Bull. Spec. Astrophys. Obs., 2001, 51, 123-139

Investigation of chemically decoupled nuclei of galaxies with the Multipupil spectrograph of the 6 m telescope of SAO RAS

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Abstract. A brief review of the investigation of chemically decoupled galactic nuclei in early-type galaxies performed with the Multipupil spectrograph of the 6 m telescope over the last ten years is presented. A relation of chemically decoupled stellar nuclei to the circumnuclear stellar disks is discussed. Some examples are demonstrated of the inner polar gas rings in morphologically undisturbed spiral galaxies — a phenomenon that we have first discovered and, possibly, connected with the origin of chemically decoupled nuclei. The first attempt has been made to statistically generalize the results of determination of the age and the ratio of magnesium and iron abundances in stellar populations of both chemically decoupled nuclei and bulges surrounding them.

Key words: galaxies: nuclei — galaxies: spiral — galaxies: structure — galaxies: abundances

1. The history of discovery of chemically decoupled nuclei of galaxies

The history of detection and investigation of chemically decoupled nuclei of galaxies began in 1989, when the first version of the Multipupil Spectrograph (Afanasiev et al., 1990) was placed in service at the Special Astrophysical Observatory. As early as in the first tests, a problem of studying chemical composition of stellar nuclei of galaxies and circumnuclear regions in normal early type galaxies was claimed. In the green range of the spectrum, near $\lambda = 5000$ Å where strong metal lines are placed, in particular magnesium and iron, panoramic spectral data were obtained for 12 nearby bright galaxies of morphological types from E to Sb; the galaxies were chosen actually at random. And at once, 7 out of these 12 galaxies were found to have chemically decoupled nuclei: one elliptical, three lenticulars and three spirals. That a nucleus is chemically decoupled was diagnosed first of all by the jump of the absorption line MgI λ 5175 equivalent width in the integrated spectrum: the EW (Mg) in the nucleus was not infrequently by 1-2 Å larger than the EW in the bulge. After the exclusion of the nucleus the magnesium line equivalent width gradient along the radius proved to be negligibly small as compared to the value of the jump between the nucleus and the bulge. Since according to the models of evolutionary synthesis of stellar populations including ours (Sil'chenko, 1984), the line MgI λ 5175 was first of all known as an indicator of the mean metallicity of the stellar population, we interpreted the magnesium line equivalent width jump between the nucleus and the bulge as a sign of the chemical, and therefore of the evolutionary detachment of stellar nuclei of galaxies: they are not only the central parts of bulges but represent independent structures with their particular evolution. We published these results in 1992 (Sil'chenko et al., 1992).

In the same years a paper by Bender and Surma (1992) appeared in which it was reported on the detection of chemically decoupled nuclei in 4 elliptical galaxies, where a rapid rotation of circumnuclear regions had earlier been recorded. This fast rotation is constrained by the same radius as is the region of increased value of the index (equivalent width) of the magnesium absorption line. Thus, at least in elliptical galaxies, chemically decoupled nuclei are decoupled also dynamically. Surma and Bender (1995) suggested later that the matter in question is circumnuclear compact stellar disks "embedded" fully in a stellar spheroid and formed in the secondary star formation burst that occurred within the galaxy centre. If this hypothesis is true, chemically decoupled nuclei must be distinguished also for a younger average age of stars, and, besides, morphological and kinematic features of compact stellar disks must be observed in the circumnuclear region.

To avoid blind quest for chemically decoupled nuclei in galaxies, we made use of the summary of literature data on the multi-aperture photoelectric study of galaxies by Longo and Vaucouleurs (1983, 1985) to make a list of the most probable candidates. The matter is that the enhanced metallicity shows itself not only by deeper metal lines in integrated spectra, it also results in a redder colour of the stellar population. That is why, using our own modification of the Kholonevsky's method, we separated galaxies in which the nucleus is distinguished from the bulge by a redder colour; such galaxies turned out to account for 25% to 50% amongst the morphological types from E to Sb, and the list of only northern sky objects numbered 34 galaxies (Sil'chenko, 1994). It remained only to check whether the red colour is due to the enhanced metallicity, but not to the dust concentration. Since that time our searches for chemically decoupled nuclei in galaxies have become systematic and ordered.

2. What we obtain with the MPFS now

In 1989, we started our investigation of central regions of galaxies with the MPFS by summing up the spectra in the concentric ring zones, thus keeping an approximately constant signal-to-noise ratio along the radius, and only after that we computed the absorption line equivalent widths. Later, with the appearance of CCD detectors, the amount of information that we came to obtain from a single exposure with the MPFS considerably increased. We passed gradually to extract a full set of characteristics for each element of the array of micropupils. It is now a real two-dimensional spectroscopy.

The investigation of a galaxy consists in that using the MPFS we obtain sets of spectra with a mean dispersion of 1-2 Å/px in two ranges: 4800–5400 Å (green range) and 6200–6900 Å (red range). The green range contains strong stellar absorption lines H_β, MgI λ 5175, FeI λ 5270 and 5335. It is used to determine the average metallicities and the age of the stellar population from the absorption line equivalent widths in each spatial element and also for the investigation of stellar kinematics. The latter goal is achieved by cross-correlation of the spectra of the elements with the spectrum of the star (generally of class G8III-K2III), which serves as a line-of-sight velocity standard. The line-of-sight velocity of the galaxy stellar component in a given point is determined from the position of the cross-correlation peak. The velocity dispersion of stars in a given point is determined from the width of the peak provided that its shape is well fitted by a Gaussian. The red range of the spectrum contains strong ionized gas emission lines Hα, [NII] λ 6583 (as a rule, the strongest line at the centres of early-type disk galaxies) and [SII] λ 6717 and 6731. We use these lines to investigate first of all the ionized gas kinematics: the ionized gas line-of-sight velocity at a given point is measured by calculation of the baricentre of the emission peak or by a direct Gauss analysis. The map of the emission surface brightness distribution can give an idea of the circumnuclear gas disk orientation.

Let us dwell in more detail upon the determination of the age and metallicity of the stellar population. These characteristics affect the absorption line depth, and they can be determined by measuring the equivalent widths of different lines. However, all spectroscopists experience a certain arbitrary rule in measuring the equivalent widths, which is connected first of all with the continuum fitting: firstly, all spectra are noisy, secondly, the metal absorption lines are so numerous in the spectra of late-type stars, beginning from F, that there are actually no blank regions of the continuum. For this reason, every spectroscopist draws the continuum in his own manner. In order to have an opportunity to compare our own observations with somebody's models or with somebody's observations, it is necessary to arrange first for the common rules of continuum fitting. It is for this reason that over the past 10 years the Lick system of indices has been so widespread among the investigators of the integrated properties of the stellar population (see, for instance, Worthey et al., 1994). The indices are exactly the equivalent widths of absorption lines, but the continuum in this case should be fitted in a strictly defined manner. Firstly, wavelength boundaries are specified for each index, within which a line is enclosed; secondly, the similar boundaries are fixed for the "left" and "right" continuum: one has to calculate the average observed flux in the "left" and "right" band of the continuum, draw a straight line between them, and with this linear continuum to calculate the equivalent width within the limits for a given line. This equivalent width would be the index. The Lick system includes presently determinations for 25 indices of the strongest absorption lines in the wavelength interval 4000–6400 Å. It is good not only because it allows different observers to measure the characteristics of absorption lines in a comparable manner, but also because good model calculations exist for the Lick indices, from which the mean metallicities and the age of the stellar population can be determined. At the times before the appearance of CCD detectors synchronous spectral observations of hundreds of bright elliptical galaxies and of hundreds of bright stars of different spectral classes, predominantly of late types, had been carried out with photon counters at the Lick 3 m telescope, under the supervision of Sandra Faber. This allowed a Faber's postgraduate Guy Worthey to calibrate Lick indices of stars as dependent on effective temperature, luminosity and metallicity (Worthey et al., 1994). These multiparameter analytical relationships were used by him later to perform synthesis of "simple" stellar populations with an age from 1.5 to 17 billion years and a metallicity [Fe/H] from −2.0 to +0.5 (Worthey, 1994). This postgraduate, who delved into every detail, calculated that the indices of Mg_2

and Mgb and of Fe 5270 and Fe 5335 are by a factor of 2–3 more sensitive to metallicity than to age, whereas the indices of the Balmer lines Hβ, Hγ and Hδ are, on the contrary, good indicators of age. In the diagram, where the metal line index is taken along one axis and the Balmer absorption line index is taken along the other, the effects of age and metallicity, as it was to be expected, separate and one can determine both simultaneously. Thus the astronomers acquired a powerful tool to investigate the properties of the stellar population from an integrated spectrum. The only constraint of Worthey's (1994) models is that they were calculated for the "solar" ratio of the elements heavier than helium, and the concept of "metallicity" is most general in them. The stars, observations of which form the basis of the models, are located basically in the vicinity of the Sun and in the disk of the Galaxy, and the ratio of the elements in them is solar. Meanwhile, the very first comparison of the Lick indices of Mg_2, Fe5270 and Fe5335 observed in elliptical galaxies with the model ones showed that their magnesium to iron abundance ratio is not solar — magnesium is more abundant (Worthey et al., 1992). The same overabundance of α-elements relative to iron was noted in stars of the halo and globular clusters of the Galaxy. Such a distinction of the average chemical composition of stars is related by the present-day theorists of chemical evolution to the short, less than 1 billion years, duration of the primary star formation epoch.

One more, a purely methodological problem is connected with the use of the Lick indices. The spectra obtained at the 3 m Lick Observatory telescope both for stars and galaxies had a spectral resolution of about 8 Å. Since the boundaries of lines in the Lick system are rigidly fixed, it was expected that the results of index measurements would be affected by the used spectral resolution and by the intrinsic velocity dispersion of stars in a galaxy, which broadens the absorption lines of the integrated spectrum. For this reason, an indespensible condition of correct calibration of indices into the Lick system is the observation of the stars from the Lick list of Worthey et al. (1994) with our facilities. In January 1998 we observed 9 stars from the Lick list with the former MPFS version with a dispersion of 1.6 Å per px (resolution $\sim$ 5 Å). Comparison of our measured indices with those measured by Worthey et al. (1994), Fig. 1, shows agreement of our indices with the Lick measurements within THEIR observational errors which are 3 times as large as ours and reach, on average, 0.3 Å. Systematic shifts of the scales of indices are absent. Then we monitored the stability of our system of indices by the line-of-sight velocity standards which were observed in each run. Fig. 1 presents a comparison of indices by the same stars, which were measured with the former MPFS with a dispersion of 1.6 Å per px and with the latter MPFS with a dispersion of 1.35 Å per px. It is seen that the systems Hβ, Mgb, Fe5270 with an accuracy better than 0.1 Å remained at their locations and only the index of Fe5335 shifted by +0.2 Å. We are apt to associate this fact not with the change in spectral resolution, but with the widening of the spectral range being measured (with the former MPFS the line FeIλ5330 fell on the edge of the range under investigation) and with the change of spectral response of the system.

At the end of the methodological part we wish to lay mild emphasis on the matters connected with the kinematic analysis. The main objective of involving kinematic data in the investigation of the chemically decoupled nuclei of galaxies is diagnostics of the character of rotation of gas and stars at the centre of the galaxy. If it is axially symmetric, then, in the case of the steep gradient of the rotation curve at the centre, we can speak of the possible presence of a circumnuclear dense disk. If it is not axially symmetric, then we diagnose the presence of a nuclear minibar. Since we obtain two-dimensional velocity fields with the MPFS, this diagnostics is simple enough: it is evident that in the case of axially symmetric density distribution, the maximum gradient of line-of-sight velocities (maximum projection of the rotation velocity onto the line of sight) will be observed along the line of nodes, which, in turn, is bound to coincide with the major axis of the visible isophotes of surface brightness distribution. But if the potential at the centre is triaxial (ellipsoidal), then, as Monnet et al. (1992) and Moiseev, Mustsevoi (2000) noted in their analytical studies, the kinematic and photometric "major axis" will depart from the line of nodes, the departure being in opposite directions. (By kinematic major axis we mean the direction of the maximum central line-of-sight velocity gradient). Thus, to diagnose the character of rotation of stars and gas in a nucleus, we construct azimuthal relations of line-of-sight velocity gradients and fit them by a cosine curve. In the case of axially symmetric rotation the fit will be good and the maximum position of the cosine curve will coincide with the orientation of the photometric major axis:

$$dv_r/dr = \omega \sin i \cos (PA - PA_0),$$

where ω is the central angular velocity of rotation in the galaxy plane, i is the inclination of the rotational axis to the line of sight, and PA_0 is the orientation of the line of nodes coincident with the photometric major axis. If the relationship plotted does not resemble the cosine curve, and its maximum is not coincident with the photometric major axis, this is a minibar. It is of interest that we repeatedly encountered the cases where the cosine curve maximum did not coincide with the GLOBAL line of nodes defined from

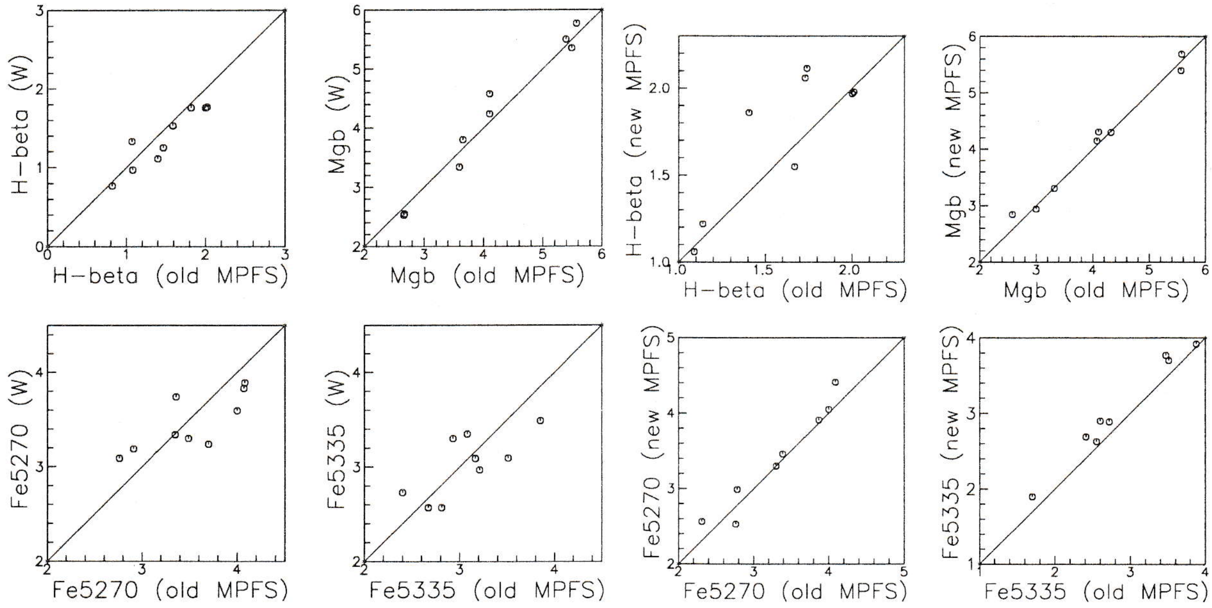


Figure 1: *Comparison of systems of indices: the standard Lick Observatory system (Worthey et al., 1994) vs our system for the old version of the MPFS (left) and our system for the new version of the MPFS vs our system with the old version of the MPFS (right).*

outer disk of the galaxy. However, if the circumnuclear isophotes are elongated exactly in the direction of the line of the maximum line-of-sight velocity gradient, we diagnose an inclined circumnuclear disk.

3. Chemically decoupled nuclei and circumnuclear stellar disks

The rule of the observing astronomers, which is not enough substantiated from the point of view of rigorous mathematics but justified by experience, says: the statistics begins from the number 11. By the present time we have studied in detail 17 disk galaxies with chemically decoupled nuclei and therefore we can already try to isolate some regulations: with what exactly, with what other peculiarities of the galaxy is the presence of a chemically decoupled nucleus connected? The more different distinguishing features we manage to collect together, the more narrow will be the field of hypotheses of their possible origin.

One of the oldest and most fascinating hypotheses of the origin of decoupled (chemically and dynamically) nuclei is the one of Bender, which was mentioned in the Introduction. Bender and his co-authors, first of all Surma, considered that the decoupled nuclei are compact circumnuclear stellar disks formed in the secondary star formation burst after the galaxy had undergone the "dissipative merger", i.e. it absorbed an external gas having its own rotation momentum. The hypothesis was framed with reference to elliptical galaxies where the decoupled nuclei are most commonly resolved because they have a size of several arcseconds and where the unambiguous consistency between chemically, kinematically, and morphologically decoupled regions can readily be established. Still, the morphological signs of disks at the centres were found in far from all elliptical galaxies with decoupled, rapidly rotating nuclei (i. e. they were not found in NGC 2434 and NGC 7192, Carollo et al., 1997). No solution to the problem has been found yet. In the disk galaxies the situation is complicated by the fact that the majority of chemically decoupled nuclei diagnosed first of all from the spectrum absorption line of magnesium have a size of less than 2″ and are not resolved in ground-based observations. True, for many galaxies images obtained with the Hubble Space Telescope are available; the resolution there is an order of magnitude better. Thus, the question of relation of chemically decoupled nuclei to circumnuclear disks is as if broken into two parts: 1) if compact circumnuclear disks are always present in galaxies with chemically decoupled nuclei and 2) if their sizes are coincident, i.e. if these structures are identical in the spatial and evolutionary sense. We can even now answer with assurance "yes" to the first question, if any oblate structure with an exponential profile of the surface brightness is considered to be a "disk", including the so-called exponential bulges, which can be interpreted as very thick disks. We cannot give an unambiguous answer to the second question. However, there are some hints that could be interesting to advance further. We will illustrate them taking the nearby lenticular galaxy NGC 1023 as an example (Sil'chenko, 1999a) in which 1″ corresponds

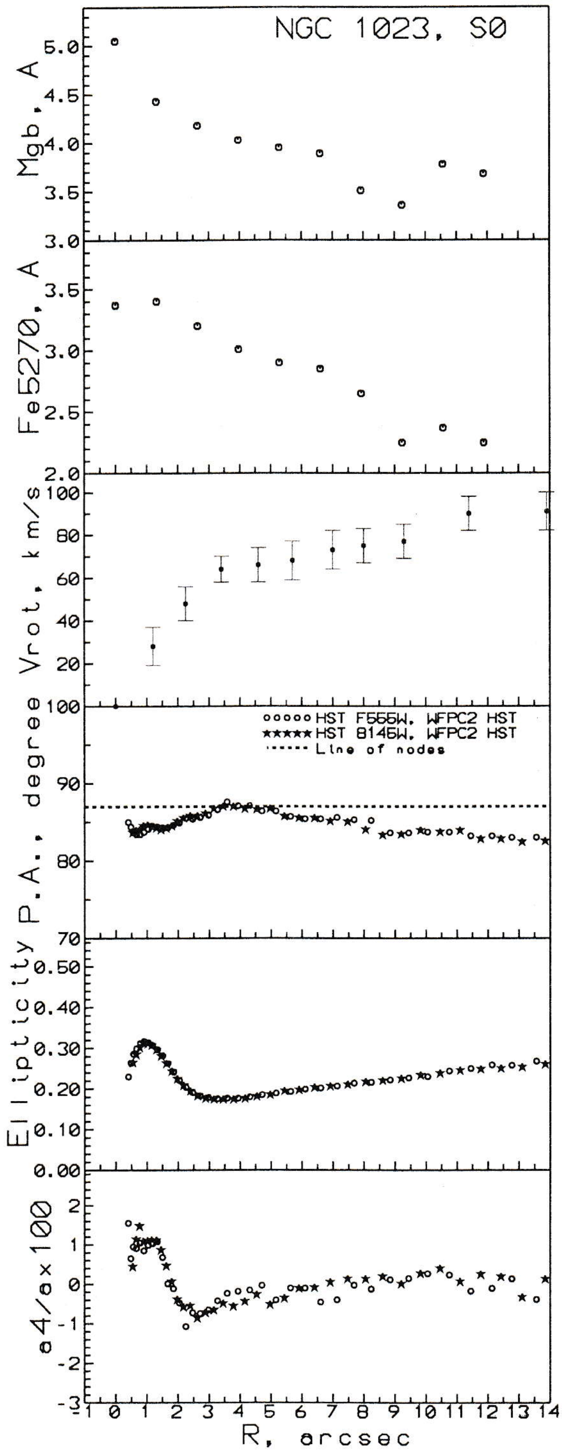


Figure 2: *The central parts of profiles in the lenticular galaxy NGC 1023, from top to bottom: Lick Observatory indices of magnesium and iron from our measurements with MPFS, stellar rotation velocities from the data of Simien and Prugniel (1997), morphological characteristics of isophotes from our measurements of two images taken from the archive of Hubble Space Telescope.*

to only 50 pc.

Fig. 2 shows a comparison of radial variations of the indices of Mgb and Fe5270 (related to magnesium and iron abundances in stars) and morphological characteristics of isophotes. The nucleus of NGC 1023 is chemically decoupled; however, the magnesium index shows a maximum at the very centre, while the iron index exhibits a peak at $R = 1''$ and a flatter decline than the magnesium index. This discrepancy would seem to be negligible — when observing with the MPFS, the seeing was $1''.6$ and it would be difficult for us to lay claim to isolation of arcsecond and subarcsecond structures. However, the photometric HST data obtained with a resolution of $0''.1$ reveal reliable local maxima of ellipticity and of the coefficient of azimuthal Fourier–expansion of brightness a4 precisely at $R = 1''$. Since the position angle of the major axis of the isophotes at this location is close to the line of nodes, we diagnose with some assurance a circumnuclear stellar disk with a radius no more than $1''.5 - 2''$ which is co-planar to the main plane of symmetry of the galaxy. Within the limits of the same radius, our azimuth-average MPFS data show radical variations of the stellar population characteristics. At the very centre, the magnesium-to-iron ratio is twice as large as the solar, and the average stellar population age is 7 billion years; and in a ring of radius $1''.3$ (where the contribution of the circumnuclear disk is a maximum) the magnesium-to-iron ratio is solar and the mean stellar population age is 5 billion years. In the bulge, beginning with $R = 3''$, with the solar magnesium-to-iron ratio, the age of the stellar population is not less than 12 billion years. Thus, the circumnuclear region with $R < 2''$ is obviously isolated evolutionarily and morphologically. It is not unlikely that it formed in the secondary star formation burst resulting from "dissipative merger", or at least from a certain catastrophic event that led to gas concentration (maybe the galaxy's own gas, if it had been a spiral by that time) in the nucleus. That we succeeded in resolving the evolutionarily isolated structure allows us to reason concerning the possible run of the nuclear star formation burst. The matter is that the overabundance of magnesium observed in both the majority of elliptical galaxies (Worthey et al., 1992) and in stellar halos of our own Galaxy (Nissen et al., 1994; Gratton et al., 2000) is generally considered at the present stage of development of the chemical evolution theory as an indication of short (shorter than 10^9 years) duration of star formation burst. Magnesium, as well as oxygen, is produced by supernova stars of type II, which are the final product of evolution of stars more massive than $10\,M_{\odot}$ — while iron is basically the product of Ia–type supernovae, most of which are stars of intermediate masses in binary systems. Accordingly, every new generation of stars will eject its newly-produced magnesium into the surrounding medium as early as 10^7 years after the onset of the star formation burst, and it will immediately enter the stars of the next generation. And the newly-produced iron will appear only in 2–3 billion years after the onset. If this flare would have been "stopped", say, with a lapse of time of 1 billion years after the onset, then all "new" magnesium had already had a chance to appear in young stars, while the "new" iron would not be there. The solar magnesium-to-iron ratio is consistent with an approximately constant process of star formation during a few billion years. A short star formation burst yields a magnesium overabundance 2–4 times higher with respect to iron. Thus, proceeding from our data, the secondary star formation burst in the region of the decoupled nucleus of NGC 1023 was short in the (unresolved) centre, shorter than 10^9 years, while in the circumnuclear disk it lasted much longer; this explains at the same time the different Mg/Fe ratio and the difference of 2 billion years in the average age of the stellar population of the centre and the disk.

Although our statistics is not large so far, an impression is made that such a structure of the chemically isolated circumnuclear region of NGC 1023 is not a certain exceptional phenomenon. The central isolines of the iron index have a more elongated shape, and the region of the maximum of Fe5270 itself has a larger extension than in the magnesium index, also in spiral galaxies NGC 7217 (Sil'chenko, Afanasiev, 2000) and NGC 7331 (Sil'chenko, 1999b). Something of this kind is observed in the more extended (to $R \approx 11''$) circumnuclear disk of NGC 4594 (Emsellem et al., 1996). It is not improbable that a short star formation burst in the nucleus and an extended one in the circumnuclear region is a regular process. By the way, the frequently occurring Hα rings can be related to this process. Up to the present, one has tried to "put" them on the inner Linblad resonance of the bar, and it has been unclear where they come from in the galaxies without a bar. Or maybe this is merely the last stage of formation of a chemically decoupled nucleus in a galaxy?

4. Polar gas rings and counterrotating stars - is it exotic?

Will the relationship between the chemically decoupled nuclei and detached circumnuclear stellar disks, that we have revealed, help refine the origin of decoupled nuclei? We are already quite certain that there was the secondary star formation burst in the galaxy centre, that it occurred (on average) "half-way" of the galaxy evolution, i.e. few billion years ago. But what is exactly the gas that fueled this burst — the gas of its own from the global disk of the galaxy, which fell suddenly onto the centre or is it an external gas accreted in the interaction from another galaxy? And what provoked the sudden accretion of gas onto the centre — external action or internal bar-like instability of the global gas disk? Here are our modest statistics concerning circumnuclear stellar disks in galaxies with chemically decoupled nuclei: in 5 galaxies the rotation plane of the central stellar component coincides with the main symmetry of the galaxy (the plane of the global disk), in 7 galaxies we have detected a noticeable inclination of the circumnuclear disk plane to the main galactic plane. It can be suggested with assurance that it is exactly the flat axially symmetric circumnuclear disk that is inclined, because we checked every time that the orientations of the major kinematic and photometric axes coincide, i.e. no mini-bar exists, the rotation of stars is closely symmetric. Thus, assuming that the orientation of the rotation momentum does not change, we can conclude that the chances of external or internal origin of material for the secondary star formation burst are approximately equal. But, apart from the orientation of circumnuclear stellar disks, there are more impressive indicators of the large-scale accretion or even "minor merger" (when the mass of the "absorbed" galaxy does not exceed 10% of the "cannibal" galaxy mass). The polar rings are such signatures.

It has long been known a small class of peculiar galaxies "galaxies with polar rings". In these galaxies, which are referred basically to morphological type S0, a gas-dust ring is seen across the main "body" (i.e. perpendicular to the global disk plane). The radius of the ring is approximately equal to the global disk optical radius, and the ring rotates at a velocity also approximately equal to the rotation velocity of matter in the main plane of symmetry of the galaxy. Galaxies with large-scale polar rings are rather rare objects of exotic character: only 6 kinematically confirmed cases of polar rings and 27 "reliable candidates" to the polar rings, most of them being rather faint and distant, are listed in the catalogue of Whitmore et al. (1990) among all the galaxies of UGC and ESO catalogues. These are the polar rings, together with the tidal tails, that have so far been believed to be the most vivid consequences of the vigorous event of "absorption" (with tearing to small pieces) of another dwarf galaxy. We have investigated with the MPFS two arbitrarily chosen galaxies with polar rings, NGC 2685 and IC 1689 (Sil'chenko, 1998); they turned out to have actually chemically decoupled nuclei.

The most interesting fact is that we have found polar gas rings (disks) also in the nearby bright spiral galaxies with regular morphology and chemically decoupled nuclei. But these proved to be quite small rings, a few hundred parsecs in radius. The more external gas, which is the main gas content of these galaxies, is distributed and rotates in the global disk, whereas at the very centre it goes for some reason into the polar plane. The circumnuclear stars rotate in a plane orthogonal to the plane of gas rotation, while the rotation velocities and velocity dispersions are approximately coincident, as it was to be expected with a spherically symmetric potential of the circumnuclear region. Can it be that this polar gas was accreted from outside? And how could it manage to avoid collision with the main galactic gas and be undisturbed by the latter. Let us give a closer scrutiny to specific cases.

Figs. 3, 4 and 5 present the velocity fields of stars and ionized gas in the central parts of the nearby galaxies NGC 2841 (SA(r)b, $i = 66°$, Sil'chenko et al., 1997), NGC 4138 (SA(r)0+, or from some classifications Sa, $i = 50°$), NGC 7217 ((R) SA(r)ab, $i = 35°$ Sil'chenko and Afanasiev, 2000). For NGC 6340 (SA(s)0/a, $i = 26°$, Sil'chenko, 2000) we presented only the cross-section along the major photometric axis (Fig. 6), because the galaxy is seen nearly face-on, and the amplitude of variation of radial velocities over a field of 16″ is small. All velocity fields were obtained with the MPFS at BTA in different years. In Table 1 are indicated the orientations of the kinematic major axes of gas and stars, and also of the photometric major axis within the central 3″ and of the line of nodes of the global disk. The circumnuclear gas and stars rotate in the planes strongly inclined to each other. In the case of NGC 6340 we merely view this configuration from above, and the polarity of the planes of rotation of the gas and stars is presented in monstrous difference of the central gradients of radial velocities. However, occasionally none of the planes is precisely coincident with the galaxy global plane of symmetry (although the stars are undoubtedly closer to it). What strange skewed structures? We have analysed the global morphology of the galaxies and made sure that although the four galaxies are considered officially as "nonbarred", slack signs of nonaxisymmetry still exist in all of them: in NGC 2841 — a triaxial bulge with shock waves at the edges (Afanasiev and Sil'chenko, 1999), in NGC 6340 — also a triaxial bulge (Sil'chenko, 2000), in NGC 4138 — a ring of stars and HII regions (Rogge, 1989; Jore et al., 1996), in NGC 7217 — three rings at once (Verdes-Montenegro et al., 1995; Buta et al., 1995). Bars are known to have vertical instabilities (see e.g. Pfenniger, 1985). A few years ago Sofue and Wakamatsu (1994) concluded that the viscous gas in the bar must lose the tangential and radial velocity components, but preserve the z component. Rolling to the centre, near the nucleus it moves onto the polar orbits. Maybe the complex configurations of rotation of the gas and stars in the circumnuclear regions of the above-mentioned galaxies are related to a triaxial potential?

It is interesting that in 3 out of 4 galaxies presented in Figs. 3, 4, 5 and 6 a counterrotating stellar component has been found in the global disks

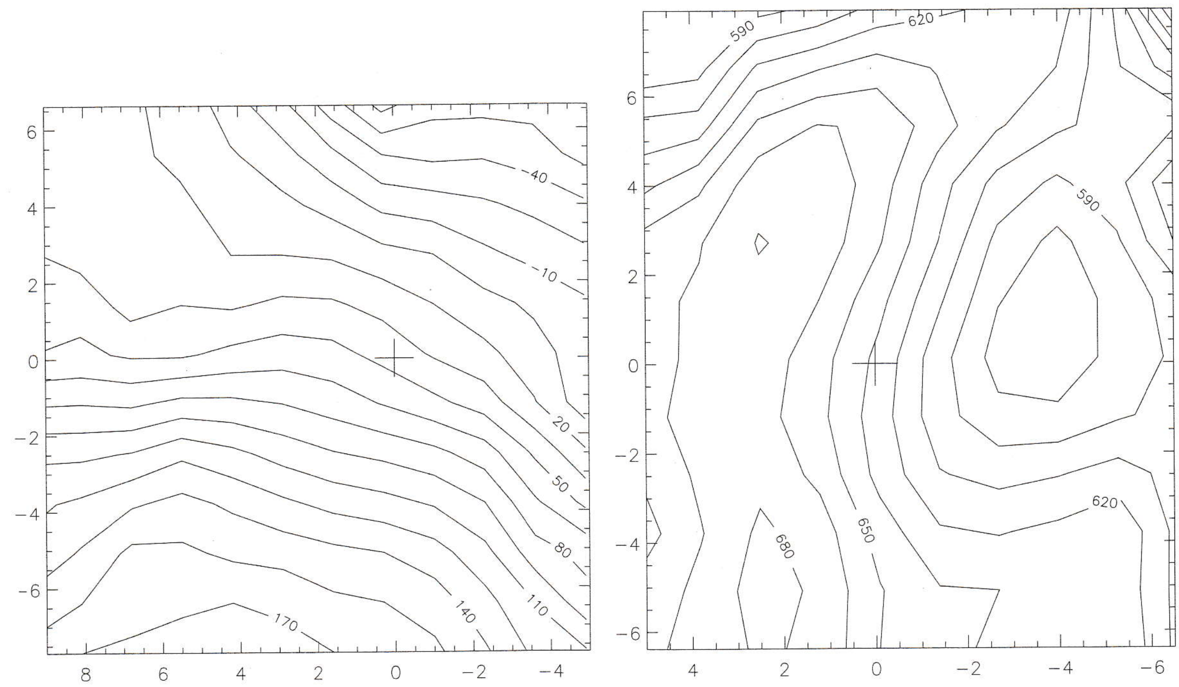


Figure 3: *Velocity fields of stars (left) and ionized gas (right) at the centre of NGC 2841; the cross marks the galaxy photometric centre.*

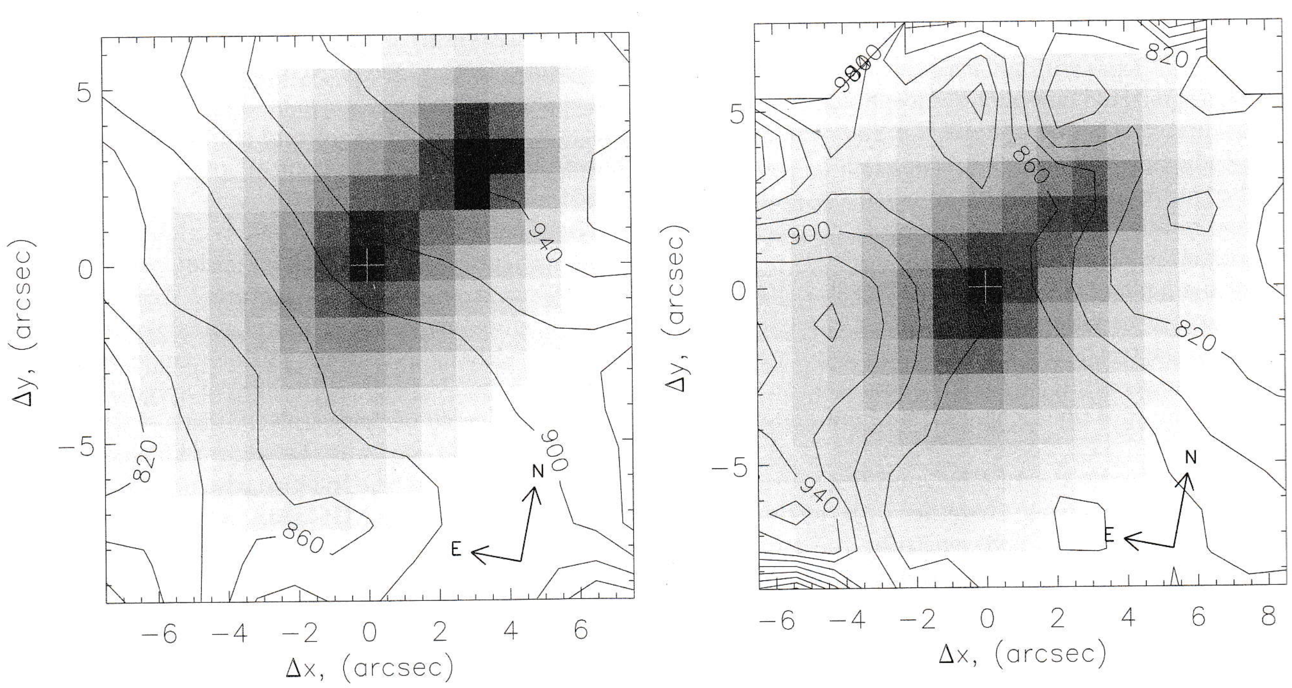


Figure 4: *Velocity fields of stars (left) and ionized gas (right) at the centre NGC 4138; the photometric centre of the galaxy is marked by the cross.*

(NGC 4138, Jore et al., 1996; NGC 7217, Merrifield and Kuijken, 1994) or in the bulge (NGC 2841, Afanasiev and Sil'chenko, 1999). It is possible that no counterrotating stars have been found in NGC 6340 only because the galaxy is observed face-on. Many researchers think that counterrotating stars may have appeared in the disk galaxies only as a result of a "minor merger" or accretion (e.g. Thakar and Ryden, 1996, 1998). However theorists-dynamicians (for instance, Wozniak and Pfenniger, 1997; Athanassoula,

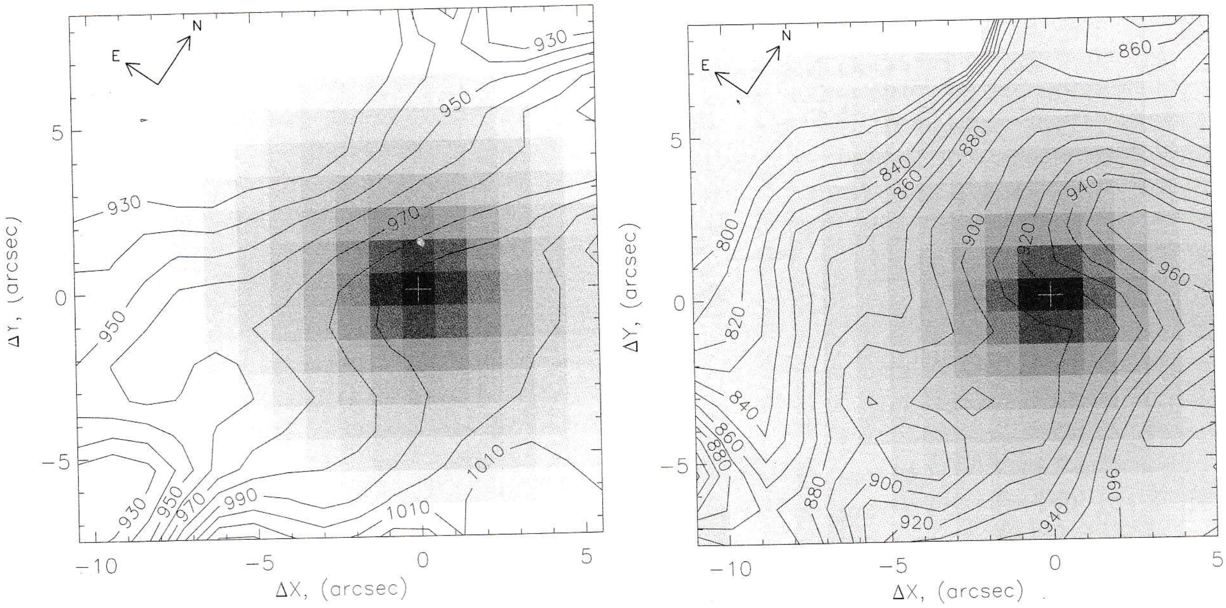


Figure 5: *Velocity fields of stars (left) and ionized gas (right) at the centre of NGC 7217; the photometric centre of the galaxy is marked by the cross.*

Table 1: *Orientation characteristics of rotational planes in the galaxy centres*

NGC	$PA_{kyn,gas}$	$PA_{kyn,*}$	$PA_{phot,center}$	PA(line-of-nodes)
2841	68°	160°	154°	150°
4138	116°	−23°	160°	152°
6340	115°	–	60° – 80°	140°
7217	−31°	−119°	75° – 90°	90°

1996; Tremaine and Yu, 2000) point out that from the dynamical point of view the appearance of the counterrotating stellar component is inevitable for the intrinsic reasons — when the external triaxial potential (a global bar or even a triaxial halo) evolves dynamically (switches on — switches off, accelerates — decelerates). Thus, although we manage to relate the presence of a chemically decoupled nucleus to such kinematically distinguished subsystems as the polar rings and counterrotating stars, this cannot not solve unambiguously the problem of their origin.

5. The properties of the stellar population in the nuclei and bulges of disk galaxies

Over the 10 year period of investigation of chemically decoupled nuclei of galaxies we have had time to analyse in details the kinematics of gas and stars in 17 objects. However, good enough data in the green region of a spectrum have been obtained with the BTA MPFS for the number of galaxies twice as large. They are tabulated in Table 2. In this Section we will make the first attempt of statistics of ages and abundances of chemical elements in stars of the nuclei and bulges of spiral and lens galaxies. With this end in view, we will compute the Lick indices Hβ, Mgb and $<$ Fe $>\equiv$ (Fe5270 + Fe5335)/2 from the spectra of the nuclei and bulges (for the sake of homogeneity, bulges will be taken within $3'' - 5''$ from the nucleus) and compare them with the model calculations of Worthey (1994). As I noted in Section 2, comparison of the indices of hydrogen and metals allows the influence of age and metallicity on the integrated spectrum of the stellar population to be separated and both parameters to be determined simultaneously. There is one more remark: the results of our statistics refer, of course, only to galaxies with chemically decoupled nuclei but not to disk galaxies in general.

Fig. 7 shows a diagram "iron index versus magnesium index" for the spiral galaxies of the sample, from which one can readily estimate the mean magnesium-to-iron abundance ratio. The Mg/Fe ratio has to be determined in advance since the age estimate will depend upon it. Besides, this ratio is of interest in itself since it characterizes the duration of the last noticeable star formation burst. It has now been reliably established that in the overwhelming majority of ellip-

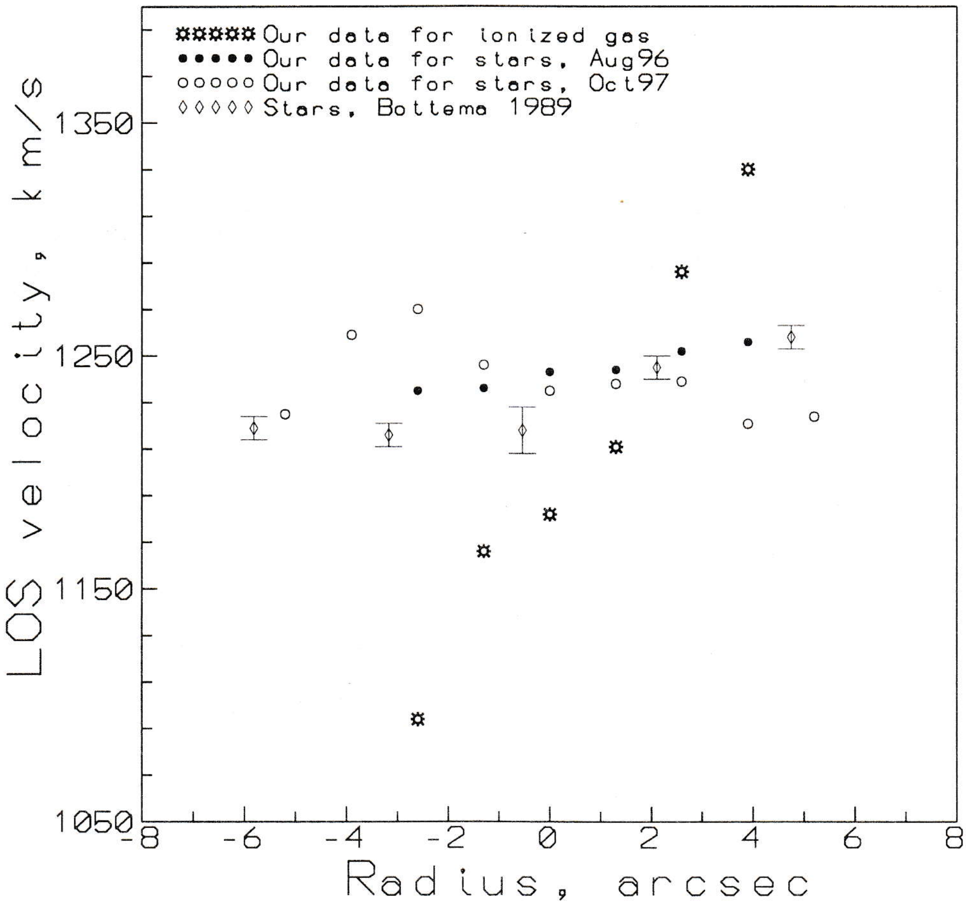
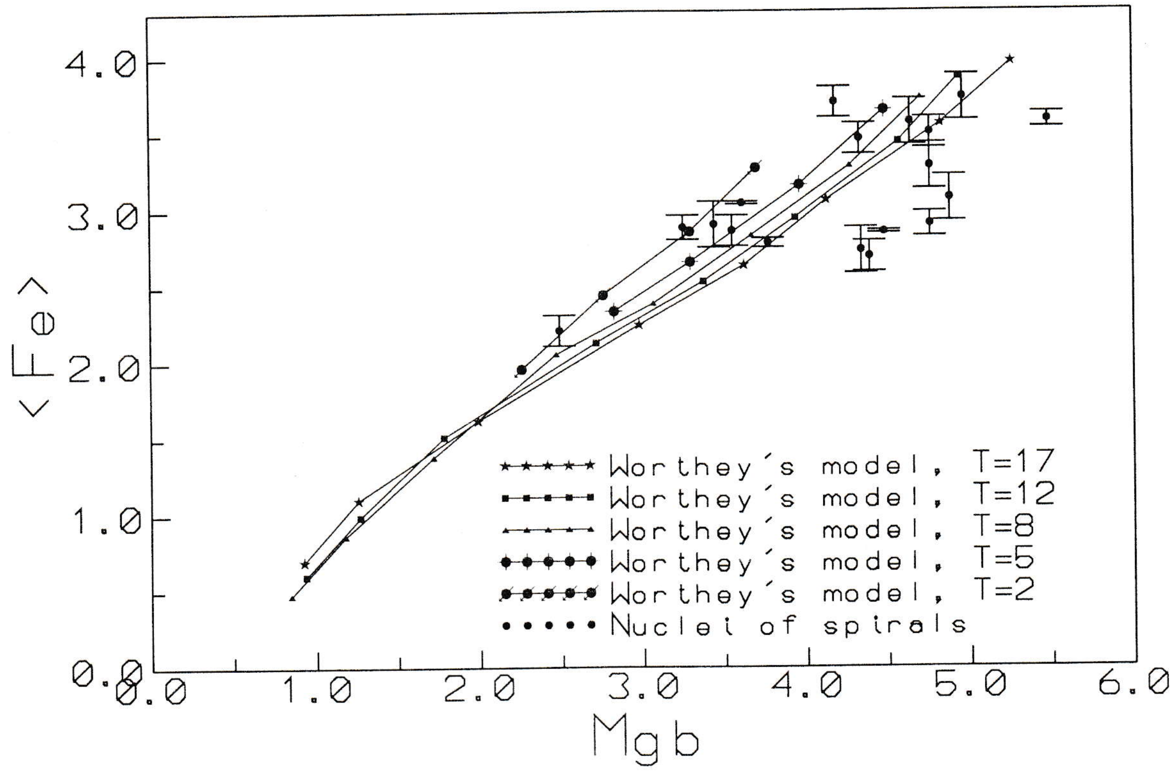


Figure 6: *A cross-section by the major axis (PA = 130°) of the velocity fields of stars and ionized gas in the center of NGC 6340; the data on stellar rotation from the long-slit observations of Bottema (1989) are presented for comparison.*

tical galaxies, including those of moderate luminosity, $M_V \approx -20$, magnesium is found to be overabundant with respect to iron by a factor of 2 to 4. One relates this to the short ($\Delta t < 10^9$years) duration of the main star formation burst. Here it is interesting that inside of a particullar elliptical galaxy the total metallicity changes along the radius (decreases), while the Mg/Fe ratio does not. All radial variations in the diagram $<$ Fe $>$ vs Mgb occur in parallel with the model sequence [Mg/Fe]=0. For early-type disk galaxies, though their central regions resemble in colour elliptical galaxies, the data on their magnesium-to-iron ratio have so far been extremely inconsistent. Using the BTA scanner, in my early work (Sil'chenko, 1993b) I measured Mg/Fe ratio in the integrated spectra of central regions of $2'' \times 4''$ (including the nucleus and the bulge) for a few tens of a nearby galaxies and drew a conclusion that in all disk galaxies, from Sc to S0, the Mg/Fe ratio at the centre is solar. However, Fisher et al. (1996), who observed a small sample of S0 galaxies with a long slit, found examples of nuclei of lenticular galaxies with obvious magnesium overabundance. Jablonka et al. (1996), who integrated again the bulges together with the nuclei, concluded that all depends on the bulge luminosity: large bright bulges resemble elliptical galaxies, and their [Mg/Fe]$>$ 0 and occasionaly to +0.6; in small bulges of late-type galaxies the Mg/Fe ratio is solar. In Fig. 7 is presented a sample of 18 S0/a-Sb galaxies, and now we can separate with assurance the nuclei (chemically decoupled in the galaxies of our sample) and the bulges. Neither the nuclei nor the bulges of early-type spirals show anything bearing resemblance to the distribution of the elliptical galaxies filling the horizontal band at $<$ Fe $>\approx 2.9$. In both parts of the figure, one can observe, however, a marked scattering of [Mg/Fe], from 0 to $\sim +0.4$; in about half of the cases the magnesium overabundance in the nuclei is rather sharply defined. This half is approximately halved again: in M 31, NGC 488 and NGC 2841 the [Mg/Fe] ratios are nearly equal in the nucleus and bulge. This ratio in NGC 4216, 5533, 6340 and 7331



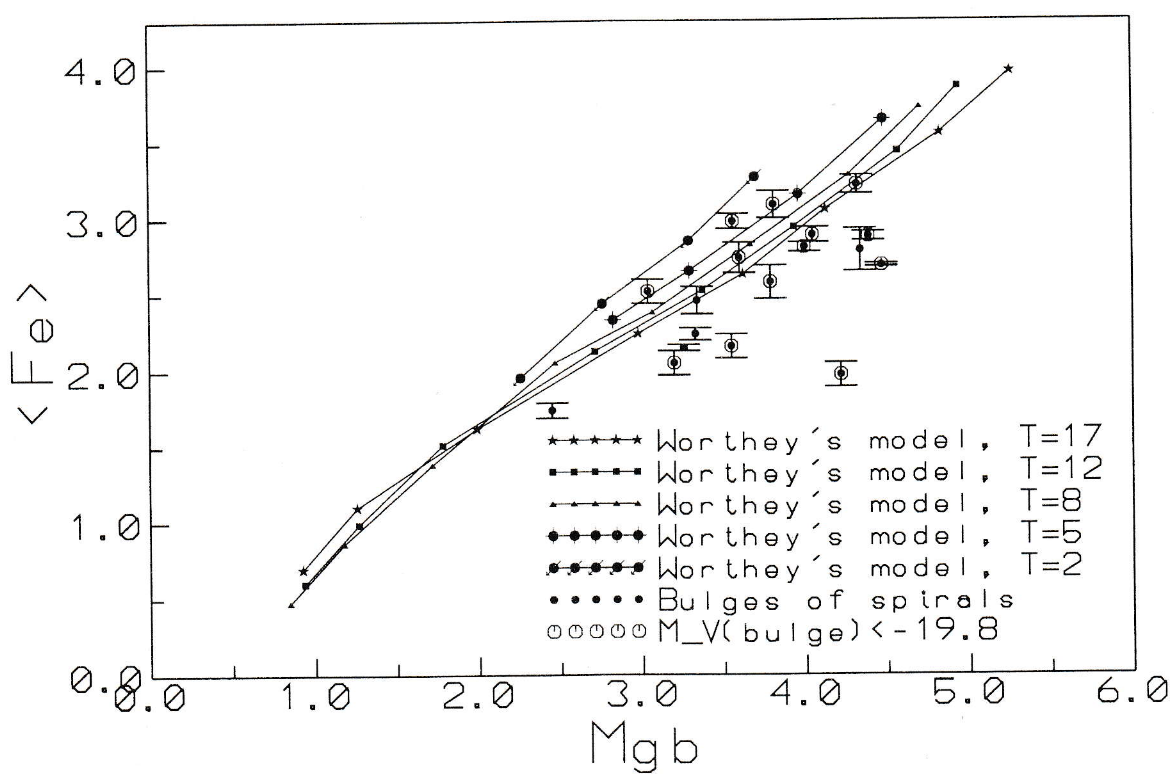


Figure 7: *Diagram "magnesium index vs iron index" for the nuclei (top) and bulges (bottom) of the studied early-type spiral galaxies. The observations are compared to the models of the old stellar populations with the solar magnesium-to-iron ratio (Worthey, 1994); the legends show the model ages in billion years, the signs mark the reference values at following metallicities (from top to bottom):* [Fe/H] $= +0.50, +0.25, 0.00, -0.22, -0.50, -1.00, -1.50, -2.00$. *At the bottom the large signs show the bright bulges.*

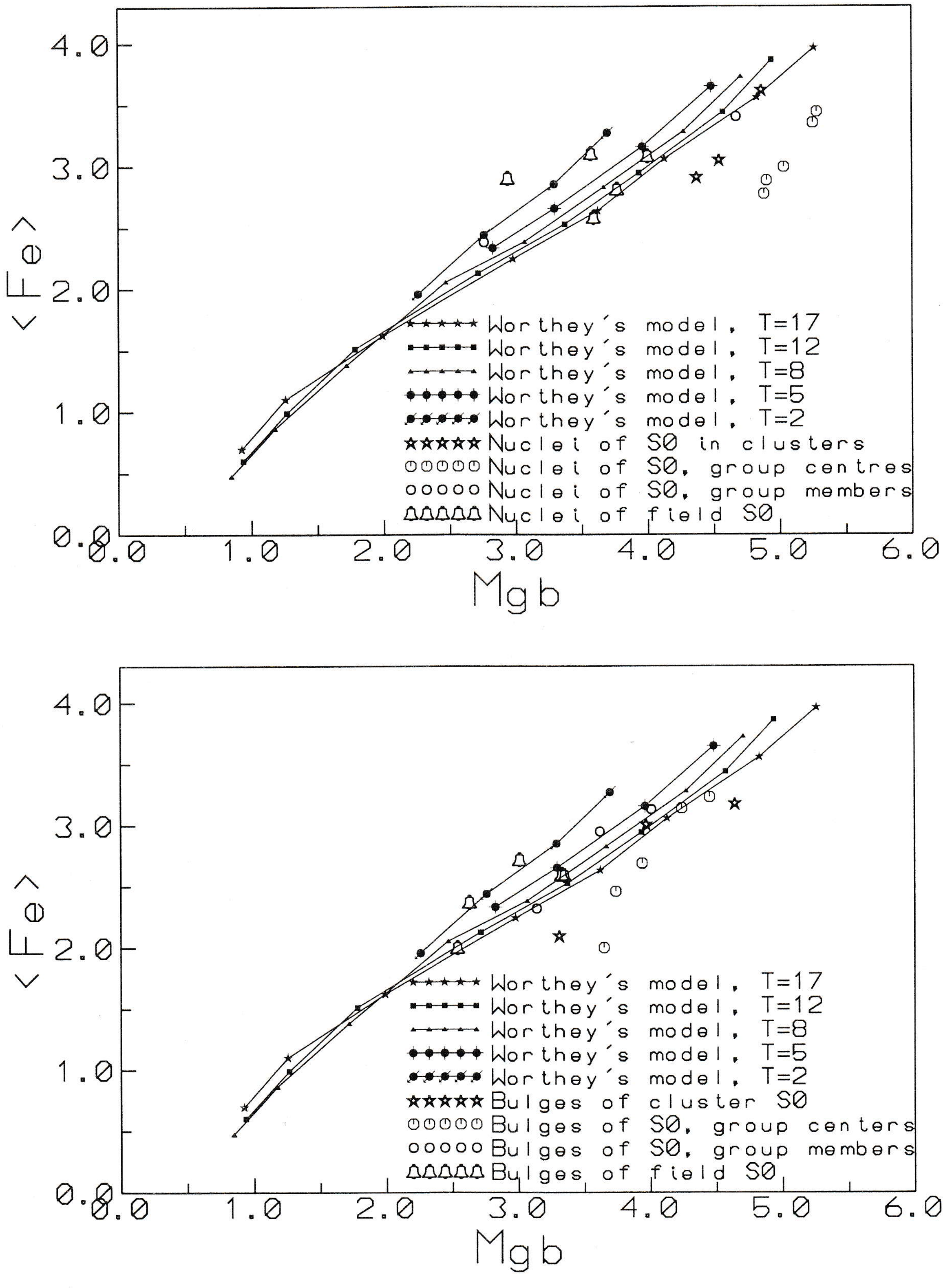


Figure 8: *Diagram "magnesium index vs iron index" for the nuclei (top) and bulges (bottom) of the studied lenticular galaxies. The observations are compared to the models of the old stellar populations with the solar magnesium-to-iron ratio (Worthey, 1994); the legends show the model ages in billion years, the signs mark the reference values at following metallicities (from top to bottom):* $[Fe/H] = +0.50, +0.25, 0.00, -0.22, -0.50, -1.00, -1.50, -2.00$. *Different signs show the cluster galaxies, galaxies in the centres of the groups, galaxies at the periphery of the groups and the field galaxies.*

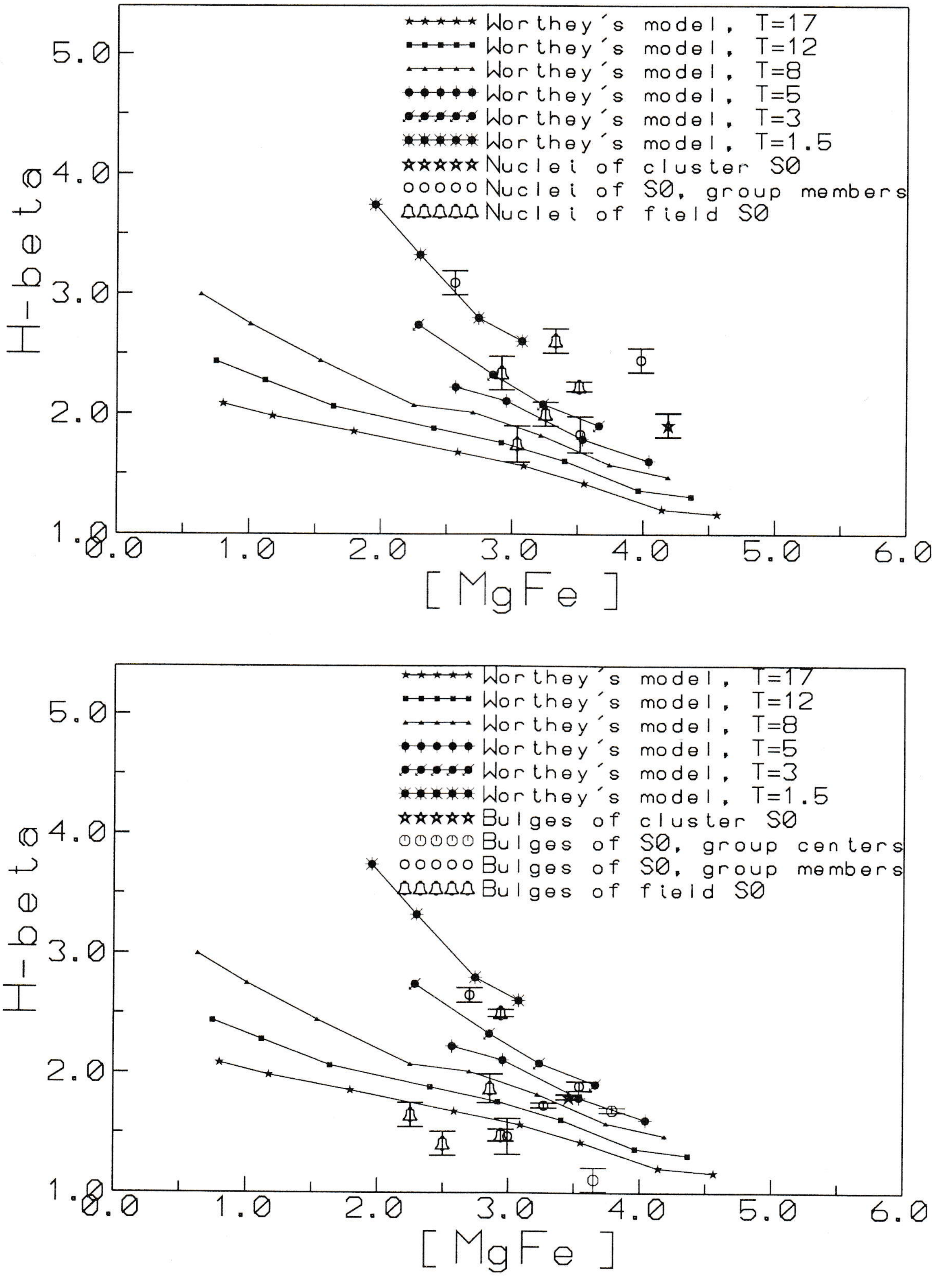


Figure 9: *Diagnostic diagram for determination of the average age of stellar population in the nuclei (top) and bulges (bottom) of the lenticular galaxies with the solar magnesium-to-iron ratio. The observations are compared to the models of the old stellar populations with the solar magnesium-to-iron ratio Worthey (1994); the legends show the model ages in billion years, the signs mark the reference values at the following metallicities (from right to left):* [Fe/H] $= +0.50, +0.25, 0.00, -0.22, -0.50, -1.00, -1.50, -2.00$. *Different signs show the cluster galaxies, galaxies in the centres of the groups, galaxies at the periphery of the groups and the field galaxies.*

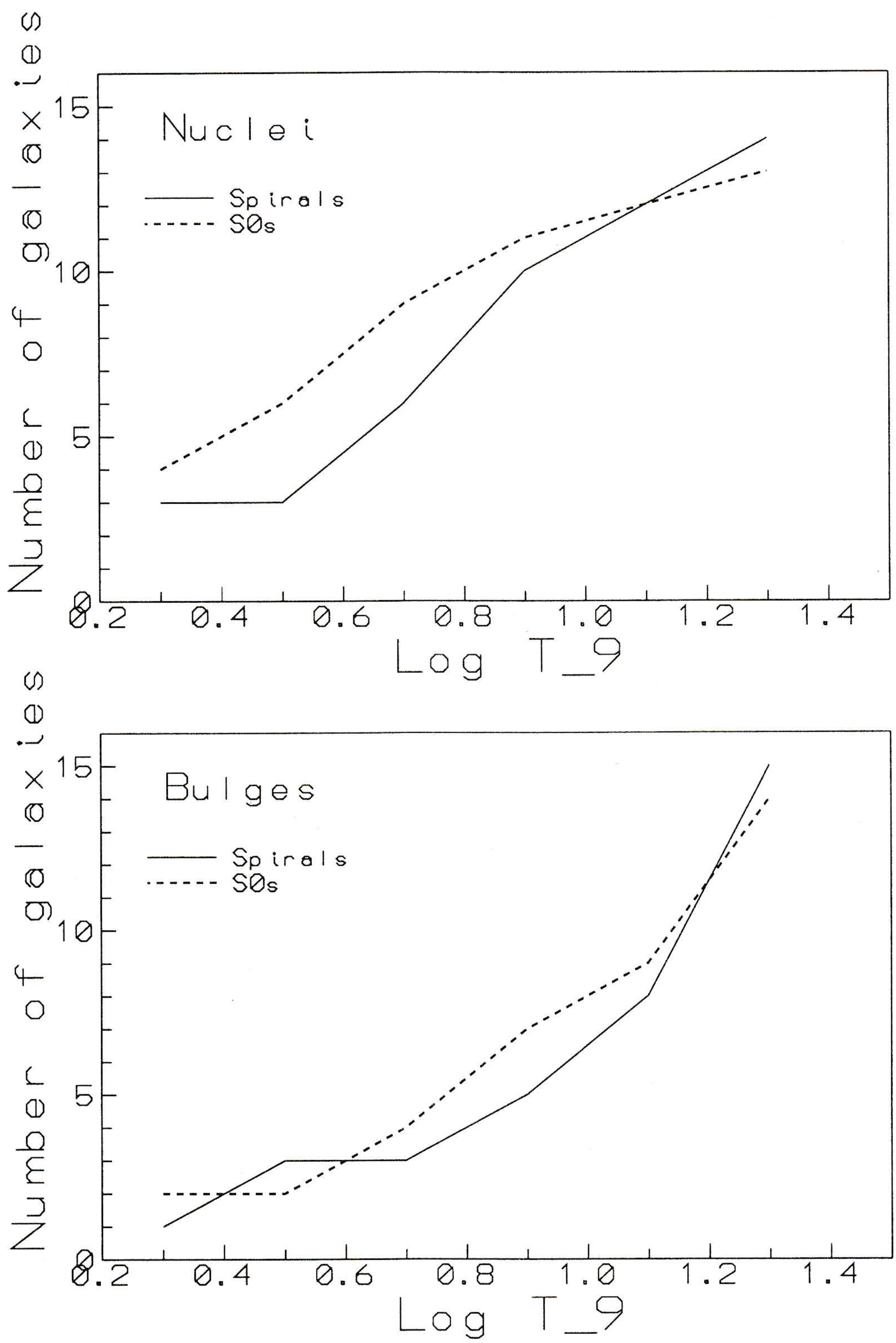


Figure 10: *Cumulative distribution of ages of stellar population in the nuclei (top) and bulges (bottom) of the galaxies under study: the solid line shows the distribution for the spiral galaxies, and the dashed line presents that for the lenticular ones.*

Table 2: *Our sample of galaxies*

Galaxy	Type(NED)	$M_V(bulge)$	σ_0, km/s	Central emission $H\alpha$?	Dates of observations
N0224	SA(s)b	-20.40	161	–	Sep96, Z1000, Long-slit
N0488	SA(r)b	-21.24	203	–	Jan98
N0615	SA(rs)b	–	140	–	Jan98
N2655	SAB(s)0/a	-22.07	166	+	Oct99
N2683	SA(rs)b	-17.56	143	+	Oct97, Dec99
N2841	SA(r)b	-21.16	215	+	Feb96
N3368	SAB(rs)ab	-21.00	131	+	Feb2000
N3623	SAB(rs)a	-21.29	173	+?	Feb2000
N3627	SAB(s)b	-20.92	120	+	Feb2000
N4216	SAB(s)b	-21.36	219	–	May97
N4501	SA(rs)b	-19.49	154	+	May96, May97
N4548	SB(rs)b	-20.45	123	+	May97
N5055	SA(rs)bc	-20.77	117	+?	Jun99
N5533	SA(rs)ab	-21.93	250	+	Feb95, May95, May96
N6340	SA(s)0/a	-19.29	130	–	Aug96, Oct97
N7013	SA(r)0/a	–	90	+	Oct96, Aug98
N7217	(R)SA(r)ab	-21.27	152	+	Aug98
N7331	SA(s)b	-22.03	146	–	Oct96
N0080	SAO-	-22.62	234	–	Aug96
N0524	SA(rs)0+	-22.39	245	–	Oct97
N1023	SB(rs)0-	-19.82	206	–	Oct96
I1689	S0 pec	-20.71	129	–	Oct96
N2685	(R)SB0+pec	-20.35	99	–	Oct94
N2911	SA(s)0:	–	236	+	Dec99
N3384	SB(s)0-	-19.98	142	–	Dec99
N4036	SO-	-20.20	200	+	May97, Jan98
N4138	SA(r)0+	-19.85	174	+	Jan98, Dec99
N4379	S0-	-19.10	150	–	Jun99
N4429	SA(r)0+	-20.54	194	+	Feb95, Jun99
N4550	SB0	-20.15	80	+	Jan98, Jun99
N5574	SB0-?	-19.35	–	–	Jun99
N5866	$S0_3$	-20.78	144	+?	Aug98
N7280	SAB(r)0+	–	111	–	Aug98
N7332	S0 pec	-20.41	134	–	Aug96, Oct97
N7457	SA(rs)0-?	-18	75	–	Oct99, Dec99

drops markedly when passing from nucleus to bulge. Probably, disk galaxies underwent a diversified evolution of their central parts with different characteristic times of star formation in the nucleus and bulge. It is difficult to suggest yet on what this evolution depends. Triaxial structures (bars) occur in galaxies with any Mg/Fe ratio both in the nucleus and in the bulge. We tried to separate bulges according to luminosity by placing the boundary at the location where it was placed by Jablonka et al. (1996). This proved to be of no help either: bright bulges filled uniformly the entire band from [Mg/Fe]=0 to +0.6. Perhaps a certain hint of the causes of the [Mg/Fe] differences at the centres of disk galaxies is provided only by Fig. 8 where we plotted lenticular galaxies in the < Fe > vs Mgb diagram, having classified them by the type (density) of their surroundings. It turned out that [Mg/Fe]= +0.3 – +0.4 is demonstrated by the nuclei of all five S0 galaxies, which are central in the groups, and by no one more. Half-way between this friendly community and all the rest, having the solar Mg/Fe ratio, there settled the nuclei of two S0 galaxies — cluster members. All the field S0 galaxies and peripheral members of the groups have the solar Mg/Fe ratio both in the nucleus and in the bulge. Although the statistics are modest yet, maybe we have managed to reveal the influence of the surroundings.

After the Mg/Fe ratio has been determined, one can estimate also the average (weighted with luminosity) age of the stellar population by comparing observations with models. In Fig. 9 is displayed the diagram for the nuclei and bulges of S0 galaxies with the solar magnesium-to-iron ratio. The qualitative pattern for the objects with [Mg/Fe]= +0.3 proves to be approximately the same as for the objects with [Mg/Fe]=0. We can see from Fig. 9 that the nuclei of S0 galaxies are much younger than bulges. The stellar population of lenticular galaxies has thus far been considered as old because of its red colour. In actual fact the overwhelming majority of the nuclei of S0 galaxies are younger than 5 billion years in all types of surroundings. This result has something in common with our inference made a long time ago (Sil'chenko, 1993a) that half of ALL lenticular galaxies (but not only those whose nuclei are chemically decoupled) have an average stellar population age younger than 5 billion years in the central regions. The red colour is due to high metallicity, it is nearly always higher than the solar in the nuclei, and the younger, on average, the stellar population (i.e. the more vigorous was the secondary star formation burst?) the higher the metallicity. The average age of stars in bulges is about 12 billion years, though systems with an age of 2–3 billion years also occur among bulges (we, however, took bulges formally, as rings of radius $3'' - 5''$, and if the circumnuclear disk is extended, it can "contaminate" the measurements of the bulge).

We present in Fig. 10 a summary of all age estimates of the stellar population in the nuclei and bulges of spiral and lenticular galaxies. Since it always causes alarm that the Hβ absorption line equivalent width is underestimated because of blending by the Balmer emission, it is safer to consider that we define the age upper limit from the diagram of the type of Fig. 9. For this reason in Fig. 10 we plotted along the ordinate axis the number of nuclei (bulges) YOUNGER than the age laid off on the abscissa axis. It can be seen that the ages of the bulges of spiral and lenticular galaxies are similar: the median age of both is 9–12 billion years. The nuclei in spiral and lenticular galaxies are nearly always younger than the bulges (note that the matter in question is only chemically decoupled nuclei). It is of interest that the nuclei of lenticulars look on average somewhat younger than those of spiral galaxies — the median age of the former is 4 billion years, that of the latter is 6 billion years. Thus, Fig. 10 shows that the chemically decoupled nuclei in the early-type disk galaxies formed in the secondary star formation bursts a few (1–5) billion years ago. There is also a hint that the burst in the nuclei of S0 galaxies was on average more vigorous: maybe this will open the clue to the origin of lenticular galaxies.

Acknowledgements. I am grateful to my co-authors in the papers devoted to investigation of chemically decoupled nuclei of galaxies, astronomers of the Special Astrophysical Observatory V.L. Afanasiev, A.N. Burenkov and V.V. Vlasyuk for long-term fruitful co-operation. The 6 m telescope of SAO operated under financial support of the RF Ministry of Science (registration number 01-43). Over the past few years my work has been funded through grants of the RFBR 98-02-16196, of the President of the Russian Federation for Young Doctors of Science 98-15-96029, and of the State Science-Technological Programme "Astronomy. Fundamental Space Research" (section "Astronomy"), No 1.2.4. The work is based in part on the HST archival data (NASA/ESA) obtained from the data archive at the Space Telescope Science Institute. STScI is operated by the Association of Universities for Research in Astronomy, Inc. under the NASA contract NAS 5-26555.

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