low-contrast
triaxial bulge extends up to 40″ \div 50″ from the center in NGC 7331.

The last interesting question concerns a possible presence of the black hole in the center of NGC 7331. In Afanasiev et al. (1989) we argued that the fast decoupled axisymmetric rotation of the ionized gas inside $R = 2″$ proved strong mass concentration in the nucleus; this mass concentration might be a black hole. But Bower et al. (1993) have noticed no decoupled rotation by studying a stellar component; and what is the most important, they have not found a peak of stellar velocity dispersion in the nucleus. How can we agree gas and star behaviours? In Afanasiev et al. (1989), Zasov and Sil’chenko (1996) we noted that a misaligned minibar in the center of a galaxy may mimic a presence of kinematically decoupled nucleus by increasing a visible central slope of the major-axis velocity profile due to non-circular motions. But in NGC 7331 the situation is more complex: the rotation of the gas and stars in the very center is circular, and the bar effect (non-circular gas motions) is felt only outside the zone of decoupled rotation. However, the result is the same: the nucleus looks kinematically decoupled though no point-like central mass concentration is required for this. By summarizing, since Cowan et al. (1994) and Stockdale et al. (1998) have found the unresolved radio- and X-ray source in the center of NGC 7331, it may be a black hole, but it cannot be a supermassive black hole, like those in NGC 4594, NGC 3115, and M 87, because its dynamical influence is nowadays indeterminate. As supermassive black holes are now detected in some three dozens galaxies, a correlation is found between black hole mass and galactic spheroid luminosity. By using this relation taken e. g. from Cattaneo et al. (1999) one can try to estimate a possible black hole mass in the center of NGC 7331. Unfortunately, as we have noted in the Introduction, the bulge-disk decomposition in NGC 7331 is ambiguous: if the bulge is large as Boroson (1981) or Baggett et al. (1998) reported, the black hole mass may be $10^9 M_\odot$, if it is small like that reported by Prada et al. (1996), the mean relation $M_{BH}$ vs. $L_{B, bul}$ implies $M_{BH} = 10^8 M_\odot$ for NGC 7331. If we take also into account the large scatter of this relation (Cattaneo et
al., 1999, give $\sigma = 0.74$) and the impression that the $M_{BH}$ estimates for spiral galaxies lie all below the mean relation defined mostly by ellipticals, the mass of the black hole in the center of NGC 7331 may be as small as $3 \cdot 10^7 M_\odot$. This value contributes only several percents into the total mass of the circumnuclear disk ($5 \cdot 10^8 M_\odot$, Afanasiev et al., 1989), so it may be undetectable in kinematical studies of moderate spatial resolution like ours.

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Fig. 1.— An example of raw data cube: small pieces of spectra containing emission lines Hα and [NII]λ6548,6583 are displayed on the gray-scaled continuum image. P.A.(top) = 97°, N is to the left, south is to the right.

Fig. 2.— Isophotes of the emission line [NII]λ6583 surface brightness distribution on the gray-scaled continuum λ6500.

Fig. 3.— Isolines of the surface distributions of: a – continuum brightness at λ5100, b – the absorption-line index Mgb, c – the absorption-line index < Fe >, d – the absorption-line index Hβ. The continuum is calibrated in arbitrary units; the indices are in the Lick system multiplied by 100. The cross marks the position of continuum peak brightness.

Fig. 4.— Comparison of our observational data for NGC 7331 with the models of Worthey (1994) for [Mg/Fe]=0 on the diagram (Fe5270, Mgb). The points connected by a dashed line are azimuthally averaged and taken along the radius with the step of 1''3. The ages of the Worthey’s (1994) models are given in billion years.

Fig. 5.— The age-diagnostics diagrams for NGC 7331: a – Hβ vs < Fe >, the models of Tantalo et al. (1998) for [Mg/Fe]=+0.3 valid for the nucleus and for the bulge at R > 3'', b – Hβ vs < Fe >, the models of Tantalo et al. (1998) for [Mg/Fe]=0.0 valid for the circumnuclear disk, c – Hβ vs [MgFe], the models of Worthey (1994) for [Mg/Fe]=0, valid for the circumnuclear disk. The points connected by a dashed line are azimuthally averaged and taken along the radius with the step of 1''3; the points corresponding to the Fe-rich circumnuclear disk are for individual spatial elements. The ages of the models are given in billion years; the metallicities for the Worthey’s models are +0.50, +0.25, 0.00, −0.22, −0.50, −1.00,−1.50, −2.00, if one takes the signs from the right to the left, and for the models of Tantalo et al. they are +0.4, 0.0, and -0.7.

Fig. 6.— Two-dimensional line-of-sight velocity fields for the stars (a) and for the ionized
gas (b). The cross marks the position of the continuum peak brightness.

Fig. 7.— The direct view of the stellar LOSVD along the major axis of NGC 7331 obtained from the long-slit data. The horizontal axis is a velocity direction, with the full range of 2250 km/s; the vertical axis is a spatial direction (along the slit), with the full range of 111″, the nucleus is at the middle.

Fig. 8.— Line-of-sight stellar velocity profiles along the major axis (a) and along the minor axis (b) obtained for NGC 7331 from the long-slit data.