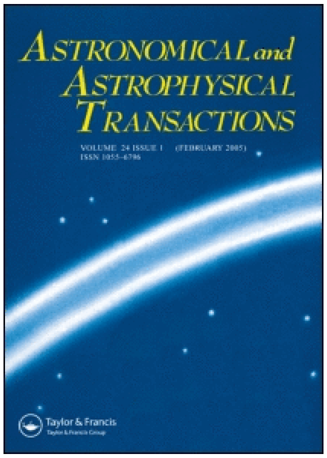

Astronomical & Astrophysical Transactions
The Journal of the Eurasian Astronomical Society
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713453505

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Online Publication Date: 01 April 2006
To cite this Article: Sil'chenko, O. K. (2006) 'Evolution of the central parts of S0 galaxies', Astronomical & Astrophysical Transactions, 25:2, 199 - 203
To link to this article: DOI: 10.1080/10556790600895992
URL: http://dx.doi.org/10.1080/10556790600895992

Astronomical and Astrophysical Transactions
Vol. 25, Nos. 2–3, April–June 2006, 199–203

Evolution of the central parts of S0 galaxies

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(Received 6 July 2006)

The results on the properties of the stellar population of the central parts in nearby lenticular galaxies which are obtained with the multipupil fibre–field spectrograph of the 6 m telescope during the last 10 years are reported. Most S0 galaxies show prominent signs of nuclear star formation bursts some 3–5 Gyears ago; the unresolved nuclei are on average much younger than the surrounding bulges. Also the present author found that there is a link between the mean luminosity-weighted stellar population ages and the galaxy environment; in dense environments the stellar populations are older on average, both in the nuclei and in the bulges.

Keywords: Lenticular galaxies; Stellar populations; Galaxy nuclei; Evolution of galaxies

1. Introduction

Lenticular galaxies had been introduced by E. Hubble in 1936 [1] as an intermediate type between elliptical galaxies and spiral galaxies. Indeed, these galaxies look as red and homogeneous as elliptical galaxies and have global stellar discs as spirals. It is a unique case when we know exactly how the lenticular galaxies form; they are transformed from spiral galaxies. Now, when high-resolution imaging with the Hubble Space Telescope is possible, we see directly how the spiral galaxies infalling into galaxy clusters at $z = 0.5$–0.7 lose their gas, stop their star formation and become 'passive' spiral galaxies which are obvious progenitors of lenticular galaxies with their red homogeneous stellar discs. Whereas at $z = 0$ the lenticular galaxies constitute the dominant population of galaxy clusters (50–60%), and the spiral galaxies represent the minority (20%), already at $z = 0.5$ the lenticular galaxies make up 10% and the spiral galaxies are dominant (50%) [2]. Concerning the particular mechanisms providing the transformation of spiral galaxies into lenticular galaxies, they may be multiple; in the literature, some of these mechanisms have been considered: ram pressure by hot intracluster medium [3], tidal stripping and heating [4, 5], harassment [6], minor merger, etc. Probably, different mechanisms may be effective in different environment types; because there are lenticular galaxies in the field although less numerous than in clusters, they must form but not through the ram pressure of an intracluster medium. However, for us the most interesting

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Astronomical and Astrophysical Transactions
ISSN 1055-6796 print/ISSN 1476-3540 online © 2006 Taylor & Francis
http://www.tandf.co.uk/journals
DOI: 10.1080/10556790600895992

feature is that almost all these mechanisms lead to gas concentration in the very centres of the lenticular galaxies at the moment of their transformation. This means that we can expect nuclear star formation bursts, and just at the moment of their transformation the temporal maximum of which was about 5 Gyears ago. Now we can expect to find the intermediate-age stellar populations in the nuclei of nearby lenticular galaxies – the remnants of these nuclear star formation bursts.

The observational results on the age of the stellar population in the centres of lenticular galaxies which are presented here are obtained with the multipupil fibre–field spectrograph (MPFS) of the 6 m telescope. The integral-field unit of the 6 m telecope of the Special Astrophysical Observatory of the Russian Academy of Sciences, the MPFS, started working in 1989 [7] and so was one of the first integral-field spectrographs in Europe, together with the TIGER [8] and the HEXAFLEX [9]. Two-dimensional spectroscopy obtaining simultaneously hundreds of spectra over extended areas of galaxies allowed us to set quite new problems and to achieve qualitatively new results. The very first observational run with the MPFS in 1989 was very successful just for studying the stellar population properties in the centres of early-type galaxies; among the 12 galaxies selected almost arbitrarily we found seven with chemically decoupled nuclei [10]. In particular, among four nearby lenticular galaxies observed in 1989–1990 with the MPFS, three appeared to have chemically decoupled nuclei which might be remnants of secondary nuclear star formation bursts. During the last 16 years, several modifications of the MPFS have been made; the fibres were removed in 1994 and restored in 1998, several charge-coupled devices of permanently increasing sizes replaced each other, and the optics were improved significantly. Now we have a field of view of $16'' \times 16''$ and a spectral range of 2000 elements, or of 1500–6000 Å with various gratings. During 16 years, many galaxies has been studied by us with the aim of estimating the parameters of the stellar population; several dozens of new chemically decoupled nuclei have been found. In particular, we paid attention to the lenticular galaxies whose formation scenario is the most clear at a moment.

2. Stellar populations in the centres of S0 galaxies

We have studied nearby lenticular galaxies using a rather representative sample and have retrieved a list of bright ($B_T < 13$), northern ($\delta_{2000} > 0$), nearby ($v_r < 3000\,\mathrm{km\,s^{-1}}$) lenticular ($-3 \leqslant T \leqslant 0$) galaxies from the HyperLeda database. It includes 122 objects without strong Seyfert nuclei and star formation bursts; among these, 40 galaxies are Virgo members. We have taken half of the non-Virgo galaxies and have added eight Virgo members and a few more faint or more distant (and so more luminous) galaxies. The present sample of 58 nearby lenticular galaxies uniformly distributed over four types of environment is analysed [11]: 11 cluster galaxies including Virgo and Ursa Major S0 galaxies, 17 group central galaxies, 18 second-rank group members and 12 field lenticular galaxies. We consider separately the unresolved nuclei (compact star clusters?) and the bulges taken in the rings between $R = 4''$ and $R = 7''$ from the centres. Owing to the benefits of three-dimensional spectroscopy, the S/N ratios of the nuclear and off-nuclear spectra are comparable despite the radial decline in surface brightness. The Lick indices Hβ, Mg b, Fe 5270 and Fe 5335 are calculated both for the nuclei and for the bulges. Our index system is properly calibrated on to the Lick standard system [12]; so we are able to determine the properties of the stellar population by comparing our data with the evolutionary synthesis models published so far. The Mg-to-Fe ratios of the bulges appeared to be between 0 and 0.3. Interestingly, we have found that there is an obvious difference between the mean Mg-to-Fe ratio of the brightest group galaxies and those of the second-rank group members. This difference still persists if we take galaxies in the common range of the masses and stellar velocity dispersion, 145–210 $\mathrm{km\,s^{-1}}$, with the same mean of 170 $\mathrm{km\,s^{-1}}$. According to their Mg-to-Fe ratio distribution which is in fact the characteristics of the star formation burst duration [13], the central group galaxies resemble cluster galaxies and the second-rank group members resemble field galaxies; the central star formation bursts in S0 galaxies in dense environments are much shorter than those in S0 galaxies in sparse environments.

In the diagram of Hβ versus [MgFe], which is rather independent of the Mg-to-Fe ratio, we separate age and metallicity effects and determine the parameters for both the nuclei and the bulges of our sample lenticular galaxies. The nuclei are mostly younger than the bulges and both the nuclei and the bulges of the lenticular galaxies in clusters and group centres are older than those in the field and group non-central areas. This is seen best of all when looking at the cumulative age distributions. We have combined the cluster galaxies and the group central galaxies into the subsample of dense environment and the field galaxies and the second-rank group members into the subsample of the sparse environment. The estimates of the median ages are obtained as follows: 3.7 and 6 Gyears for the nuclei of the galaxies in sparse and dense environments respectively, and 4.8 and 8.3 Gyears for their bulges.

Recently, a correlation between the mean age of the stellar population and stellar velocity dispersion in the centres of early-type galaxies has been found [14]. Since our dense environment subsample contains galaxies more massive on average than our sparse environment subsample, we must check whether the age difference reported above is a true environment effect, and not a mass effect. We have made this analysis and have found that the low-mass lenticular galaxies in both types of environment appear to show identical age versus σ trends, but above $\sigma_* = 170\,\mathrm{km\,s^{-1}}$ the sequences of the dense- and sparse-environment galaxies separate, the dense-environment galaxies looking older at the same galaxy masses.

3. Inner gas polar rings and discs

One particularly spectacular phenomenon which we study with the MPFS is the inner gas polar rings and discs in lenticular and spiral galaxies. Until today, we have found six inner polar ionized-gas rings in regular spiral galaxies and 14 inner polar ionized-gas rings and discs in non-interacting S0 galaxies. As for the lenticular galaxies, after a few occasional findings we have decided to select targets where the inner polar rings are seen ‘by eye’ at the optical-band Hubble Space Telescope images as dust lanes perpendicular to the isophote major axes. Gas is thought to be coupled to dust. We have obtained the gas and star two-dimensional velocity fields for these selected galaxies with the MPFS and, indeed, the kinematic major axes of the ionized gas and of the stars seem to be nearly orthogonal [15]. What are the common and perhaps unusual properties of the lenticular galaxies with inner polar gas? We have found the following.

(i) Many of these galaxies have large bars or triaxial bulges.
(ii) The majority are in the centres of groups or are in clusters; so they belong to the ‘dense-environment’ subsample.
(iii) Almost all these galaxies have already been detected in the HI 21 cm line, which is rather unusual for lenticular galaxies.

The two latter properties seem to favour a hypothesis of gas accretion from some other galaxy with polar intrinsic or orbital momentum. However, when large-scale maps of the neutral hydrogen distribution and HI velocity fields are available, they demonstrate decoupling between the inner ionized gas and outer neutral gas. The outer gas is usually distributed regularly and is confined to the planes close to the main symmetry planes of their global stellar discs. Taking into account the regular rotation of the outer neutral hydrogen in the disc galaxies with the inner polar rings, we can propose two possible scenaria. We may be dealing with a consequence of an *exactly* vertical central infall of gas, which seems improbable owing to the large number of cases found, or we suggest that the outer planar gas is pushed on to polar orbits when drifting to the centre by some dynamic mechanism. We have found theoretical considerations for both these scenaria. Van Albada *et al.* [16] considered the consequences of gas accretion on to a tumbling triaxial potential under the condition of arbitrary orientation of the spin. In the centre of a galaxy the accreted gas settled quickly into the plane orthogonal to the largest axis of the ellipsoid, so forming a polar ring; but the outer parts of the gas distribution seem to warp by up to 90° so that the outer gas appeared to counterrotate with respect to the stellar triaxial body. On the contrary, Friedli and Benz [17] started from the presence of a counterrotating gas in the global stellar–gaseous galactic disc; as the disc is unstable, it formed a bar, and then the gas lost its moment in the bar and drifted to the centre. The numerical simulations have shown that near the centre the counterrotating gas left the plane of the global disc and settled on highly inclined orbits, demonstrating stable rotation in the nearly polar plane. Both theories imply the presence of a counterrotating gas beyond the radius of the polar rings. Recently, the present author [18] found observational data satisfying the theoretical expectations. We have claimed the presence of an inner polar ring in NGC 7280 in 2000 [19] as a result of our observation with the MPFS. Later this galaxy was observed with the SAURON. By utilizing the larger field of view of the SAURON, $33'' \times 41''$, we have seen that the gas counterrotates stars at radii larger than $7''$ whereas inside $4''$ it is polar. The same situation is observed in NGC 7332; both galaxies have bars with sizes of about 1 kparsec.

4. Summary

The representative sample of nearby lenticular galaxies was analysed by considering separately the unresolved nuclei and the central parts of the bulges surrounding the nuclei. The sample galaxies are uniformly distributed over four types of environment: galaxy clusters, the centres of galaxy groups, the off-central parts of galaxy groups, and the field. By estimating the duration of the last star formation bursts in the centres of S0 galaxies through the Mg-to-Fe ratio, we have assured that the group central galaxies together with the clusters members have very short (less than 1 Gyear) last star formation events whereas the group second-rank galaxies, just as the field lenticular galaxies, show signs of long continuous star formation in their central parts. This implies that the environment effect on the properties of the stellar population may be purely dynamic, unrelated to the mass of dark halo and its assembly history. The unresolved nuclei (central compact star clusters) are on average much younger than the surrounding bulges. It was also found that there is a link between the mean luminosity-weighted stellar population ages and the galaxy environment; in dense environments the stellar populations are older on average, both in the nuclei and in the bulges.

Let us summarize our results on the distribution of luminosity-weighted stellar population ages in the nuclei of the lenticular galaxies, this time without separation according to the environment type. Chemically decoupled nuclei are defined here as the nuclei which are more metal rich than the surrounding bulges by a factor of 2 or more. 42% of our sample S0 galaxies have chemically decoupled nuclei as defined above. We can consider the chemically decoupled galactic nuclei as the remnants of the most powerful nuclear star formation bursts, giving the most prominent contribution to the integrated spectrum. Indeed, whereas the total S0 nuclei have rather a flat age distribution from 2 to 8 Gyears, chemically decoupled nuclei demonstrate a maximum at 3 Gyears and so they are on average younger than the other nuclei. The nuclei of the lenticular galaxies with the inner polar rings have two maxima in their age distribution. The 'younger' peak at 3 Gyears includes five galaxies with the inner polar gas *and* chemically decoupled nuclei. The nuclei of the lenticular galaxies with the inner polar rings that are not chemically decoupled nuclei are all older than 12 Gyears. This result is consistent with the prediction of the dynamic models surveyed above, namely that polar gas orbits which are perpendicular to the major axis of the triaxial potential are very stable; so the polar gas has little chance of falling into the very centre and provoking a nuclear star formation burst.

Acknowledgements

The present author is grateful to the astronomers of the Special Astrophysical Observatory of the Russian Academy of Sciences, V.L. Afanasiev, A.N. Burenkov, V.V. Vlasyuk, S.N. Dodonov and A.V. Moiseev, for their support with the MPFS observations at the 6 m telescope. The 6 m telescope is operated under the financial support of the Science Ministry of Russia (registration number 01-43); thanks are also due to the Programme Committee of the 6 m telescope for allocating the observational time. During the data analysis we used the Lyon–Meudon Extragalactic Database (HyperLeda) supplied by the LEDA team at the Centre de Recherche Astronomique de Lyon, Observatoire de Lyon (France). This research is partly based on data taken from the ING Archive of the UK Astronomy Data Centre and on observations made with the National Aeronautics and Space Administration (NASA)–European Space Agency Hubble Space Telescope, obtained from the data archive at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555. The study of galaxies in the nearby galaxy groups is supported by grant 04-02-16087 from the Russian Foundation for Basic Research.

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