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

The Leo I Cloud: Secular nuclear evolution of NGC 3379, NGC 3384, and NGC 3368?

O. K. Sil’chenko

*Sternberg Astronomical Institute, Moscow, 119992 Russia
and Isaac Newton Institute of Chile, Moscow Branch
Electronic mail: olga@sai.msu.su

A. V. Moiseev, V. L. Afanasiev

*Special Astrophysical Observatory, Nizhniy Arkhyz, 369167 Russia
Electronic mails: moisav@sao.ru, vafan@sao.ru

V. H. Chavushyan, J. R. Valdes

*Instituto Nacional de Astrofísica, Optica, y Electrónica, A.P. 51 y 216, C.P. 72000 Puebla, Pue., México
Electronic mails: vahram@inaoep.mx, jvaldes@inaoep.mx

ABSTRACT

The central regions of the three brightest members of the Leo I galaxy group – NGC 3368, NGC 3379, and NGC 3384 – are investigated by means of 2D spectroscopy. In all three galaxies we have found separate circumnuclear stellar and gaseous subsystems – more probably, disks – whose spatial orientations and spins are connected to the spatial orientation of the supergiant intergalactic H I ring reported previously by Schneider et al. (1983) and Schneider (1985, 1989). In NGC 3368 the global gaseous disk seems also to be inclined to the symmetry plane of the stellar body, being probably of external origin. Although the rather young mean stellar age and spatial orientations of the circumnuclear disks in NGC 3379, NGC 3384, and NGC 3368 could imply their recent formation from material of the intergalactic H I cloud, the time scale of these secondary formation

1Guest Investigator of the UK Astronomy Data Centre
events, of order 3 Gyr, does not support the collision scenario of Rood & Williams (1985), but is rather in line with the ideas of Schneider (1985, 1989) regarding tidal interactions of the galaxies with the H I cloud on timescales of the intergroup orbital motions.

Subject headings: galaxies: nuclei — galaxies: individual (NGC3368) — galaxies: individual (NGC3379) — galaxies: individual (NGC3384) — galaxies: evolution — galaxies: structure

1. Introduction

The origin of S0 galaxies is long-standing problem which was posed almost at the moment of the birth of the Hubble morphological classification scheme. However, this has been one of those rare cases when the first idea was correct, this being later confirmed more than once. From the beginning many investigators thought that lenticulars formed (more exactly, transformed) from spirals. Now with the advent of high-resolution imaging, including the HST as well as some ground-based work, using adaptive optics, there is direct evidence that rich clusters, presently populated mostly by S0’s, at $z = 0.5 - 0.8$ contain a lot of spirals which are in the course being accreted by these clusters. Evidently, dense environments, or deep potential wells, or hot intracluster gas pressure, provides the conditions to transform the spirals into lenticulars. Two famous theoretical papers concerning particular mechanisms of this transformation must be mentioned here: Spitzer & Baade (1951) propose collisions between spiral galaxies, which are frequent in dense clusters with high velocity dispersions, in which in a passage of one galaxy through another, all the gas is swept out of their galactic disks. The other paper is by Larson et al. (1980) who analysed a less violent event during which tidal stripping removes a diffuse gaseous halo from a spiral galaxy. The secular disk building by gas accretion onto the equatorial plane having ceased, the gas remaining in the disk is typically consumed by star formation in a few billion years.

Therefore one can easily imagine – and even directly observe – how spirals transform into lenticulars in clusters. But clusters are not the only place where S0’s live; there are a lot of lenticulars in the field and in loose groups. What is their origin? There are suggestions that field S0s form in a different way from that of cluster S0s. There exists one loose galaxy group where the scenario of Spitzer & Baade (1951) may apply: it is the Leo I group. Twenty years ago a unique supergiant intergalactic HI cloud was discovered in this galaxy group (Schneider et al. 1983), and Rood & Williams (1985) suggested that this gas was swept out of galactic disks during a collision between NGC 3368 and NGC 3384 some $5 \times 10^8$ yrs ago. Now the HI cloud is located exactly half-way between two galaxies, and NGC 3384 looks like a bona-fide
lenticular galaxy. But Schneider himself (Schneider 1985, 1989) gave another explanation to this phenomenon. The cloud has fainter filaments which encircle the galaxy pair NGC 3384/NGC 3379; the whole HI-complex may be treated as a clumpy gaseous ring with a radius of some 100 kpc. Velocities measured in several clumps imply a Keplerian rotation of the ring with a period of 4 Gyr, the SW-part of the ring being receding. If the intrinsic shape of the ring is circular, it is inclined to the line of sight with the line of nodes at $PA \approx 40^\circ$; interestingly, the close orientation and sense of rotation is repeated by the global stellar disk of NGC 3384. Even though symmetry (rotation) axes of the rest of the galaxies of the group are not aligned with those of the HI-ring and NGC 3384, Schneider (1985, 1989) conclude that this supergiant, $1.7 \cdot 10^9 M_\odot$, HI-cloud may represent left-over primordial (pre-galactic) gas from which all the galaxies of the group have been formed.

As the HI-ring is rather massive, it contributes to the common potential; in particular, tidal interactions of the group galaxies with the ring are possible. Schneider (1989) have analysed the possible interaction of the ring with NGC 3368 – the nearest and the brightest neighbor of the NGC 3384/NGC 3379/HI-ring complex. He suggested that the intergroup orbit of NGC 3368 is inclined to the plane of the ring and that this galaxy has had two close passages near the ring during a Hubble time. In this case, the cycle time of interaction is about 5 Gyr, instead of $5 \cdot 10^8$ yrs as proposed in the model of Rood & Williams (1985).

Well after the first simulations of tidal interactions of galaxies by Toomre & Toomre (1972), demonstrating spectacular outer tidal structures (tails, bridges, etc.), it was realized that an external tidal impulse affects also the innermost (circumnuclear) structure of the galaxy – see e.g. Noguchi (1987). So a history of nuclear star formation may reflect in some way the history of galaxy interactions, especially if the galaxy possesses an early morphological type and lacks its own gas. In this paper we study the properties of nuclear stellar populations in NGC 3379, NGC 3384, and NGC 3368 – three of the four brightest galaxies of the Leo I group and three nearest neighbors of the unique intergalactic HI-ring. We are searching for signs of synchronous evolution of the nuclear stellar populations in these galaxies; obviously, the characteristic time of this evolution may help to discriminate between various scenarios of the origin of the HI-ring.

The global parameters of the galaxies are given in Table 1. The distance to the spiral galaxy NGC 3368 is determined from Cepheid observations (Tanvir et al. 1999), and the distance to the high surface brightness elliptical NGC 3379 by the surface-brightness fluctuations method (Morris & Shanks 1998); the distance to NGC 3384 was assumed to be the same as to NGC 3379 as their planetary nebula systems seem to imply (Ciardullo et al. 1993).

The layout of the paper is as follows. We report our observations and other data
which we use in this paper in Section 2. The radial variations of the properties of the stellar population are analysed in Section 3, and in Section 4 two-dimensional velocity fields obtained by means of 2D spectroscopy are presented. Section 5 presents a discussion and our conclusions.

2. Observations and data reduction

The spectral data which we analyse in this work were obtained with two different integral-field spectrographs. Integral-field spectroscopy is a rather new approach that was first proposed by Prof. G. Courtes some 15 years ago – for a description of the instrumental idea see e.g. Bacon et al. (1995). It allows one to obtain simultaneously a set of spectra in a wide spectral range from an extended area on the sky, for example, from a central part of a galaxy. A 2D array of microlenses provides a set of micropupils which are projected onto the entrance window of a spectrograph. After reducing the full set of spectra corresponding to the individual spatial elements, one obtains a list of fluxes for the continuum and for the lines, line-of-sight velocities, both for stars and ionized gas, and of emission- and absorption-line equivalent widths which are usually expressed as indices in the well-formulated Lick system (Worthey et al. 1994). This list can be transformed into two-dimensional maps of the above mentioned characteristics for the central part of the galaxy under study. Besides the panoramic view benefits, such an approach gives a unique opportunity to overlay various 2D distributions over each other without any difficulties with positioning. In this work we use the data from two 2D spectrographs: the fiber-lens Multi-Pupil Fiber Spectrograph (MPFS) at the 6m telescope BTA of the Special Astrophysical Observatory of the Russian Academy of Sciences (SAO RAS) and the international Tigre-mode SAURON at the 4.2m William Herschel Telescope at La Palma.

A new variant of the MPFS became operational at the prime focus of the 6m telescope in 1998 (http://www.sao.ru/~gafan/devices/mpfs/). With respect to the previous one, in the new variant the field of view is increased and the common spectral range is larger due to using fibers: they transmit light from $16 \times 15$ square elements of the galaxy image to the slit of the spectrograph together with additional 16 fibers which transmit the sky background light taken away from the galaxy, so separate sky exposures are not necessary anymore. The size of one spatial element is approximately $1'' \times 1''$; a CCD TK 1024 \times 1024 detector is used. The reciprocal dispersion is 1.35 Å per pixel, with a rather stable spectral resolution of 5 Å. To calibrate the wavelength scale, we expose separately a spectrum of a hollow cathode lamp filled with helium, neon, and argon; an internal accuracy of linearizing the spectrum was typically 0.25 Å in the green and 0.1 Å in the red. Additionally we checked the accuracy
and absence of a systematic velocity shift by measuring strong emission lines of the night sky, [O\textsc{i}]\text{λ}5577 and [O\textsc{i}]\text{λ}6300. We obtained the MPFS data mostly in two spectral ranges, the green one, 4300–5600 Å, and the red one, 5900–7200 Å. The green spectra are used to calculate the Lick indices H\text{β}, Mgb, Fe5270, and Fe5335 which are suitable to determine the mean (luminosity-averaged) metallicity, age, and Mg/Fe ratio of old stellar populations (Worthey 1994). Also, they are used for cross-correlating with a spectrum of a template star, usually of K0III–K3III spectral type, to obtain in such a way a line-of-sight velocity field for the stellar component and a map of stellar velocity dispersion. The red spectral range contains strong emission lines of H\text{α} and [N\text{ii}]\text{λ}6583 and is used to derive line-of-sight velocity fields of the ionized gas. To calibrate the new MPFS index system onto the standard Lick one, we observed 15 stars from the list of Worthey et al. (1994) during four observing runs and calculated the linear regression formulas to transform our index measurements to the Lick system; the rms scatter of points near the linear regime is about 0.2 Å for all 4 indices under consideration, i.e., within the observational errors quoted by Worthey et al. (1994). To correct the index measurements for the stellar velocity dispersion which is usually substantially non-zero in the centers of early-type galaxies, we smoothed the spectrum of the standard star HD 97907 by a set of Gaussians of various widths; the derived dependence of index corrections on \( \sigma \) were approximated by 4th order polynomials and applied to the measured index values before their calibration to the Lick system.

The second 2D spectrograph which data we use in this work is a new instrument which is being operated at the 4.2m William Herschel Telescope on La Palma since 1999, named SAURON – for its detailed description see Bacon et al. (2001). We have taken the data for NGC 3379 and NGC 3384 from the open ING Archive of the UK Astronomy Data Centre. Briefly, the field of view of this instrument is 41′′ × 33′′ with spatial element sizes of 0.′′94 × 0.′′94. The sky background at 2 arcminutes from the center of the galaxy is exposed simultaneously with the target. The fixed spectral range is 4800-5400 Å, the reciprocal dispersion is 1.11 Å-1.21 Å per pixel varying from the left to the right edge of the frame. The comparison spectrum is neon, and the linearization is made using a 2nd order polynomial with an accuracy of 0.07 Å. The index system is checked by using stars from the list of Worthey et al. (1994) that have been observed during the same observing runs as the galaxies. The regressions describing the index system of the February-1999 run when NGC 3379 was observed can be found in our paper (Afanasiev & Sil’chenko 2002b), and the regressions for the March/April-2000 run are presented in Fig. 1. The relations between instrumental and standard-system indices were approximated by linear fits which were applied to our measurements to calibrate them on to the standard Lick system. The stellar velocity dispersion effect was corrected in the same manner as for the MPFS data.

The full list of exposures made for NGC 3368, NGC 3379, and NGC 3384 with two 2D
spectrographs is given in Table 2.

We have also observed the global kinematics of the ionized gas in NGC 3368 with the scanning Fabry-Perot Interferometer (IFP) at the 6m telescope. In contrast to the integral-field 2D spectrographs MPFS and SAURON, the IFP allows us to obtain spectral information over a large field of view, but over a relatively small spectral range. We use the IFP in interference order 235 (for $\lambda 6563 \, \AA$). The IFP is installed at the pupil plane of a focal reducer attached to the f/4 prime focus of the 6m telescope. A brief description of this device is available from http://www.sao.ru/~gafan/devices/ifp/ifp.htm. The detector was a CCD TK 1024 $\times$ 1024 working with a binning of 2 $\times$ 2 pixels. The resulting pixel size was 0.68 and the field of view was about 5.8. During every object exposure we obtain 32 frames with interference rings for varying IFP gaps. The full spectral range (interfringe) was 28 Å, the spectral resolution was about 2.5 Å. A narrow-band filter with $FWHM \approx 15 \, \AA$ was used to select a spectral domain around the redshifted galactic emission lines H$\alpha$ and [NII]$\lambda 6583 \, \AA$. The log of the observations with the IFP is given in Table 3.

Besides the 2D spectral data, we have obtained NIR photometry for two of the galaxies under consideration. The observations were made at the 2.1m telescope of the National Astronomical Observatory of Mexico “San Pedro Mártir” with the infrared camera CAMILA. The camera is equipped with a NICMOS3 detector with a format of 256 $\times$ 256 pixels; mostly the mode with a scale of 0.85 (f/4.5) has been used, except for NGC 3368 which has also been observed with a higher sampling. The details of the photometric observations are given in Table 4. Additionally, for all three galaxies we have retrieved the NICMOS/HST data from the HST Archive. NGC 3368 was observed on May 4, 1998, with the NIC2 camera, through the filters F110W and F160W during 128 sec in the framework of a program of Massimo Stiavelli (ID 7331), and on May 8, 1998, with the NIC2 camera through the F160W filter during 320 sec in the framework of a program of John Mulchaey (ID 7330). NGC 3379 was observed on June 14, 1998, with the NIC3 camera through the F160W filter during 192 sec as part of a program of William Sparks (ID 7919). NGC 3384 was observed on April 3, 1998, with the NIC2 camera through the F160W filter during 128 sec for the program of John Tonry (ID 7453).

Almost all the data, spectral and photometric, except the data obtained with the MPFS, have been reduced with software produced by V.V. Vlasyuk at the Special Astrophysical Observatory (Vlasyuk 1993). Primary reduction of the data obtained with the MPFS was done in IDL with software created by one of us (V.L.A.). The Lick indices were calculated with our own FORTRAN program as well as by using a FORTRAN program written by A. Vazdekis. For the reduction of the IFP data we used our IDL software (Moiseev 2002); also the ADHOC software developed at the Marseille Observatory by J. Boulesteix (see
Table 1: Global parameters of the galaxies

<table>
<thead>
<tr>
<th>NGC</th>
<th>3368</th>
<th>3379</th>
<th>3384</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type  (NED\textsuperscript{1})</td>
<td>SAB(rs)ab</td>
<td>E1</td>
<td>SB(s)0-:</td>
</tr>
<tr>
<td>$R_{25}$, kpc (LEDA\textsuperscript{2})</td>
<td>12.6</td>
<td>9.8</td>
<td>9.8</td>
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<tr>
<td>$B_T^0$ (RC3\textsuperscript{3})</td>
<td>9.80</td>
<td>10.18</td>
<td>10.75</td>
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<tr>
<td>$M_B$ (LEDA)</td>
<td>$-20.9$</td>
<td>$-20.5$</td>
<td>$-19.6$</td>
</tr>
<tr>
<td>$(B - V)_T^0$ (RC3)</td>
<td>0.79</td>
<td>0.94</td>
<td>0.91</td>
</tr>
<tr>
<td>$(U - B)_T^0$ (RC3)</td>
<td>0.25</td>
<td>0.52</td>
<td>0.43</td>
</tr>
<tr>
<td>$V_r$, km $\cdot$ s$^{-1}$ (NED)</td>
<td>897</td>
<td>911</td>
<td>704</td>
</tr>
<tr>
<td>Distance, Mpc</td>
<td>11.2</td>
<td>12.6</td>
<td>12.6</td>
</tr>
<tr>
<td>Inclination (LEDA)</td>
<td>55$^\circ$</td>
<td>32$^\circ$</td>
<td>90$^\circ$</td>
</tr>
<tr>
<td>$PA_{\text{phot}}$ (LEDA)</td>
<td>5$^\circ$</td>
<td>71$^\circ$</td>
<td>53$^\circ$</td>
</tr>
</tbody>
</table>

\textsuperscript{1}NASA/IPAC Extragalactic Database
\textsuperscript{2}Lyon-Meudon Extragalactic Database
\textsuperscript{3}Third Reference Catalogue of Bright Galaxies

Table 2: 2D spectroscopy of the galaxies studied

<table>
<thead>
<tr>
<th>Date</th>
<th>Galaxy</th>
<th>Exposure</th>
<th>Configuration</th>
<th>Field</th>
<th>Spectral range</th>
<th>Seeing</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 Feb 99</td>
<td>NGC 3379</td>
<td>60 min</td>
<td>WHT/SAURON+CCD 2k $\times$ 4k</td>
<td>33$''$ $\times$ 41$''$</td>
<td>4800-5400 Å</td>
<td>1$''$5</td>
</tr>
<tr>
<td>8 Feb 00</td>
<td>NGC 3368</td>
<td>45 min</td>
<td>BTA/MPFS+CCD 1024 $\times$ 1024</td>
<td>16$''$ $\times$ 15$''$</td>
<td>4200-5600 Å</td>
<td>1$''$4</td>
</tr>
<tr>
<td>13 Feb 00</td>
<td>NGC 3368</td>
<td>40 min</td>
<td>BTA/MPFS+CCD 1024 $\times$ 1024</td>
<td>16$''$ $\times$ 15$''$</td>
<td>6000-7200 Å</td>
<td>2$''$3</td>
</tr>
<tr>
<td>28 Mar 00</td>
<td>NGC 3368</td>
<td>140 min</td>
<td>BTA/MPFS+CCD 1024 $\times$ 1024</td>
<td>16$''$ $\times$ 15$''$</td>
<td>4840-6210 Å</td>
<td>2$''$5</td>
</tr>
<tr>
<td>11 Dec 99</td>
<td>NGC 3384</td>
<td>45 min</td>
<td>BTA/MPFS+CCD 1024 $\times$ 1024</td>
<td>16$''$ $\times$ 15$''$</td>
<td>4200-5600 Å</td>
<td>1$''$6</td>
</tr>
<tr>
<td>4 Apr 00</td>
<td>NGC 3384</td>
<td>120 min</td>
<td>WHT/SAURON+CCD 2k $\times$ 4k</td>
<td>33$''$ $\times$ 41$''$</td>
<td>4800-5400 Å</td>
<td>3$''$4</td>
</tr>
</tbody>
</table>

Table 3: IFP observations of NGC 3368 at the 6m telescope

<table>
<thead>
<tr>
<th>Date</th>
<th>Exposure</th>
<th>Spectral range</th>
<th>Seeing</th>
</tr>
</thead>
<tbody>
<tr>
<td>28 Feb 00</td>
<td>32 $\times$ 150 sec</td>
<td>around $H\alpha$</td>
<td>2$''$7</td>
</tr>
<tr>
<td>28 Feb 00</td>
<td>32 $\times$ 200 sec</td>
<td>around [NII]$\lambda$6583</td>
<td>3$''$5</td>
</tr>
</tbody>
</table>
http://www-obs.cnrs-mrs.fr/ADHOC/adhoc.html) was used. The observational data were converted into a “data cube” of 32 images. The data reduction includes subtraction of the night sky emission, channel-by-channel correction (Moiseev 2002), wavelength calibration, and spatial and spectral gaussian smoothing. The velocity fields and monochromatic images in both emission lines (Hα and [NII]λ6583) have been constructed by Gauss fitting spectral line profiles; also, images in the red continuum close to the emission lines were calculated from the same IFP “data cubes”.

3. Lick indices and stellar population properties

Up to now there have been a few attempts to map 2D distributions of Lick indices by means of integral-field spectroscopy; we mention here papers by Emsellem et al. (1996) on NGC 4594, by Peletier et al. (1999) on NGC 3379, 4594, and 4472, and by Davies et al. (2001) on NGC 4365. In addition we mention our own papers (Sil’chenko 1999; Sil’chenko & Afanasiev 2000, 2002; Afanasiev & Sil’chenko 2002a,b; Sil’chenko et al. 2002) on NGC 7331, NGC 7217, NGC 4429, NGC 7013, NGC 5055, NGC 4138, NGC 4550, NGC 5574, and NGC 7457. A difficulty entering reliable mapping of Lick indices comes from the fact that we calibrate extended (panoramic) data but are using point-like calibration sources – Lick standard stars that are usually placed in the center of the field-of-view or frame. If the spectral resolution, or the spectral response, or both, vary over the frame, this may result in a systematic distortion of the Lick index distributions over the field of view. We check this effect by measuring Lick-index distributions in twilight exposures: the surface index distributions of the Hβ, Mgb, Fe5270, and Fe5335 calculated from twilight frames must be flat, and the mean level of every index distribution must be close to the values measured by us earlier: Hβ⊙ = 1.86 Å, Mgb⊙ = 2.59 Å, Fe5270⊙ = 2.04 Å, and Fe5335⊙ = 1.59 Å (Sharina et al. 2003). Additionally, we compare azimuthally-averaged index radial profiles with well-calibrated long-slit measurements found in the literature. Figures 2 and 3 present such comparisons for NGC 3379 and NGC 3384, respectively.

The long-slit data along the major axis of NGC 3379 are taken from Vazdekis et al. (1997). Their errors exceed the errors of the azimuthally-averaged SAURON data by several times; however, the Mgb-profile (Fig. 2, middle) allows us to conclude that there is no systematic shift between the SAURON- and Vazdekis et al.’s long-slit data for this particular index. It means that we have properly taken into account, or have justly neglected, the effects which are not related to the wavelength (spectral localization) of the features, i.e., the effects of the spectral resolution and stellar velocity dispersion broadening or contamination by one of the neighboring spectra which does not exceed 2%-3% according to our estimates.
Meantime, the SAURON measurements of H$\beta$ are marginally too high (by less than 0.2 Å), and the SAURON measurements of Fe5270 are certainly too low by 0.3–0.4 Å.

The radial profiles of the Lick indices in NGC 3384 (Fig. 3) have been measured even more thoroughly than those in NGC 3379: we have plotted the azimuthally-averaged MPFS and SAURON data as well as major- and minor-axis long-slit measurements from Fisher et al. (1996). Again, the radial profile of Mgb looks the most reliable among all the indices—probably, because the magnesium line falls in the middle of the spectral range observed. The H$\beta$ measurements outside of the nucleus according to SAURON are higher by 0.3–0.4 Å as compared to the MPFS, and in this particular case the Fisher et al.’s measurements support the SAURON results. But as for Fe5270, the SAURON data are again too low by ~0.4 Å, as seen already in the case of NGC 3379. de Zeeuw et al. (2002) present preliminary SAURON results on NGC 3384 and noted this disagreement between their and Fisher et al. (1996) measurements, but they insisted that their results were more correct. Since our MPFS data for Fe5270 in NGC 3384 agrees with that of Fisher et al. (1996) and since the same systematic shift of Fe5270 is observed in NGC 3379, we suppose that the SAURON values of the iron index are systematically underestimated.

However, intrinsically the SAURON azimuthally-averaged data are very precise: a typical error for every point in the profiles of Figs. 2 and 3 is 0.02 – 0.04 Å (the accuracy of the MPFS azimuthally-averaged indices is about 0.1 Å). Their high quality allows us to diagnose chemically distinct cores in both galaxies NGC 3379 and NGC 3384: although the magnesium- and iron-index breaks are of rather low amplitude, we note a certain change of the profile slopes at $R \approx 4\arcsec$. Let us also note that we predicted the existence of a chemically distinct nucleus in NGC 3379 from the multi-aperture photometric data (Sil’chenko 1994). If we approximate the ‘bulge’ data at $R \geq 4\arcsec$ by linear fits (the parameters of these fits are given in Table 5), we can obtain extrapolated ‘bulge’ indices at $R = 0\arcsec$, or in the very centers of NGC 3379 and NGC 3384, and compare them to the real nuclear indices; the differences would characterize a chemical distinctness of the nuclei. In NGC 3384 (Fig. 3) $\Delta$Mgb=0.64 Å and $\Delta$Fe5270=0.42 Å, ±0.08 Å. If we treat the differences of metal-line indices between the nucleus and the extrapolated bulge as a difference of metallicity and apply the evolutionary synthesis models for old stellar populations of Worthey (1994), we obtain $\Delta[Fe/H]=+0.3$, the nucleus being on average more metal-rich, the $\Delta$Mgb and $\Delta$Fe5270 results being consistent. In NGC 3379 (Fig. 2) the chemical distinctness of the core is more modest: $\Delta$Mgb=0.26 ± 0.06 Å corresponds to $\Delta[m/H]=+0.1$, and $\Delta$Fe5270=0.08 Å implies an even smaller $\Delta[Fe/H] \approx +0.05$, which is evidence for a marginally higher magnesium-to-iron ratio in the ‘nucleus’ as compared to the ‘bulge’.

High-precision radial profiles of absorption-line indices provide a zero-order diagnostic
Table 4: Photometric observations of the galaxies studied

<table>
<thead>
<tr>
<th>Date</th>
<th>Galaxy</th>
<th>Filter</th>
<th>Exposure time</th>
<th>Scale, ″ per px</th>
<th>Seeing</th>
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<tr>
<td>18 Apr 00</td>
<td>NGC 3368</td>
<td>J</td>
<td>15 min</td>
<td>0.3</td>
<td>1″.5</td>
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<td>NGC 3368</td>
<td>H</td>
<td>12 min</td>
<td>0.3</td>
<td>1″.5</td>
</tr>
<tr>
<td>18 Apr 00</td>
<td>NGC 3368</td>
<td>K'</td>
<td>12 min</td>
<td>0.3</td>
<td>1″.5</td>
</tr>
<tr>
<td>12 Mar 01</td>
<td>NGC 3368</td>
<td>J</td>
<td>15 min</td>
<td>0.85</td>
<td>2″.1 × 1″.5</td>
</tr>
<tr>
<td>12 Mar 01</td>
<td>NGC 3368</td>
<td>H</td>
<td>14 min</td>
<td>0.85</td>
<td>2″.4 × 1″.8</td>
</tr>
<tr>
<td>16 Mar 01</td>
<td>NGC 3384</td>
<td>J</td>
<td>12 min</td>
<td>0.85</td>
<td>2″.5 × 1″.85</td>
</tr>
<tr>
<td>16 Mar 01</td>
<td>NGC 3384</td>
<td>H</td>
<td>12 min</td>
<td>0.85</td>
<td>2″.2 × 1″.8</td>
</tr>
<tr>
<td>16 Mar 01</td>
<td>NGC 3384</td>
<td>K'</td>
<td>12 min</td>
<td>0.85</td>
<td>2″.1 × 1″.65</td>
</tr>
</tbody>
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Table 5: Linear fits of the Lick index gradients in the bulges

<table>
<thead>
<tr>
<th>Lick index</th>
<th>( a ), Å per arcsec</th>
<th>( b ), Å</th>
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<tr>
<td>NGC 3379</td>
<td></td>
<td></td>
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<tr>
<td>Mgb</td>
<td>(-0.0261 \pm 0.0023)</td>
<td>4.59 ± 0.002</td>
</tr>
<tr>
<td>Fe5270</td>
<td>0</td>
<td>2.64 ± 0.01</td>
</tr>
<tr>
<td>NGC 3384</td>
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</tr>
<tr>
<td>Mgb</td>
<td>(-0.0381 \pm 0.0036)</td>
<td>4.04 ± 0.03</td>
</tr>
<tr>
<td>Fe5270</td>
<td>(-0.0142 \pm 0.0036)</td>
<td>2.61 ± 0.03</td>
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of the central stellar substructures; but with 2D index distributions we are able to discuss a morphology of the chemically distinct entities and their relation to photometric substructures, in particular to compact circumnuclear disks. Let us consider in detail every galaxy of our small sample.

3.1. NGC 3379

Figure 4 presents Lick-index maps for the central part of NGC 3379. As expected, the chemically distinct nucleus is better seen in Mgb; the central maximum of Fe5270 is of rather low contrast, and the distribution of Hβ looks almost flat. The core distinguished by the enhanced magnesium line is well-resolved and has an elongated shape. After heavy smoothing (Fig. 4, upper right) we are able to determine an orientation of this elongated magnesium-rich core: \( PA_{\text{core}} \approx 84^\circ \). The magnesium-index isolines trace a substructure which is more flat than the main stellar body: the axis ratio of the magnesium-index isolines is \( b/a_{\text{Mg}} \approx 0.5 \), whereas the isophote axis ratio is \( b/a_{\text{phot}} \approx 0.9 \). Is it a compact, \( R \leq 4'' \), circumnuclear disk that is seen as a chemically distinct core?

Figure 5 allows us to quantify characteristics of the stellar populations in the center of NGC 3379 at different distances from the center. The magnesium-iron diagram (Fig. 5, top) reveals a systematic shift of the galactic measurements with respect to a model locus of the populations with the solar magnesium-to-iron ratio plotted according to Worthey (1994). Although we know already from the analysis of Fig. 2 that the SAURON data of Fe5270 are slightly too low with respect to the standard Lick system, the systematic shift of the NGC 3379 measurements relative to Worthey’s models is so large that it cannot be explained by any index system bias. For example, the data of Trager et al. (1998) for the very center of NGC 3379 and the sequence obtained by substitution of the Vazdekis et al. (1997) long-slit data on Fe5270 in the radial profile table (Fig. 5, top) are also away from the model locus. We have to conclude that the nucleus (core) of NGC 3379 is magnesium overabundant, \([\text{Mg/Fe}] = +0.2 + 0.3\), and this enhanced Mg/Fe ratio holds to an approximately constant level (within 0.05 dex) as a function of radius.

So to determine an age of the stellar population in the center of NGC 3379, we must use the models with \([\text{Mg/Fe}] > 0\); such as the models of Tantalo et al. (1998) that are calculated in particular for \([\text{Mg/Fe}] = +0.3\). But the models of Tantalo et al. (1998) involve the combined iron index \( \langle \text{Fe} \rangle \equiv (\text{Fe5270} + \text{Fe5335})/2 \), and we have only Fe5270 which is unfortunately biased. By plotting an age-diagnostic diagram (Fig. 5, bottom), we have confronted the \( \langle \text{Fe} \rangle \) measurements of Vazdekis et al. (1997), which are well-calibrated on to the Lick system, though are not very precise, to our measurements of Hβ at the same
distances from the center, which on the contrary have a small error. Since the accuracy of the age estimates is determined mainly by the Hβ accuracy, we obtain a certain mean (luminosity-weighted) age estimate of 8–9 Gyr for the very center ($R < 8''$) of NGC 3379, with possible variations within one Gyr with radius. The mean age of the stellar population in the core of NGC 3379 below 10 Gyr is in agreement with the recent result of Terlevich & Forbes (2002) who have found an integrated value of 9.3 Gyr within an aperture of $R_e/8$.

3.2. NGC 3384

Figure 6 presents Lick index maps for the center of NGC 3384 which have been obtained with the MPFS, and Fig. 7 presents similar maps obtained with SAURON for a larger area; note that the iron-index map covers the full area whereas the preliminary results of de Zeeuw et al. (2002) showed only half of the field of view because of some problems they had with the data reduction. The spatial resolution of the former map is better by a factor of two than that of the latter, so in Fig. 6 we see a lot of subtle details which are not seen in Fig. 7. However, common features can also be noted: the magnesium index demonstrates a central maximum, rather compact and at high-contrast, and well-resolved. Also, the iron enhancement in the center of NGC 3384 is more diffuse and extended, so even from the analysis of Figs. 6 and 7 “by eye” it is suggestive that there is a gradient of the magnesium-to-iron ratio with radius. The metal-line enhanced areas are elongated as if they were produced by a compact circumnuclear disk appearance; however when we drew isolines of the Mgb distribution (Fig. 7, upper right), we convinced ourselves that their orientation, $P A_{M g} \approx 20^\circ - 25^\circ$, differs substantially from the orientation of the inner isophotes, $P A_{inner} \approx 40^\circ - 45^\circ$ (see the next Section), and from the line of nodes, $P A_0 = 53^\circ$ (Table 1). The Hβ distribution demonstrates an unresolved peak in the nucleus in the MPFS data only (Fig. 6, left), whereas the SAURON data is evidence for quite a flat distribution (Fig. 7, lower right).

The diagnostic diagrams for the average data at different radii are shown in Fig. 8, which includes only the MPFS data as they offer unbiased iron-index estimates. These diagrams present a slightly different picture from that in the center of NGC 3379. Indeed, there exists a Mg/Fe ratio gradient (Fig. 8, top): the nucleus is obviously magnesium-overabundant, $[\text{Mg/Fe}]_{nuc} \approx +0.3$ if one takes into account its very young mean age (see Fig. 8, bottom); and at $R \geq 5''$ the Mg/Fe ratio is about solar. Consequently, to determine a mean age, we must use two sets of stellar population models, with $[\text{Mg/Fe}] = +0.3$ and with $[\text{Mg/Fe}] = 0$. Figure 8, bottom, presents the comparison of our data to the models of Tantalo et al. (1998) for both values of $[\text{Mg/Fe}]$. One can see that the unresolved nucleus of NGC 3384 is rather young for a lenticular host: its mean stellar age is less than 5 Gyr, and probably close to
3 Gyr; the general metallicity is higher than the solar one: \([m/H]_{\text{nuc}} \approx +0.3 - +0.4\). In the nearest vicinity of the nucleus the metallicity drops to the quasi-solar value, and the mean age increases to 7–8 Gyr. Therefore, although in the center of NGC 3384 an extended region looks chemically distinct (the net dimensions of this region are difficult to determine because they are comparable to our resolution limit), the unresolved stellar nucleus has probably followed its own, quite separate evolution.

3.3. NGC 3368

The maps of the metal-line Lick indices for the central part of NGC 3368 (Fig. 9) demonstrate a qualitative difference with respect to the maps of the centers of NGC 3379 and NGC 3384: instead of peaks in the nuclei they show ‘holes’ – net minima of Mgb and \(\langle \text{Fe} \rangle\) just where the surface brightness has a maximum. These holes may be evidences for a metal deficiency of the nuclear stellar population, or more likely, for its extreme youth. Magnesium- and iron-index enhancements can also be seen in the maps of Fig. 9, especially on the February MPFS maps (Fig. 9, top) which have a better spatial resolution, but these peaks are off-nuclear. The Mgb index has two maxima at the major axis located at \(R \approx 4''\) symmetrically with respect to the nucleus, and the iron index \(\langle \text{Fe} \rangle\) demonstrates something like a half-ring with a radius of \(2'' - 3''\). Such features associated usually to star-forming rings and ‘bright circumnuclear spots’ are clear signatures of a bar presence; indeed, the isophotal twist in the center of NGC 3368 can be noticed even over the very limited area covered by the MPFS frame. In the recent study of NGC 3368 structure and kinematics by Moiseev et al. (2002) the presence of the minibar with an extension of about \(5''\) has also been noted.

The age diagnostics in the center of NGC 3368 is complicated because of rather intense ionized-gas emission: the H\(\beta\) absorption-line index is contaminated by the Balmer emission line. We have tried to take into account the effect of H\(\beta\) in emission when calculating azimuthally-averaged index profiles: we have co-added separately the blue and the red spectra in the same concentric rings; then, by using the red spectra at various radii, we estimated equivalent widths of the H\(\alpha\) emission line which is stronger than H\(\beta\) and can be surely measured even inside a deep H\(\alpha\) absorption line; after that we calculated the H\(\beta\)-index correction by involving the mean relation between H\(\alpha\) and H\(\beta\) emission lines in normal galaxies, \(EW(H\beta_{\text{em}}) = 0.25EW(H\alpha_{\text{em}})\) (Stasinska & Sodre 2001). The corrected indices taken as a function of radius are plotted in the diagnostic diagrams presented in Fig. 10. The correction applied to the H\(\beta\) index is close to the minimal possible one (corresponding to pure radiative ionization), so the derived ages may be slightly overestimated. By considering both diagrams in Fig. 10 together, one can conclude that the nuclear stellar population has
a mean age of 3 Gyr and a mild magnesium overabundance, $[\text{Mg}/\text{Fe}] \approx +0.2$. When moving toward $R \approx 10''$ in radius, the mean age strongly increases, and the magnesium-to-iron ratio drops to the solar value.

The ages that we determine by confronting the measured integrated-spectra indices to simple (one-age, one-metallicity) stellar population models are indeed mean luminosity-weighted ages: if one has a mix of populations of different ages, each of them would contribute to the integrated spectrum proportionally to its luminosity, and from the diagnostic diagrams like that in Fig. 10 (bottom), one could obtain an age estimate, intermediate between extreme individual stellar generation ages. So although we have obtained a mean age of 3 Gyr for the nuclear stellar population in NGC 3368, it does not mean that all stars there have been formed 3 Gyr ago; it means that we see a superposition of an intermediate-age stellar generation onto the older stellar bulge. To illustrate this idea, we have constructed a model experiment for the age-diagnostic diagram of Fig. 10: to a moderately metal-poor ($[\text{Fe}/\text{H}]=-0.22$), old ($T = 12$ Gyr) bulge we added a relatively young “poststarburst” population with $[\text{Fe}/\text{H}]= +0.25$ and two trial ages – 1 and 3 Gyr, with a contribution from 1% to 80% of the total mass. The calculations were made with the ‘Dial-a-model’ machine of Guy Worthey available at his WEB-page (http://astro.wsu.edu/worthey/). Two model sequences corresponding to $T_{\text{burst}} = 1$ and 3 Gyr were plotted in Fig. 10 (bottom), along which the contribution of the young population varies. One can see that although the former sequence crosses the SSP-model line for $T_{\text{SSP}} = 3$ Gyr at a value of $\sim 20\%$ the overall trend of the $T = 1$ Gyr young starburst deviates from the observational points, whereas the $T_{\text{burst}} = 3$ Gyr sequence coincides exactly with the radial trend in the index in the center of NGC 3368. So we conclude that the age of the secondary nuclear star formation burst of 1 Gyr or less can be excluded and that whereas $T_{\text{nuc}} = 3$ Gyr is the mean luminosity-weighted estimate, the true age of the secondary starburst does not differ strongly from this value.

4. Stellar and gaseous kinematics in the centers of the Leo I Group galaxies

Since integral-field spectroscopy provides us with two-dimensional line-of-sight velocity fields, we are able now to analyse both the rotation and central structure of the galaxies. 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 the “kinematical major axis”) should coincide with the line of nodes as well as the photometric major axis, whereas in a case of a triaxial potential the isovelocities align with the principal axis of the ellipsoid and the kinematical and photometric major axes generally diverge, showing twists in an opposite sense with respect to the line of nodes (Monnet et al. 1992; Moiseev & Mustsevoy
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 gradients within the area of solid-body rotation:

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

where \( \omega \) is the deprojected central angular rotation velocity, \( i \) is the inclination of the plane, and \( PA_0 \) is the orientation of the line of nodes, coinciding in the case of an axisymmetric ellipsoid (or a thin disk) with the photometric major axis. So by fitting azimuthal variations of the central line-of-sight velocity gradients with a cosine curve, we can determine the orientation of the kinematical major axis by its phase and the central angular rotation velocity by its amplitude. This is our main tool for kinematical analysis.

Let us note that the method of the analysis of line-of-sight velocity gradients works correctly only within the area of solid-body rotation. Therefore it cannot be used for a large-scale velocity field (beyond the central kpc region). For analysis of the IFP’s velocity fields we applied a method usually referred to as the ‘tilted-ring’ method (Begeman 1989). In the framework of this method the velocities were fitted in elliptical rings (elongated along the PA of the galactic disk major axis) by a model of pure circular rotation. As a first step we found and fixed the rotation center position which is the center of symmetry of the velocity fields. As a second step we calculated the radial dependence of the model parameters: systemic velocity \( V_{sys} \), rotational velocity \( V_{rot} \), disk inclination \( i \) and position angle of the kinematical major axis \( PA_0 \). And finally, \( i \) and \( V_{sys} \) were fixed at their mean values and the run of \( V_{rot}(r) \) and \( PA_0(r) \) with radius were obtained. Radial variations of \( PA_0 \), if present, can be used for detecting various types of non-circular motions – see Moiseev & Mustsevoy (2000) for details and references.

4.1. NGC 3379

NGC 3379 was treated earlier as an example of a classic elliptical galaxy – round and homogeneous. However, recent kinematic studies by using a long-slit technique (Statler & Smecker-Hane 1999; Pastoriza et al. 2000) have proved that at least the central part of the galaxy consists of several subsystems including a highly inclined dust (and gaseous?) ring and that NGC 3379 may be a misclassified S0. Since we analyse the results of 2D kinematic mapping, new details showed up to complicate the picture.

Figure 11 shows the stellar line-of-sight velocity field and the stellar velocity dispersion
field measured from the SAURON data. The former field demonstrates a rather fast (for an elliptical galaxy), quasi-axisymmetric rotation; the latter field reveals a prominent maximum in the center with a quasi-axisymmetric radial decrease of the velocity dispersion –both facts were already noted, e.g. by Statler & Smecker-Hane (1999). We have measured an orientation of the kinematical major axis up to $R \approx 5''$, which is the approximate edge of the rapidly rotating area, and have found that it changes significantly from a $PA_{kyn} = 265^\circ$ (85°) at $R \approx 2''$ to $PA_{kyn} = 256^\circ$ (76°) at $R = 4'' - 5''$. We compare the orientation of the kinematical major axis to that of the photometric major axis according to the data of Frei et al. (1996) and to the NICMOS/HST image analysis results in Fig. 12; we would like also to refer to the results of the analysis of the WFPC2/HST images of NGC 3379 by Pastoriza et al. (2000). Within $R \leq 15''$ the photometric major axis deviates in a positive sense from the tabulated outer isophote orientation $PA_0 = 70^\circ$ (see the Table 1) and agrees well with the kinematical major axis. Let us also remind here that the isolines of the enhanced magnesium index deviate from the outer isophote orientation too, although they are aligned with the kinematical major axis; and they have a more flattened distribution than the isophotes. Such coincidences are evidence for a compact stellar disk in the center of NGC 3379 which may be inclined to the main symmetry plane of the galaxy. There exists another inclined circumnuclear disk in NGC 3379 – a dust-gaseous one, with a radius of 2'' and $PA_0 = 125^\circ$ (Pastoriza et al. 2000). Are they related? In our Fig. 12, and also in Fig. 3 of Pastoriza et al. (2000), based on the high-resolution results of the HST/WFPC2 F555W and F814W isophote analysis, one can see a strong twist of the major axis when approaching the center, inside the central arcsecond. Pastoriza et al. (2000) thought it to be an effect of the dust ring projection. But the dust ring with an orientation of $PA = 125^\circ$ would force an isophote twist in a polar direction, so in a negative sense with respect to the line of nodes $PA_0 = 70^\circ$. Such a turn is really observed in the radius range of $0''.8 - 1'.5$ (Fig. 12). However within $R = 0'.4$ the effect of the dust ring having a radius of 2'' is negligible. We would think the circumnuclear isophote twist of $PA \approx 102^\circ$ in our measurements, or even up to $PA \approx 120^\circ$, as the rectified analysis of Pastoriza et al. (2000) suggests, to be real and to represent a signature of the inclined circumnuclear stellar disk which is probably related to the dust-gaseous one. Some discrepancies of the position angle estimates can be explained by different spatial resolutions of the data.

4.2. NGC 3384

Figure 13 presents the stellar line-of-sight velocity field and that of the stellar velocity dispersion in the center of NGC 3384, according to the data from MPFS (top) and SAURON (bottom). The stellar LOS-velocity field reveals a fast regular rotation, with isovelocity
features typical for a disk embedded into a massive bulge (tight isovelocity crowding near the line of nodes, etc). The presence of the compact circumnuclear stellar disk with a radius of 6″ in the center of NGC 3384 was found earlier from a photometric analysis by Busarello et al. (1996), so we confirm their finding from a kinematical point of view. Yet another exotic subcomponent – a stellar polar ring suggested by Davoust et al. (1984) and Whitmore et al. (1990) – can be discarded with certainly based on the same kinematical arguments. This latter feature is localized in the radius range of 10″ – 25″, and the large SAURON velocity map for the stars in the center of NGC 3384 does not show any switch of the spin orientation (toward the polar direction) at $R = 10″ – 15″$. Hence we diagnose this morphological feature (identified as “EC” in the terminology of Busarello et al.) as a bar. Bars belong always to disks (cold dynamical subsystems), so we conclude that the inclination of 90° given for NGC 3384 by LEDA (see the Table 1) is erroneous: one would not see a bar along the minor axis as an elongated structure under edge-on orientation of the global disk; in the meantime, the refined analysis of Busarello et al. (1996) has demonstrated a very elongated, almost “peanut”-shape structure, with $PA = 132°$, in this radius range. We show radial variations of the characteristics of global isophotes in NGC 3384 obtained through the NIR broad-band filters in Fig. 14. The sharp maximum of isophote position angle at $R = 15″$ and the corresponding minimum of the ellipticity refer to a superposition of a flattened spheroid with $PA_0 ≈ 50°$ and of a bar almost along the minor axis. An asymptotic ellipticity at $R > 60″$, $1 - b/a = 0.45$, implies a possible disk inclination as low as 57°, (Barbon et al. (1975) obtained $i = 63.5°$). If the symmetry plane of NGC 3384 is inclined by some 60° to the line of sight, the proposed “polar ring” is indeed a bar in the disk plane with a radial extension of $\sim 2.5 \text{ kpc} (40″)$. The presence of the bar in NGC 3384 is confirmed by the stellar velocity dispersion distribution in the center of the galaxy (Fig. 13): it has a strongly elongated shape with a flat maximum aligned roughly with the minor axis. As Vauterin & Dejonghe (1997) have shown from dynamical modelling, within the bar potential the stellar velocity dispersion distributions are elongated along the bars. Just this picture is observed in the center of NGC 3384.

Let us quantify the kinematical arguments in favor of the circumnuclear disk. In Fig. 15 we compare orientations of the photometric (according to the HST data) and the kinematical (according to the MPFS and the SAURON data) major axes within $R \approx 5″$ from the center. The agreement is good within $1° - 2°$, or certainly to within our accuracy limits. However both photometric and kinematic major axes ($PA_{\text{phot}} = 46° (226°)$ and $PA_{\text{kin}} = 225.5° \pm 1.2°$) deviate significantly (and consistently!) from the line of nodes, $PA_0 = 53°$. Such behavior is evidence for an inclined circumnuclear stellar disk. Interestingly, as the orientation of the bar is $PA_{\text{bar}} = 132°$ (Busarello et al. 1996), obviously we deal with a disk which is polar with respect to the bar. Such a configuration can be often encountered when
studying circumnuclear gas rotation within a triaxial potential (Afanasiev & Sil’chenko 1999; Sil’chenko & Afanasiev 2000). Here for the first time we have faced a similar, but completely stellar substructure.

4.3. NGC 3368

The kinematical picture in the center of NGC 3368 can be presented in more detail than that in NGC 3379 and NGC 3384 because its intense emission lines provide us with the velocity field of the ionized gas. However more information does not clarify the situation but rather makes it quite puzzling.

Figure 16 presents the stellar velocity field and the stellar velocity dispersion distribution in the center of NGC 3368 according to the MPFS data of February 2000; the analogous data of the March 2000 observations are described by Moiseev et al. (2002). The isovelocities demonstrate a regular solid-body rotation of stars; but the kinematical major axis is strongly different from the orientation of the inner isophotes which have a noticeable twist of the major axis over the radius range of $0'' - 8''$, unlike the isovelocities. The stellar velocity dispersion map is rich with subtle details and looks quite unusual: the nucleus is not distinguished, neither by a peak nor by a minimum of $\sigma_*$, but two arc-like regions – one of low stellar velocity dispersion at $R \approx 4'' - 6''$ and another of high stellar velocity dispersion at a larger radius – prevent any reasonable interpretation of this data.

Figure 17 shows the ionized-gas velocity field and the 2D distributions of the emission-line surface brightness for [NII] $\lambda 6583$ and H$\alpha$ which are obtained with MPFS. Again, the gas rotates rather regularly and as a solid body up to the edges of the area investigated. As for the emission maps, here there is a surprise: whereas the [NII] emission distribution repeats roughly the shape of the continuum isophotes, the H$\alpha$ emission-line intensity distribution is elongated orthogonally, approximately along the minor axis of the inner isophotes. Is this structure real? Let us appeal to high-resolution imagery. Figure 18 shows, firstly, the WFPC2/HST map of NGC 3368 in the visual regime and secondly, the NICMOS/HST color map (close to $J-H$). One can see a quasi-polar compact dust ring encircling the north-west part of the central elongated structure (of a minibar?). The dust (and gas?) density in this polar ring is so high that it is seen very well even at wavelengths longer than 1 mkm; it manifests itself at the color map as a red lane aligned in $PA \approx 30^\circ - 35^\circ$ to the north-west from the blue nucleus. Since this dust polar ring is traced by the H$\alpha$ emission, but is unseen in the [NII] emission line, we may suppose that it is a site of intense current star formation. Why is it polar? Inner gas polar structures are often met in the galaxies with a triaxial central potential as we have already mentioned when considering NGC 3384.
Let us quantify, as is usually done, a characteristic of rotation of the stars and ionized gas in the center of NGC 3368. In Fig. 19 we have plotted some selected azimuthal dependencies of the central LOS velocity gradients for the stars in radius ranges of 2′′0–2′′8 and of 3′′0–4′′2 and for the ionized gas in a radius range of 2′′3–3′′3; for the stars we have plotted both the February and the March MPFS data, their agreement being excellent. The stars rotate slightly slower than the gas: 19 ± 2 km/s/arcsec versus 26.4 ± 4.2 km/s/arcsec. The long-slit observations by Vega Beltrán et al. (2001) also confirm this kinematical feature. It is natural because the stellar velocity dispersion in the center of NGC 3368 is larger than 100 km/s, and the emission lines are narrow. However the orientation of the kinematical major axes for the ionized gas and for the stars are rather similar: 176° ± 2° for the former and 167.5° ± 1.5° for the latter subsystem. Indeed, we have no serious reasons to treat the gas and stellar rotations as different – they may rotate together. The coincidence of the kinematical major axes near $PA_{kyn} \approx 170°$, an orientation which is not marked in any way in the central part of NGC 3368, is very strange. One could understand a rotation of the central ionized gas in the plane towards $PA = 170°$, because the outermost neutral hydrogen is distributed in an extended disk with just this line of nodes (Schneider 1989). Meanwhile the molecular gas in the central part of the galaxy demonstrates elliptical isodensities elongated in $PA \approx 40°$ (Sakamoto et al. 1999) – the direction that coincides with the line of nodes of the dust polar ring; but the velocity field of the molecular gas over the entire area covered by mapping resembles rather a prolate rotation, with $PA_{kyn} \approx 170°$ (Sakamoto et al. 1999). So, once more, for the ionized gas the orientation of the rotational plane at $PA_{kyn} = 170° – 175°$ is kinematically understandable; but among the visible stellar structures in NGC 3368 there are none with a distinguishing orientation at this position angle – see Figs. 20 and 21. Figure 20 shows a comparison of the NICMOS/HST isophote characteristics with orientation of the kinematical major axes. The $PA_{kyn} \approx 170°$ holds in the radius range of 2′′ – 5′′ whereas the orientation of the isophotes holds at $PA_{phot} \approx 125°$ (closer to the nucleus the isophotes twist by more than 100°, and we think this twist to be caused by an effect of the dust polar ring projection). Moiseev et al. (2002) have argued from the azimuthal Fourier analysis of the large-scale surface brightness distributions that the line of nodes of the inner ($R < 140′′$) disk of NGC 3368 is $PA_0 = 135°$ and that the value of 5° given by LEDA may be related only to the very outermost part of the galaxy. So we are convinced that in the center of NGC 3368 we see a minbar with a semimajor axis of 5′′; however non-circular streaming motions around the bar with $PA_{bar} = 125°$ located in the disk with $PA_0 = 135°$ would cause a twist of the kinematical major axis from the line of nodes in a positive sense, as observed, but only by about 10° (Monnet et al. 1992). Meanwhile it turns by at least 30°, and therefore this turn cannot be explained by a simple dynamical effect of minbar triaxiality. Do we observe a rotation of a rather young faint stellar subsystem which is formed from the circumnuclear gas and shares its spin? It would be possible if this subsystem is much colder than the bulge
dominating the surface brightness.

Fig. 21 shows large-scale radial variations of the isophote characteristics of NGC 3368 to illustrate its very complex structure. While the surface brightness profile of the galaxy looks very regular, with a single-scale exponential disk dominating the bulge at $R > 22''$ (Kent 1985), the isophote orientation and ellipticity change all the way up to the optical edges of the galaxy, implying either disk oval distortions or a strong disk warp. As mentioned in Section 2 we used the scanning Fabry-Perot data to study the large-scale $(r = 100'' - 200'')$ kinematics of the ionized gas in two emission lines ($\text{H}\alpha$ and $[\text{NII}]\lambda 6583$). The velocity fields in both lines are shown in Fig. 22. Unfortunately stellar absorption and interference orders which overlap distort the emission line profiles in the $\text{H}\alpha$ datacube over the central region of the galaxy. We cannot resolve this problem because the free spectral range of the IFP is small ($\sim 28\,\text{Å}$). Therefore the $\text{H}\alpha$ line-of-sight velocities were measured only in the star-forming ring ($r=50'' - 90''$) and in fragments of spiral arms. But the $[\text{NII}]$ velocity field was constructed over the full range in radius (Fig. 22). The shape and orientation of the isovelocity contours at $r < 7''$ demonstrate an agreement with the MPFS velocity field in $[\text{NII}]\lambda 6583$ of Fig 17. The ‘tilted-ring’ analysis of our Fabry-Perot velocity fields confirms the stable orientation of the ionized gas kinematical major axis at $PA_{kyn} = 170^\circ - 175^\circ$ over the global disk of the galaxy out to a distance of 200'' from the center. So the global dust-gaseous disk of the galaxy is probably decoupled completely from the stellar one, having its own orientation in space. Since an HI bridge is seen between the intergalactic gaseous ring and NGC 3368 (Schneider 1985), we suggest that all the gas in this spiral galaxy is of recent external origin and is not yet relaxed with respect to the main symmetry plane of the galaxy. We must stress the good agreement between the measurements of the $PA_{kyn}$ in two independent IFP velocity fields; but also we note a discrepancy of the rotational velocity amplitudes. The differences between the rotational velocities in the $\text{H}\alpha$ and $[\text{NII}]$ (Fig 22) may be explained in the frame of the hypothesis of the inclined gaseous disk. As it is shown in Fig 22, the $[\text{NII}]$ rotation velocity at $r = 50'' - 90''$ is systematically slower by $\sim 50\,\text{km}\cdot\text{s}^{-1}$ than the $\text{H}\alpha$ one (under the assumption of a disk inclination of $i = 48^\circ$). If the gaseous disk is inclined to the main galaxy plane then shock-wave fronts can exist at the cross-section of the global stellar and gaseous disks, because gas strikes the gravitational well. Moreover, the strong stellar spiral arms in this region intensify the contrast of the gravitational potential. Therefore the low $[\text{NII}]$ velocities may be explained if the part of the nitrogen emission line is emitted by shock-excited gas slowed down by collisions with the stellar disk and spiral arms.
5. Discussion

We have considered the three brightest galaxies in the vicinity of the intergalactic gaseous ring in the Leo I group. We have found that all three galaxies have peculiarities, or extra components, in their centers; and the space orientations of these extra components are related to the line of nodes of the intergalactic gaseous ring, $PA_{\text{ring}} \approx 40^\circ$, in all three cases. NGC 3384 has a circumnuclear stellar disk with the line of nodes at $PA = 45^\circ$, inclined to the main symmetry plane of the galaxy but aligned with the global intergalactic gaseous ring. NGC 3368 has a polar (relative to the central minibar) dust-gaseous ring with a projected major axis at $PA \approx 35^\circ$, and its CO distribution is also elongated in $PA \approx 40^\circ$. NGC 3379 has a circumnuclear dust-(and gaseous) ring (and probably a stellar disk) with the major axis at $PA = 120^\circ - 125^\circ$, orthogonal to the intergalactic ring orientation; but it is the only elliptical galaxy among ours, with a clear signature of triaxiality (Statler & Smecker-Hane 1999), so its triaxial main body may provoke gas transfer on to a polar orbit when spiraling to the center. These are too many coincidences, if one takes into account the diversity of the global major axis orientations (see Table 1). We can suggest that all the circumnuclear structures mentioned above have the origin related to accretion of the gas from the intergalactic ring; in this case the spin conservation would provide alignment of the circumnuclear disks at $PA_0 = 40^\circ$, except in NGC 3379. Geometry and sizes of the circumnuclear structures must depend strongly on the global structures of the galaxies under consideration, in particular on their triaxiality and spheroid/disk ratios. And finally, the closely related mean ages, 3 Gyr, of the nuclear stellar populations in NGC 3368 and NGC 3384 (in NGC 3379 it may seem older because of the larger contribution of the old spheroid to the integrated spectrum) imply that a characteristic time between accretion events, or a timescale for interaction between the galaxies and the intergalactic ring, is of the order of several Gyrs, or of order the revolution time of the intergalactic ring which is 4 Gyr, or of order of the crossing time in the Leo I group. This result rejects conclusively the scenario of Rood & Williams (1985) who proposed a collision between NGC 3368 and NGC 3384 only 0.5 Gyr ago.

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Fig. 1.— The Lick-system index calibration of the SAURON data obtained during the observing run of March/April 2000; 18 stars from the list of Worthey et al. (1994) are used. Dashed lines are the bisectors of the quadrants, solid straight lines are the regression lines calculated by the least-square method.
Fig. 2. — Comparison of the SAURON set of the azimuthally-averaged index measurements for NGC 3379 with the long-slit data taken along the major axis by Vazdekis et al. (1997). The central 4''-aperture measurements from Trager et al. (1998) and Kuntschner et al. (2001) are also plotted. To stress the break of the Mgb behavior at $R \approx 5''$ the straight line fitted by the least-square method to the SAURON data at $R = 5'' - 12''$ is drawn in the middle plot.
Fig. 3.— The comparison of the SAURON and MPFS sets of the azimuthally-averaged index measurements for NGC 3384 with the long-slit data taken along the major and minor axes by Fisher et al. (1996). The central 4′-aperture measurements from Trager et al. (1998) and Kuntschner et al. (2001) are also plotted.
Fig. 4.— The SAURON index maps for NGC 3379. A green ($\lambda$5000 Å) continuum is overlaid as isophotes in three plots out of four. At the top right the Mgb index distribution, smoothed heavily with a 2D Gaussian of $FWHM = 3''5$ is plotted by isolines to show the orientation of the chemically decoupled structure; here the green continuum is gray-scaled. In all plots the North is up, the East is left.
Fig. 5.— The ‘index vs index’ diagnostic diagrams for the azimuthally-averaged SAURON index measurements and long-slit data from Vazdekis et al.(1997) for NGC 3379. The SAURON data points (open circles) are taken along the radius of the galaxy with a step of 0.94. As a reference frame, the model equal-age sequences from Worthey (1994) for old stellar populations with [Mg/Fe]=0 are shown in the top plot as small signs connected by thin lines; the metallicities for 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. Since the stellar population in NGC 3379, according to the top plot, has [Mg/Fe]> 0, the models of Tantalo et al.(1998) for [Mg/Fe]= +0.3 are used for the age diagnostics at the bottom plot; for these models the metallicities are +0.4, 0.0, and -0.7
Fig. 6.— The MPFS index maps for NGC 3384 \((\langle \text{Fe} \rangle \equiv (\text{Fe}5270+\text{Fe}5335)/2)\). A green \((\lambda 5000 \text{ Å})\) continuum is overlaid by isophotes. The images are direct, \(PA(top) = 46^\circ\).
Fig. 7.— The SAURON index maps for NGC 3384. A green (λ5000 Å) continuum image is overlaid as isophotes in three plots out of four. At the top right the Mgb index distribution smoothed heavily with a 2D Gaussian of FWHM = 3′5 is plotted by isolines to show the orientation of the chemically decoupled structure; here the green continuum is gray-scaled. In all plots the North is up, the East is left.
Fig. 8.— The ‘index vs index’ diagnostic diagrams for the azimuthally-averaged MPFS index measurements in NGC 3384. The MPFS data points (open circles) are taken along the radius of the galaxy with a step of 1″. As a reference, the model equal-age sequences from Worthey (1994) for old stellar populations with [Mg/Fe]=0 are shown in the top plot as small signs connected via thin lines; the metallicities for 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 (only the four first for the younger models). Since the stellar population in the nucleus of NGC 3384, according to the top plot, has [Mg/Fe]> 0, the models of Tantalo et al.(1998) for [Mg/Fe]= +0.3 are used for the age diagnostics in the nucleus and the models of the same authors for [Mg/Fe]=0 for the off-nuclear points in the bottom plot; for these models the metallicities are +0.4, 0.0, and −0.7.
Fig. 9.— The MPFS index maps for NGC 3368: Mgb and \(\langle Fe \rangle \equiv (\text{Fe}5270+\text{Fe}5335)/2\) for two different observing dates. A green (\(\lambda5000\) Å) continuum is overlaid as isophotes. The images are direct, in the top row plots \(PA(top) = -19^\circ\), in the bottom row plots \(PA(top) = +11^\circ\)
Fig. 10.— The ‘index vs index’ diagnostic diagrams for the azimuthally-averaged MPFS index measurements in NGC 3368. The MPFS data points (open circles) are taken along the radius of the galaxy with a step of 1". As a reference, the model equal-age sequences from Worthey (1994) for old stellar populations with [Mg/Fe]=0 are shown as small signs connected by thin lines; the metallicities for 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 (only the first four for the younger models). At the bottom plot, which is age-diagnostic diagram, the Hβ index measurements are corrected for the embedded emission as described in the text. The ”post-starburst models” are also shown, as open squares and triangles: the ”young population” of 1 or 3 Gyr old and with [Fe/H]=+0.25 is superposed onto the ”old population” of 12 Gyr and [Fe/H]=–0.22 in various proportion, from 1% to 30% (for a 1-Gyr old burst) or to 80% (for a 3-Gyr old burst).
Fig. 11.— Line-of-sight velocity field for the stellar component (isovelocitity lines overlaid onto the continuum image) and stellar velocity dispersion map (grayscale, with the green continuum isophotes overlaid) in NGC 3379 according to the SAURON data. In all plots the North is up, the East is left.
Fig. 12.— Comparison of the orientations of the isophotal (photometric) major axis and the kinematical major axis (see the text) in NGC 3379 and radial variations of the isophotal ellipticity.
Fig. 13.— Line-of-sight velocity field for the stellar component (isovelocity lines overlaid onto the continuum image) and stellar velocity dispersion map (grayscale, with the green continuum isophotes overlaid) in NGC 3384 according to the MPFS (top) and SAURON (bottom) data. The images are direct, in the top row plots $PA(top) = +46^\circ$, in the bottom row plots $PA(top) = -2^\circ$. 
Fig. 14.— Radial variations of the isophotal characteristics in NGC 3384 according to our and to NICMOS/HST near-infrared photometric data
Fig. 15.— Comparison of the orientations of the isophotal (photometric) major axis and the kinematical major axis (see the text) in the center of NGC 3384 (top) and circumnuclear radial variations of the isophotal ellipticity (bottom); at the upper plot an orientation of the outer disk line-of-nodes is shown by the dashed line.
Fig. 16.— Line-of-sight velocity field for the stellar component (isovelocity lines overlaid onto the continuum image) and stellar velocity dispersion map (grayscale, with green continuum isophotes overlaid) in NGC 3368 according to the MPFS data. The images are direct, $PA(top) = -19^\circ$
Fig. 17.— Line-of-sight velocity field for the ionized gas (isovelocity lines overlaid onto the continuum image) and emission-line surface brightness distributions (grayscale, with red continuum isophotes overlaid) in NGC 3368 according to the MPFS data. The images are direct, $PA(top) = +5^\circ$
Fig. 18.— An optical-band WFPC2/HST image of NGC 3368 combined from raw data in several filters in order to best reveal the dust patches; two ellipses delineate the orientation of the outermost isophote (the larger one) and the circumnuclear polar dust ring (the smaller one). For the area outlined by a square the color map obtained by dividing the NICMOS/F160W image by the NICMOS/F110W image is shown in the upper right corner; the darker features are the redder ones
Fig. 19.— Azimuthal dependence of the central line-of-sight velocity gradient for the ionized gas and stars in the center of NGC 3368 in several radial bins; filled and open circles represent the MPFS data of different observing dates; solid lines show the best-fit sinusoids.
Fig. 20.— Comparison of the orientations of the isophotal (photometric) major axis and the
kinematical major axis (see the text) in the center of NGC 3368 and circumnuclear radial
variations of the isophotal ellipticity
Fig. 21.— Radial variations of the isophotal characteristics in NGC 3368 according to our near-infrared and to Frei et al.’s (1996) optical photometric data.
Fig. 22. — Results of the observations of NGC 3368 with the IFP: top – the velocity fields in the Hα (left) and [NII] (right) emission lines. The step between isovelocity contours is 50 km · s$^{-1}$. The black contour marks the systemic velocity of the galaxy center; bottom – the radial distributions of the rotational velocities and $PA$ of the kinematical axis that are calculated on the basis of the ionized-gas velocity fields. Open diamonds and filled circles correspond to the measurements in the Hα and [NII] lines, respectively. The dotted line marks the $PA$ of the gaseous disk (see the text).