Formation and evolution of S0 galaxies: a SAURON case study of NGC 7332

Jesús Falcón-Barroso1,2*, Reynier F. Peletier1,3, Eric Emsellem3, Harald Kuntschner4, Kambiz Fathi1,3, Martin Bureau5†, Roland Bacon3, Michele Cappellari2, Yannick Copin6, Roger L. Davies7, Tim de Zeeuw2
1 School of Physics & Astronomy, University of Nottingham, Nottingham, NG7 2RD, United Kingdom
2 Sterrewacht Leiden, Niels Bohrweg 2, 2333 CA, Leiden, The Netherlands
3 CRAL, Observatoire de Lyon, F-69561 St-Genis Laval cedex, France
4 Space Telescope European Coordinating Facility, European Southern Observatory, Karl-Schwarzschild-Str. 2, 85748 Garching, Germany
5 Columbia Astrophysics Laboratory, 550 West 120th Street, 1027 Pupin Hall, MC 5247, New York, NY 10027
6 Institut de physique nucleaire de Lyon, 4 rue Enrico Fermi, 69622 Villeurbanne Cedex, France
7 University of Oxford, Astrophysics, Keble Road, Oxford, OX1 3RH, United Kingdom

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ABSTRACT
We present SAURON integral-field observations of the S0 galaxy NGC 7332. Existing broadband ground-based and HST photometry reveals a double disk structure and a boxy bulge interpreted as a bar viewed close to edge-on. The SAURON two-dimensional stellar kinematic maps confirm the existence of the bar and inner disk but also uncover the presence of a cold counter-rotating stellar component within the central 250 pc. The Hβ and [OIII] emission line maps show that the ionised gas has a complex morphology and kinematics, including both a component counter-rotating with respect to the stars and a fainter co-rotating one. Analysis of the absorption line-strength maps show that NGC 7332 is young everywhere. The presence of a large-scale bar can explain most of those properties, but the fact that we see a significant amount of unsettled gas, together with a few peculiar features in the maps, suggest that NGC 7332 is still evolving. Interactions as well as bar-driven processes must thus have played an important role in the formation and evolution of NGC 7332, and presumably of S0 galaxies in general.

Key words: galaxies: abundances – galaxies: elliptical and lenticular, cD – galaxies: evolution – galaxies: formation – galaxies: individual (NGC 7332) – galaxies: kinematics and dynamics – galaxies: stellar content

1 INTRODUCTION
The nature of S0 galaxies has been a matter of controversy since their appearance in the first morphological classification schemes (Hubble 1936; de Vaucouleurs 1959; van den Bergh 1960a,b) and many authors refer to them as normal spirals stripped of their gas (e.g., Sandage & Visvanathan 1978; Dressler 1980). Studies of S0 galaxies in clusters suggest that interactions between galaxies can lead to the loss of interstellar matter in the disk and convert spirals into S0s. Other theories favour gas loss through ram-pressure stripping from the intergalactic medium (Gunn & Gott 1972) or via galactic winds (Faber & Gallagher 1976), or assert that S0 galaxies are primordial galaxies which have entirely consumed their gas due to a high star formation rate (Larson et al. 1980).

When studying the formation of S0 galaxies, one is often drawn to examine the order of events during galaxy assembly. Early formation models favour the formation of the bulge before the disk, which is supported by several photometric studies (e.g., Caldwell 1983; Terndrup et al. 1992; Peletier & Balcells 1996; Peletier et al. 1999) and by the fact that S0s behave like ellipticals in the widely known scaling relations (i.e. color-magnitude, Mg−σ or fundamental plane). Numerical simulations raised the possibility of an alternative scenario (e.g., Pfenniger 1995), in which bulges are formed via secular evolution processes after the disk (e.g., Sellwood & Wilkinson 1993; Courteau et al. 1999; Carollo 1999). Although such studies naturally focus on the two major components, i.e. the large-scale disk and the bulge, galaxies often show more struc-
tures, e.g., central disks, stellar kinematically decoupled components (KDCs) and multiple gaseous components. These are commonly observed in galaxies all along the Hubble sequence and are often used to emphasize the role of mergers during the formation of early-type galaxies [Tioonra 1977; White & Rees 1978; Schweizer 1984; Franx & Illingworth 1988].

In the last 15 years, evidence for the presence of KDCs in early-type galaxies (e.g., NGC 4406, Bender 1985; NGC 4365, Wagner et al. 1988) has usually been revealed through long-slit measurements. This can introduce a priori assumptions about the geometry of the central structures, and several works have tried to overcome this limitation by mapping the galaxies with multiple slits at different positions angles (Fisher et al. 1994; Fisher 1997; Statler & Snecker-Hand 1999; Cappellari et al. 2002). However, the arrival of a new generation of integral-field units (IFUs) providing contiguous field-of-views (FOVs), such as OASIS (e.g., NGC 4621, Wernli et al. 2002) or SAURON (Bacon et al. 2001), de Zeeuw et al. 2002), offers a much more efficient way to detect KDCs.

Early SAURON results (Bacon et al. 2001; de Zeeuw et al. 2002) reveal a variety of structures much richer than usually recognized in early-type galaxies. It is therefore important to use the information contained in these features to elucidate the key processes at work during galaxy formation. The galaxies concerned can become the ideal benchmarks against which to test the predictions of galaxy formation and evolution theories. NGC 7332, the galaxy studied in this paper, may be such a keystone. NGC 7332, a boxy edge-on S0 galaxy, was studied extensively in the past. The galaxy is mainly known for a bright counter-rotating and a faint co-rotating [O III] gas component with respect to the stars [Bertola et al. 1993; Fisher et al. 1994]. These gas structures were confirmed by Plana & Boulestein (1996), who mapped the Hα emission via Fabry-Perot observations. NGC 7332 exhibits a rather regular broad-band morphology (Peletier & Balcells 1997) and its colours are somewhat bluer than those of elliptical galaxies of the same luminosity. Spectral analysis of the central regions reveals a luminosity-weighted age of about 6 Gyr (Vazdekis & Arimoto 1999).

In this paper, we use SAURON observations to characterize new and known features and improve our understanding of the morphology and dynamics of NGC 7332. We focus on the analysis of the central structures, and several works have tried to come over this limitation by mapping the galaxies with multiple slits at different positions angles (Fisher et al. 1994; Fisher 1997; Statler & Snecker-Hand 1999; Cappellari et al. 2002). However, the arrival of a new generation of integral-field units (IFUs) providing contiguous field-of-views (FOVs), such as OASIS (e.g., NGC 4621, Wernli et al. 2002) or SAURON (Bacon et al. 2001), de Zeeuw et al. 2002), offers a much more efficient way to detect KDCs.

2 OBSERVATIONS & DATA REDUCTION

2.1 SAURON observations & data reduction

We observed NGC 7332 with the integral field spectrograph SAURON attached to the 4.2-m William Herschel Telescope (WHT) of the Observatorio del Roque de los Muchachos at La Palma, Spain, on 13 Oct 1999. We obtained 4 largely overlapping exposures of 1800 s each, producing more than 1500 spectra per exposure, including 146 sky spectra 1.9 away from the main field. SAURON delivers a spectral resolution of 4.3 Å (FWHM) and covers the narrow spectral range 4810 – 5350 Å (1.1 Å pixel⁻¹). The spatial sampling of individual exposures is performed by an array of square lenses of 0.94 Å, producing a FOV of ∼ 33′′ × 41′′. The seeing at the time of the observations was stable at about 1.1′′ (FWHM). Flux, velocity and line-strength standard stars were observed during the same observing run for calibration purposes. Arc lamp exposures were taken before and after each target frame for wavelength calibration. A tungsten lamp exposure was also taken at the end of the night in order to build the mask allowing us to extract the data from the CCD frames.

We followed the procedures described in [Bacon et al. 2001] for the extraction, reduction, and calibration of the data, using the specifically designed SAURON software. The sky level was measured with the help of the dedicated sky lenses and subtracted from the target spectra. We merged the 4 individual extracted datacubes by spatially resampling the spectra onto a common squared spatial sampling of individual exposures is performed by an array of square lenses of 0.94 Å, producing a FOV of ∼ 33′′ × 41′′. The seeing at the time of the observations was stable at about 1.1′′ (FWHM). Flux, velocity and line-strength standard stars were observed during the same observing run for calibration purposes. Arc lamp exposures were taken before and after each target frame for wavelength calibration. A tungsten lamp exposure was also taken at the end of the night in order to build the mask allowing us to extract the data from the CCD frames.

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2.2 STIS spectroscopy & data reduction

We also retrieved Space Telescope Imaging Spectrograph (STIS) data from the Hubble Space Telescope (HST) archive at the Space Telescope Science Institute2 (STScI) to obtain high spatial resolution spectroscopy of NGC 7332’s centre. The data form part of the observations of proposal ID 7566 by R. Green, covering the CaII

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1 The galaxy is classified S0p in the RC3 [de Vaucouleurs et al. 1991] due to its boxy bulge (Sanda 1961).

2 Based on observations made with the NASA/ESA Hubble Space Telescope, 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 NASA contract NAS 5-26555.

| Table 1. Properties of NGC 7332 |
|---------------------------------|
| Parameter                      | Value   | Source                   |
|---------------------------------|---------|--------------------------|
| Morphological Type             | S0p     | de Vaucouleurs et al. 1991|
| M_B [mag]                      | -21.86  | Balcells & Peletier 1994  |
| B - R [mag]                    | 1.40    | Balcells & Peletier 1994  |
| Outer Ellipticity              | 0.75    | Andrekakis et al. 1995   |
| Distance Modulus [mag]         | 31.81   | Tonry et al. 2001        |
| Distance scale [pc / arcsec]   | 111.6   |                          |

| Parameter                      | Value   | Source                   |
|---------------------------------|---------|--------------------------|
| Distance scale [pc / arcsec]   | 111.6   |                          |
region between 8282 and 8835 Å. The G750M grating was used together with the 52′′ × 0′′2 slit aperture, providing a dispersion of 0.56 Å pix−1 and a spatial sampling of 0′′05 pix−1. We retrieved the data reduced by the pipeline, making use of the best calibration files available at the time, but corrections for the effect of fringing and cosmic ray removal were still required. Fringing corrections were applied using the prescriptions in Goudfrooij et al. (1997), whereas we used the RedDia package (Cardiel 1999) to perform the cosmic ray rejection. A K0III star (HR7615) from the same data set was also retrieved and underwent the same reduction processes. It was used as a template for kinematical measurements.

2.3 HST & ground-based imaging

Imaging data were retrieved from several archives to perform a structural analysis. We retrieved a set of Wide-Field Planetary Camera (WFPC-1) images from the HST archive at STScI from the observing program of S. Faber (Prop. ID 2600, see Lauer 1995). The observations were made using the F555W filter (V-band). The data set consists of 3 target frames with exposure times of 35, 140 and 140 s, respectively, and spatial sampling 0′′044 pixel−1. We combined the individual exposures and rejected cosmic rays with the routine creff, available within the IRAF3 package, thus resulting in a cosmic ray-cleansed merged image. We also made use of a fully-reduced ground-based Cousins I-band image from Peletier & Balcells (1993), taken with the Isaac Newton Telescope (INT) located in the Observatorio del Roque de los Muchachos in La Palma, Spain. The exposure time was 200 sec and the seeing 1′′0. We overlay in Figure 1 the contours from this I-band image and the FOV and contours of the SAURON reconstructed total intensity map (obtained by summing the data in wavelength). Finally, the photometric analysis performed by Fisher et al. (1994) from an R-band image, taken in 1′′3 seeing, was also used.

3 PHOTOMETRIC ANALYSIS

We analysed the WFPC-1 data in order to study morphological substructures in NGC 7332. A comparison of our analysis with that of Fisher et al. (1994) from an R-band image is shown in Figure 2 and the agreement in the overlapping region is excellent. This comparison is possible because the color gradients in this galaxy are small (Peletier & Balcells 1993) and the emission lines can be neglected (e.g., Hα and [NII] in the R-band image).

The isophotal analysis of the HST image reveals a number of maxima and minima in the c4 parameter, which describes deviations of the isophotes from pure ellipses (positive c4 indicates disky isophotes and negative c4 boxy isophotes; see e.g., Carter 1978). Positive values are present in the inner 0′′5 but may be strongly influenced by the halo of the pre-COSTAR WFPC-1 point-spread-function (PSF). Positive c4 values are also observed in the region 1′′5 ≤ r ≤ 7′′, where the maximum reaches about 3 per cent. The isophotes are then elliptical or slightly boxy at intermediate radii (7′′ ≤ r ≤ 12′′) and again strongly disky at large radii (r ≥ 12′′). A complementary representation is shown in Figure 2 (top-left panel), where we divide our image by a 2D model from the best fitting pure elliptical isophotes. This confirms the c4 behaviour and highlights the excess of light above the fitted elliptical model in the central 1′′ - 7′′ of the galaxy. We associate this with a central disk whose major-axis coincides with that of the galaxy, at a position angle (PA) of 160°. The presence of such a central disk was already reported by Seifert & Scorza (1994). There is also evidence for a secondary disk at larger radii (r ≥ 12′′), revealed by an excess of light and a positive c4 parameter (Figure 2).

Another noteworthy feature is the position angle twist observed from the centre to the outer regions of the galaxy. The magnitude of the twist is about 5°. This PA change is most likely a projection effect due to a point symmetric structure (i.e. spiral-like structure) showing up in the outer disk, viewed at a large but not perfectly edge-on inclination.

4 STELLAR KINEMATICS

We measured the SAURON stellar kinematics of NGC 7332 by fitting its spectra with a linear combination of single-age, sin-
ingle metallicity population models from Vazdekis (1999) convolved with a Gaussian-Hermite fit to the instrumental resolution (rendered uniform over the FOV). For each target spectrum, we then perform the following steps:

1. We measure the stellar kinematics using pPXF in the wavelength range $4830 - 5280$ Å, avoiding the regions with nebular emission (e.g., H$\beta$, [O III] and [N I] lines). This procedure provides the best template fit to the full wavelength range.

2. The subtraction of the best template fit from the original dataset results in a ‘pure emission line’ spectrum that is used to extract the gas kinematics. For this, we fit the emission spectrum approximating each line with a Gaussian. The Gaussian fit is then removed from the original data, yielding an ‘emission line-free’ spectrum from which clean line-strength indices can be derived.

An illustration of this procedure for NGC 7332 is presented in Section 5.

In order to check the accuracy of our results, we compared them with the best available long-slit stellar kinematics of NGC 7332 (Fisher et al. 1994). In Figure 3, the velocity and velocity dispersion profiles along two perpendicular position angles, PA = 155° and PA = 65°, are shown. They are consistent within the errors.

4.2 A KDC & central disk in NGC 7332

As seen in Figure 4, NGC 7332’s stellar kinematics displays a rather smooth velocity field with rotation along the major-axis, but it also shows some peculiarities. One is a KDC reported here for the first time ($r < 2.5$”) and revealed by an ‘S’-shaped zero-velocity contour in the SAURON stellar velocity field, emphasized in the enlarged version provided in Figure 5 (bottom left panel). We also present a comparison of the STIS spectroscopy and SAURON data along PA ≈ 160° (the apparent major-axis in the inner parts; see Fig. 6). At the spatial resolution of SAURON, we only detect a weak central counter-rotating structure, but the signature is clear in the STIS data, with an amplitude of about 30 km s$^{-1}$ in the central 2$''$.

In order to emphasize these central features, we have modeled the SAURON velocity field on large scales with a simple exponential disk (Freeman 1970), excluding the central 2$'$ from the fit to avoid being affected by the KDC. The result is shown in Figure 5. The best model was forced to have PA = 160°, consistent with the photometric major-axis as measured in Section 4.1 and from the SAURON reconstructed total intensity image. The residual image (Fig. 5 bottom right panel) highlights the KDC component: its angular momentum projected onto the minor-axis of NGC 7332 is negative, justifying its identification as a counter-rotating component (CRC). The kinematic major-axis of this CRC seems however tilted by about 20° with respect to that of the main galaxy.

We note that there is only very weak evidence for a flattening of the velocity profile in the central arcseconds along PA = 155° (see Fig. 5 Section 4.3) and we cannot find any conclusive evidence for the presence of counter-rotation at this PA. It is however clearly seen at PA = 160° (the major-axis; see Fig. 6). And although the detection of this structure is strongly dependent on the spatial resolution, it again illustrates the advantage of IFUs over long-slit spectrographs.

The velocity dispersion map shown in Figure 5 reveals a central dip of about 10 km s$^{-1}$ along the major-axis of NGC 7332 (see also Fig. 5 Section 4.3), in contrast with the traditional peak found at the center of the bulges of most early-type galaxies. This drop in velocity dispersion is on the same scale as the KDC ($r < 2.5$”) and may well be associated with it.

In addition to the photometric evidence presented in Section 4, there are also kinematic features supporting the presence of a central disk on a larger scale than the KDC. In particular, the Gauss-Hermite moments $h_3$ (≈ 0.1 in amplitude) are strongly anticorrelated with $V$ in the region where the central disk is postulated. The superposition of a fast-rotating disk to a moderately rotating spheroid produces a similar asymmetry in the line-of-sight velocity distributions (LOSVDs).

We have therefore discovered a remarkably unusual situation in the core of NGC 7332, with a stellar KDC ($r < 2.5$”) and a larger central disk ($r < 7$”).

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Figure 4. Stellar kinematics of NGC 7332 from SAURON. a) Reconstructed total intensity (mag arcsec$^{-2}$, arbitrary zero point), b) mean velocity (km s$^{-1}$), c) velocity dispersion (km s$^{-1}$), d) and e) Gauss-Hermite moments $h_3$ and $h_4$. The SAURON spectra have been spatially binned to a minimum $S/N$ of 60 by means of the Voronoi 2D binning algorithm of Cappellari & Copin (2003). Isophotes from the reconstructed total intensity image are overlaid on all maps in 1 mag arcsec$^{-2}$ steps.

Figure 5. Fit to the SAURON velocity field of an exponential disk model (Freeman 1970). Top panels: original velocity field as shown in Figure 4 (left) and fitted model (right). Bottom panels: zoom on the SAURON velocity field with the zero iso-velocity curve over-imposed (solid line; left) and the same region after subtraction of the best fit model (residual $V - V_{\text{model}}$; right). All the maps are in units of km s$^{-1}$. The area within the dashed circle was excluded from the fit.

5 GAS KINEMATICS

NGC 7332 is best known for its peculiar gas structure, namely the presence of two kinematically decoupled gas components, as observed by Bertola et al. (1992), Fisher et al. (1994) and Plana & Boulesteix (1996). Fisher et al. (1994) measured the [O III] emission using several slits along different position angles, whereas Plana & Boulesteix (1996) obtained complete 2D emission maps using the H$\alpha$ line (Fabry-Perot observations). Here, we are able to map three different emission lines within the SAURON wavelength range (H$\beta$, [O III], [N I]).

We obtained a pure emission line datacube using the procedure described in Section 4.1. An illustration of the method is shown in Figure 8 for four different locations in the SAURON FOV. The fitted synthetic spectra (red lines) are overlaid on the SAURON spectra of NGC 7332 (black lines) and the differences are shown underneath. The residuals are small outside the spectral regions where emission lines are expected to contribute, with oscillations just slightly above that expected from the corresponding noise level. As shown in Figure 5, [O III] is strong everywhere in the galaxy. The H$\beta$ line, although present, is much fainter than [O III]. We measured the H$\beta$ and [O III] kinematics by fitting a single Gaussian to each of the three lines simultaneously, which relies on the assumption that all the lines have the same velocity and velocity dispersion. We have also assumed a 1:2.96 ratio for the [O III] components (Osterbrock 1989) but left the [O III] to H$\beta$ ratio free. In our analysis, these assumptions seem to hold everywhere in the field. Located on the wing of the Mg b absorption line (5170 Å), the
[N I] doublet is very difficult to detect. Our analysis reveals negligible amounts of [N I] emission within the SAURON FOV so we have not corrected the original spectra for its presence.

In Figure 9 we present the H$^\beta$ and [O III] intensity maps as well as their kinematics in the form of mean radial velocity and velocity dispersion maps. The intensity distribution of the H$^\beta$ and [O III] lines have similarities, although the H$^\beta$ intensity is much fainter. The detection of H$^\beta$ emission at the centre is somewhat marginal (compared to the bright underlying stellar contribution). We find a bright counter-rotating ionised gas component and weak traces of a much fainter co-rotating one. We were able to obtain [O III] intensity values for the main counter-rotating component easily but the second component is much more difficult to isolate, not only because of its low relative contribution but also because of SAURON’s limited spectral resolution (see Fig. 9). We could thus only trace it in a small region of our field, and decided not to attempt to derive its velocity field. There is however no doubt that this second component exists, as emphasized by Fisher et al. (1994) and Plana & Boulesteix (1996).

The emission line maps we have obtained for NGC 7332 show a complex structure. The bulk of the [O III] emission is clearly misaligned with respect to the main stellar disk and shows strong departures from an axisymmetric distribution. We detect a long arc-like filament in the [O III] distribution on the NW side of NGC 7332, connecting onto the major-axis of the galaxy at the northern limit of the SAURON FOV. The velocity and velocity dispersion maps of the gaseous component also show strong non-axisymmetric kinematics and we find an [O III] emitting region isolated in velocity ($\approx 350$ km s$^{-1}$ from systemic) about 7$''$ SW of the galaxy centre.

Masking out all marginal [O III] detections (essentially all flux below $-3$ in Fig. 2 and the high velocity material mentioned above, the [O III] map then exhibits a bar or spiral-like structure within the central 10$''$. This structure is similar to, but less contrasted than, the one found in the other nearly edge-on lenticular galaxy NGC 3377 (Bacon et al. 2001). Assuming that NGC 7332 is close to edge-on, at an inclination of $\approx 75^\circ$ Andreadas et al. (1995), then the [O III] most likely has a substantial vertical extension and is simply seen in projection against the disk. If, on the other hand, NGC 7332 is more face-on, then this structure could indeed be in the equatorial plane.

6 STELLAR POPULATIONS

The many distinct kinematic components identified in the previous sections raise the question of the sequence of events leading to the current structure of NGC 7332. Valuable information can be obtained by investigating the stellar populations over the full FOV of SAURON. The measurement of absorption line-strengths together with predictions of stellar population models can be used to infer the luminosity-weighted age and metallicity of the stellar populations (e.g., González 1993; Worthey et al. 1994; Kuntschner & Davies 1998).

We used our flux-calibrated datacube to measure several line-strength indices available in the SAURON wavelength range (i.e. H$^\beta$, Fe5015, Mg b and Fe5270). These indices were then calibrated onto the Lick/IDS system following the procedures outlined in Kuntschner (2000). Specifically, we observed 73 stars in common with the Lick/IDS system to establish the small systematic offsets for each index (see also Worthey & Ottaviani 1997). We also estimated the velocity dispersion corrections, to account for the broadening of the spectral features by the LOSVDs, using a sub-set of model spectra by Vazdekis (1999) broadened to the Lick/IDS resolution.

The Lick/IDS Fe5270 index cannot be fully mapped with SAURON due to the varying bandpass over its FOV (de Zeeuw et al. 2002). In order to maximize the available FOV, a new index was defined (Fe5270$_{s}$) which measures the same spectral feature, but has a reduced spectral coverage in the red pseudo-continuum band. This new index was then converted onto the original Lick/IDS system via the empirical, linear relation.

$$\text{Fe5270} = 1.26 \cdot \text{Fe5270}_{s} + 0.12$$ (1)

The 1σ standard deviation of this empirical calibration is $\pm 0.05$ Å for the Fe5270 index. More details on the SAURON line-strengths system are given in a forthcoming paper of the main SAURON series that applies to the full SAURON survey.

We measured the indices before and after applying our emission subtraction procedure (Section 4.1). As can be seen in the line-strength maps shown in Figure 10, the corresponding corrections are large in the outer parts due to the substantial contamination by the emission lines (mostly H$^\beta$ and [O III]). The emission corrected line-strength values do somewhat depend on the combination of

![Figure 7. NGC 7332's stellar kinematic major-axis profiles from SAURON (PA= 160°). The radial velocity and velocity dispersion are in km s$^{-1}$.

\[\text{Figure 7. NGC 7332's stellar kinematic major-axis profiles from SAURON (PA= 160°). The radial velocity and velocity dispersion are in km s}^{-1}.
\]
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Figure 8. Optimal template fitting for NGC 7332 in four different locations: the KDC (circle), main disk (upward triangle), minor axis (square) and bar (downward triangle). Red lines represent the best fitting stellar templates (see Section 4.1) of the underlying galaxy spectra (black lines). Residual spectra are shown underneath. The central panel shows the \([\text{O} \text{\textsc{iii}}]\) intensity distribution (Fig. 9) with isophotes from the reconstructed total intensity image (Fig. 4) overlaid in 1 mag arcsec\(^{-2}\) steps.

Figure 9. \(\text{H}\beta\) and \([\text{O} \text{\textsc{iii}}]\) gas distribution and kinematics from SAURON. The intensities are in mag arcsec\(^{-2}\) (arbitrary zero point) while the velocity and velocity dispersion are in km s\(^{-1}\). Isophotes from the reconstructed total intensity image (Fig. 4) are overlaid on all maps in 1 mag arcsec\(^{-2}\) steps.

single-age, single-metallicity population models used to build the optimal template and fit the raw data. But although this procedure is critical for the removal of the \(\text{H}\beta\) contamination from the \(\text{H}\beta\) index, it is negligible for the removal of the \([\text{O} \text{\textsc{iii}}]\) contamination from the Fe5015 index, and the Mg\(b\) and Fe5270 indices are totally unaffected. The maximum error in the \(\text{H}\beta\) index introduced by using different sets of optimal template libraries is 0.08 Å (1σ).

After the emission-subtraction process, we find that \(\text{H}\beta\) remains nearly constant (within the errors) over the whole SAURON FOV. Since the fitting procedure works on the spectra completely independently from one another, it is unlikely that a flat \(\text{H}\beta\) map could be obtained by an inaccurate subtraction of the emission. The Mg\(b\), Fe5015 and Fe5270 maps show a steep increase in line-strength within 5′′ of the centre (see also Fig. 11), but outside of this inner region the metal line-strengths are approximately constant over the FOV. There is, however, some evidence that the values of the Mg\(b\), Fe5015 and Fe5270 indices decrease slightly at \(r \approx 10′′\) and increase again at the outermost radii along the major axis (see Fig. 10 and Fig. 11).

The overall line-strength distribution is sufficiently uniform that none of the galaxy components identified in the previous sections (i.e. the KDC, inner disk, bar, and outer disks) can be clearly identified in these maps. Specifically, the flat \(\text{H}\beta\) index suggests a rather uniform age across the entire FOV covered by SAURON. If the (luminosity-weighted) age of the bulge or the central disk in NGC 7332 were much different from that of the main body, it should be seen in the \(\text{H}\beta\) map (\(\text{H}\beta\) is sensitive to age and independent of metallicity changes to first order; see Worthey et al. 1994).

Index-index diagrams such as \(\text{H}\beta\) vs \([\text{MgFe}]^5\), together with

\[ [\text{MgFe}]^5 \equiv \sqrt{\text{Mg}b \times \frac{\text{Fe}5270 + \text{Fe}5335}{2}} \]
stellar population model predictions, are often used to estimate luminosity-weighted ages and metallicities of galaxies. This combination of indices is almost insensitive to non-solar abundance ratios which can otherwise significantly affect age and metallicity estimates (e.g., Trager et al. 2000; Kuntschner et al. 2001; Thomas et al. 2003). Here, the use of the Fe5270 and Mg b indices as metallicity indicators is unfortunately limited by the restricted wavelength range of SAURON. In order to minimize the effects of non-solar abundance ratios, we have thus defined a new index, 

$$[\text{MgFe52}]' \equiv \frac{(0.62 \times \text{Mg} b + \text{Fe5270})}{2.0},$$

using the model predictions of Thomas et al. (2003).

In Figure 12, we present the results of our analysis by averaging 1''.6 x 1''.6 regions (i.e. 2 x 2 lenslets) around the four key positions shown in Figure 8. The estimated luminosity-weighted age for all regions is $5 \pm 2$ Gyr. The metallicity of the central area is about 2 times solar while the outer areas show metallicities between 0.35 and 1 times solar. These results are consistent with others found in the literature. Using a similar line-strength analysis, the nucleus of NGC 7332 has been reported to host a population of luminosity-weighted age between 4 and 6 Gyr depending on the authors (Vazdekis & Arimoto 1999; Terlevich & Forbes 2003). The color gradients are also small in the disk and bulge (Peletier & Balcells 1997), consistent with our finding of an approximately constant age across the SAURON FOV.

The young luminosity-weighted age of $5 \pm 2$ Gyr detected in our analysis clearly shows that NGC 7332 has experienced relatively recent star formation. Furthermore, the uniformity of the Hβ map suggests that this star formation affected all regions of the galaxy probed by our integral-field instrument.

7 DISCUSSION

In this paper, we studied a galaxy that has sometimes been labelled peculiar. Using integral-field spectroscopy, we were able to better constrain the stellar kinematics, the ionised gas distribution and kinematics, and the stellar populations of NGC 7332. In turn, those can now be used to better constrain its evolutionary history. A summary of some key numbers extracted from the data is given in Table 2.

7.1 The presence of a bar

A number of photometric features described in Section 8 are consistent with NGC 7332 being a barred galaxy viewed close to edge-on. Indeed, soon after they form, bars buckle and settle with an increased thickness, appearing boxy-shaped when seen end-on (i.e. along the bar major-axis) and peanut-shaped when seen side-on (i.e. along the bar minor-axis; see e.g. Combes et al. 1990 and Raha et al. 1991 for N-body simulations; Merrifield & Kuijken 1999 and Bureau & Freeman 1999 for observations). The boxiness of the isophotes does not show properly in the $c_4$ profile of Figure 4 because the isophotes are simultaneously boxy (at large galactic
Fig. 1. SAURON emission-corrected line-strength major-axis profiles (Hβ, Mg b, Fe5015 and Fe5270) on the Lick/IDS system. Worthey et al. (1994). The error bars represent Poisson errors.

The rather homogeneous stellar population of NGC 7332 is also consistent with the presence of bar. Indeed, the so-called bulge and disk are then both made-up of the same (disk) material, and any population gradient that may have been present before the bar formed or may develop afterwards will be smoothed out by the large radial and vertical motions of the stars, at least within the bar region (e.g., Martin & Rox 1994; Friedli, Benz & Kennicutt 1994). Gradients in the very centre may however survive or develop due to bar-driven inflows.

The presence of a bar in NGC 7332 was already hinted at by Fisher et al. (1994), who were however left to speculate about its existence. Lützicke et al. (2000) estimated a diameter of 56″ for the weak bar in NGC 7332 via the characteristic major-axis plateau (observed here in the near-infrared). Considering the discussion above, we can now assert its presence with more confidence. For the remainder of this discussion, we will thus take for granted the presence of a bar in NGC 7332 and focus our efforts on understanding its origin and role in the evolution of the galaxy.

### 7.2 Origin and status of the gas
NGC 7332 exhibits some amount of counter-rotating ionised gas (≈ 1.5 × 10^5 M☉), which has commonly been used to argue for an external origin. In the case of NGC 7332, the ionised gas most likely comes from a tidal interaction with the neighbouring galaxy NGC 7339. We note that extended counter-rotating ionised gas is common in S0s (Bertola et al. 1992; Combes et al. 1990; Athanassoula & Misiriotis 2002), although axysymmetric configurations can also in principle give rise to cylindrical rotation (e.g., Rowley 1988).

The only major difference with the kinematic bar signatures emphasized by Bureau & Athanassoula (2004) from N-body simulations is the strong h3 − V anti-correlation in the central parts (r ≤ 7″). This is however commonly observed in boxy bulges otherwise showing strong evidence for the presence of a bar (Chung & Bureau 2004; Wozniak et al. 2003). The plateau in the line-of-sight velocities is also consistent with the presence of a bar.

The major-axis surface brightness profile at intermediate radii found above, we can now assert its presence with more confidence. For the remainder of this discussion, we will thus take for granted the presence of a bar in NGC 7332 and focus our efforts on understanding its origin and role in the evolution of the galaxy.

### Table 2. SAURON parameters for NGC 7332.

| Parameter                                      | Value       | Units   |
|------------------------------------------------|-------------|---------|
| Stellar Heliocentric Systemic Velocity         | 1206 ± 5    | km s⁻¹  |
| Gas Heliocentric Systemic Velocity             | 1206° ± 7   | km s⁻¹  |
| Stellar V_max                                  | 123° ± 5    | km s⁻¹  |
| Extent of the KDC                              | ~2.5        | arcsec  |
| Extent of the Central Disk                      | ~7.0        | arcsec  |
| Mass of counter-rotating ionised gas           | ~1.5        | 10^6 M☉ |
| EW(Hβ)                                         | 2.23 ± 0.09 | Å       |
| EW(Mg b)                                       | 3.45 ± 0.18 | Å       |
| EW([MgFe52]")                                 | 2.53 ± 0.07 | Å       |

α from the H/β and [O II] lines fitted simultaneously.

β within the SAURON field.

central aperture (15′ x 15′).

Despite the above ambiguity, it is safe to assume that an
accretion event is at the origin of the observed counter-rotating gaseous component in NGC 7332. The same accretion event could be responsible for the formation of the central KDC revealed by SAURON and STIS, as well as the dip in the velocity dispersion profile (see Section 4.2) and the increase of the Mg b and Fe5270 indices at the very centre (see Section 5). The Hα index values would then setup an upper limit of about 3-4 Gyr (luminosity-weighted) for the KDC (see Fig. 12). Another later accretion event may be required to explain the more perturbed gas clumps located further away from the equatorial plane (see Section 6), which have rather high relative velocities. This gas has certainly not settled yet, but it will eventually fall back towards the equatorial plane of NGC 7332.

7.3 Evolutionary scenarios

Any formation and evolution scenario for NGC 7332 must take into account the two main ingredients hinted at from the observations described in this paper: the presence of a bar and a recent interaction event. We now examine them in turn.

7.3.1 The role of the bar and the central stellar disk

In our view, the main morphological and kinematic features that we associate with the bar in Section 4.2 do not represent a proper illustration of bar-driven evolution processes. This is because, although those properties become more extreme as the bar strengthens, most of them are established on timescales equivalent to the bar formation itself (e.g., Combes et al. 1990; Raha et al. 1991; Bureau & Athanassoula 2001). In the following paragraphs, we thus concentrate on (presumably) bar-driven processes which take place gradually over a much longer timescale (i.e., tens of dynamical times).

In the context of the bar hypothesis, the interaction between the natural frequencies of the system (e.g., the angular and epicyclic frequencies of the circular orbits) and the pattern speed of the bar implies the existence of resonances, around which the galaxy is shaping. The photometric and kinematic features we observe in NGC 7332 will thus likely be associated with those resonances. The double disk structure is particularly interesting in this respect since it likely builds up gradually through bar-driven processes (van den Bosch & Emsellem 1998).

The inner disk is usually interpreted as marking the region within the Inner Lindblad Resonance (ILR). The major-axis plateau observed by Lattiecke et al. (2000) extends to a radius of about 25″ (≈ 2.8 kpc), setting a lower limit for the length of the bar. Assuming the standard corotation radius to bar length ratio of $r_{\text{CR}}/r_b = 1.2$ for early-type barred galaxies (e.g., Athanassoula 1992; Gerssen, Kuijken & Merrifield 2001 and references therein), $r_{\text{CR}} \approx 30″$. A simple model then predicts the ILR to be at roughly 12″ (see van den Bosch & Emsellem 1998), indeed marking the transition between the inner disk and the outer disk. This may be supported by the line-strength index maps, where there is evidence for a weak decrease of the Fe5015, Mg b and Fe5270 profiles at about 10″ along the major-axis (see Figs. 10 and 11).

A comparison with the edge-on S0 galaxy NGC 4570 appears appropriate here, since it may be at a different stage of a similar (bar-driven) process. NGC 4570 was studied in detail by van den Bosch & Emsellem (1998), who identified similar morphological features (i.e., double disk and intermediate boxy structures) to those in NGC 7332. Their study also revealed the same trends in ellipticity and boxiness ($c_b$). The case for a bar was made there almost exclusively based on the identification of two edge-on rings, exceptionally well characterized and consistent with the locations of bar resonances. The structures observed in NGC 4570 are however one order of magnitude smaller than in NGC 7332: the ‘nuclear’ disk is less than 1″ in radius and the inner ring is at a radius of ≈ 1″.7. The main difference between the two galaxies then lies in the detection of a large-scale bar of about 3 kpc in NGC 7332, whereas van den Bosch & Emsellem (1998) hinted at the presence of an ‘inner’ bar of ≈ 320 pc in NGC 4570 (with no evidence of a large-scale bar). Another obvious qualitative difference is the presence of a significant amount of counter-rotating stars and gas in the central region of NGC 7332. We could speculate on the existence of a secondary bar in NGC 7332, but its detection would require high spatial resolution photometry with high signal-to-noise (e.g., HST WFPC-2 or ACS images). It may thus well be that NGC 7332 is simply in an earlier stage of a gradual bar-driven evolutionary process.

7.3.2 The role of interactions

The formation of decoupled cores is often mentioned within the hierarchical structure formation framework (e.g., Kauffmann et al. 1993), involving multiple mergers to form galaxies. As mentioned above, although there is no evidence for a recent major merger, the gas distribution and kinematics strongly suggest that NGC 7332 was recently involved in an interaction event (most likely with NGC 7339). The KDC could then correspond to the last or one of the last major accretion (and star formation) events in such a hierarchy (e.g., Davies et al. 2001). In fact, the bar itself could be the result of that same event, as bars are easily excited by tidal interactions (e.g., Noguchi 1987; Gerin, Combes & Athanassoula 1990).

The neighbour galaxy NGC 7339, a Sb galaxy placed 5′ away from NGC 7332, is most likely the one responsible for such an event. The position of this galaxy is such that the offplane gas clump found in NGC 7332 could well be a direct continuation of
the west side of NGC 7339's disk. Additionally, the maximum receding velocity measured on the west side of this galaxy is ~1525 km s^{-1} (Courteau 1997), which is strikingly similar to the radial velocity of the high velocity clump in NGC 7332 (~1550 km s^{-1}). This picture leads to the suggestion that this clump is linked to NGC 7339. Deep HⅠ observations could confirm this idea.

It is hard to assess which of the bar or the interaction occurred first, and whether the KDC was formed from material funneled by the former or the latter. NGC 7332 will, however, continue to evolve on a timescale of a few 10^9 yr. As emphasized above, the gas will settle down due to its dissipative nature, and some of it may feed the inner few arcseconds (with or without more star formation). In this context, NGC 7332 may be seen as a precursor of the now gas-poor edge-on S0 galaxy NGC 4570.

8 CONCLUSIONS

We presented in this paper new SAURON integral-field spectroscopy observations of the edge-on S0 galaxy NGC 7332, along with a discussion of existing ground and space-based imaging.

The photometric analysis reveals a boxy bulge, a central disk and evidence for the presence of a bar (Section 5 but see also Lüticke et al. 2000). The SAURON observations provide unprecedented coverage of the stellar and gas kinematics. In particular, the stellar kinematics displays a rather smooth velocity field with rotation along the major-axis and a weak dependence of rotation on galactic height. We also discovered a stellar kinematically decoupled component (KDC) misaligned with respect to the galaxy’s kinematic major-axis, which may be related to a dip in the centre of the velocity dispersion map (r ≤ 2′.5). We finally provided kinematic evidence for the presence of a larger central stellar disk (r ≤ 7″).

NGC 7332 presents significant ionised gas emission in the spectral range studied, in particular in the Hβ (4861 Å) and [O iii] (4959 and 5007 Å) lines. We used a sophisticated technique to separate the absorption and emission lines, yielding both pure absorption spectra from which to derive the stellar kinematics and pure emission spectra for the gas kinematics (and distribution). The emission maps reveal a very complex gas morphology and kinematics. This is found especially in [O iii] which is mainly counter-rotating with respect to the stars. The gas maps (Figure 9) show significant amounts of gas at high relative velocities outside of the equatorial plane, whereas the central parts display rather ordered motions. We also found traces of a faint co-rotating ionised gas component.

The analysis of the absorption line-strengths in NGC 7332 show that its stellar populations are generally young (5 ± 2 Gyr), not only in the disk but also in the bulge, in agreement with previous studies (BalcÁ Es et al. 1994; Vazquez et al. 1996; Terlevich & Forbes 2002). The metallicity indices (i.e. Fe5015, Mg$b$, Fe5270) show an increase in the centre, contrasting with the rather homogeneous Hβ index. There is also weak evidence of a decrease at r ∼ 10′, between the central and the outer disks.

The existence of a large-scale bar in NGC 7332 can simultaneously explain most of the features found in the galaxy. The boxy morphology can be explained by the thickness of the bar after buckling, which also leads to homogeneous stellar populations across the bulge and disk. The stellar kinematics can similarly be explained by the particular orbital structure of barred disks (see Bureau & Athanassoula 2004). The KDC, on the other hand, was most likely formed through late gas infall, an accretion event perhaps related to the complex ionised gas distribution currently seen.

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REFERENCES

Andredakis Y. C., Peletier R. F., BalcÁ Es M., 1995, MNRAS, 275, 874
Athanassoula E., 1992, MNRAS, 259, 345
Athanassoula E., Misiriotis A., 2002, MNRAS, 330, 35
Bacon R. et al., 2001, MNRAS, 326, 23
Baggett W. E., Baggett S. M., Anderson K.S.J., 1998, AJ, 116, 1626
BalcÁ Es M., Peletier R. F., 1994, AJ, 107, 135
Bender R., 1988, A&A, 202, L5
Bertola F., Buson L. M., Zeilinger W. W., 1992, ApJ, 401, L79
Bureau M., Athanassoula E., 2004, submitted to ApJ
Bureau M., Freeman K. C., 1999, AJ, 118, 126
Caldwell N., 1983, ApJ, 268, 90
Cappellari M., Genzel R., 2003, MNRAS, 342, 345
Cappellari M., Emsellem E., 2004, PASP, 116, 138
Cappellari M., Verolme E. K., van der Marel R. P., Verdoes G. A. V., Illingworth G. D., Franx M., Carollo C. M., de Zeeuw P. T., 2002, ApJ, 578, 787
Cardiel N., 1999, Ph.D. Thesis, Univ. Complutense de Madrid
Carollo C. M., 1999, ApJ, 523, 566
Carter D., 1978, MNRAS, 182, 797
Chung A., Bureau M., 2004, submitted to AJ
Combes F., Debbasch F., Friedli D., Pfenniger D., 1990, A&A, 233, 82
Courteau S., 1997, AJ, 114, 2404
Courteau S., de Jong R. S., Broeils A. H., 1996, ApJ, 457, L73
Davies R. L. et al., 2001, ApJ, 548, L33
de Vaucouleurs G., 1959, Handbuch der Physik, 53, 275
