Morphology and kinematics of the ionised gas in early-type galaxies

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Abstract

We present results of our ongoing study of the morphology and kinematics of the ionised gas in 48 representative nearby elliptical and lenticular galaxies using the SAURON integral-field spectrograph on the 4.2m William Herschel Telescope. Making use of a recently developed technique, emission is detected in 75% of the galaxies. The ionised-gas distributions display varied morphologies, ranging from regular gas disks to filamentary structures. Additionally, the emission-line kinematic maps show, in general, regular motions with smooth variations in kinematic position angle. In most of the galaxies, the ionised-gas kinematics is decoupled from the stellar counterpart, but only some of them present signatures of recent accretion of gaseous material. The presence of dust is very common in our sample and is usually accompanied by gas emission. Our analysis of the [O III]/Hβ emission-line ratios, both across the whole sample as well as within the individual galaxies, suggests that there is no unique mechanism triggering the ionisation of the gas.

Key words: galaxies: elliptical and lenticular, cD, galaxies: kinematics and dynamics, galaxies: ISM, galaxies: individual (NGC 2768, NGC 2974, NGC 4278, NGC 4526)
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1 Introduction

The advent of integral-field spectrographs has opened a whole new window of possibilities for extra-galactic studies. Coupled with large telescopes and advances in adaptive optics systems (AO), integral-field units (IFUs) offer a unique opportunity to go further in the exploration of astrophysical phenomena earlier in the history of the universe and at smaller scales. It is therefore not surprising that IFUs are quickly becoming standard instruments on all the 8m-class telescopes. Besides the efforts to investigate the formation and evolution of galaxies in the early universe, much can be learned by studying in detail the *fossil* record of nearby galaxies using IFUs on intermediate-size telescopes. The SAURON project (de Zeeuw et al. 2002), is a first step in this direction. The project is designed to perform a systematic study of a representative sample of early-type, nearby galaxies using the SAURON (Bacon et al. 2001) and OASIS (Bacon et al. 1995; McDermid et al. 2004) IFUs at the 4.2m William Herschel Telescope. Early results of the survey have revealed a variety of structures much richer than usually recognised in early-type galaxies (de Zeeuw et al. 2002; McDermid et al. 2004; Emsellem et al. 2004; see also R. McDermid's contribution in this workshop).

Here we focus on the distribution and kinematics of the ionised gas of a subset of galaxies to illustrate the diversity of structures and ionisation processes present in the SAURON representative sample of 48 elliptical and lenticular galaxies. The sample contains an equal fraction of elliptical and lenticular galaxies, with equal number of field and cluster galaxies in each morphological group. We will make use of the two-dimensional information delivered by SAURON to compare the distribution and kinematics of the stars and gas and to study the nature and origin of the ionised gas in these systems. A more extended analysis of the properties of the ionised gas for the entire sample is presented in Sarzi et al. (2005). Furthermore, the study of the stellar and gas properties of the 24 Sa bulges in the SAURON sample is addressed in Falcón-Barroso et al. (2005).

2 Extraction of the ionised gas

Early-type galaxies were traditionally thought to be uniform stellar systems with little or no gas and dust. However, a considerable number of imaging and spectroscopy studies have changed this view (Sadler & Gerhard 1985; van Dokkum & Franx 1995; Goudfrooij 1999; Tran et al 2001). In the spectral range delivered by SAURON there are three potential emission lines that can be measured (i.e. Hβ, [O III]$\lambda\lambda$4959, 5007, [N I]$\lambda\lambda$5198,5200). Given that the stellar contribution to the overall spectrum in our sample of galaxies remains significant, it is important to perform an accurate continuum subtraction in order to determine reliably the fluxes and kinematics of the emission lines. We investigated several methods to perform this task and settled on a procedure that *simultaneously* fits both the stellar and gaseous contributions to derive the fluxes, velocities and velocity dispersions of the emission lines.

Traditional methods to separate the stars and gas consisted of the subtraction of the best matching stellar template, in the regions free of emission, to the full spectrum of the galaxy. As described in Sarzi et al. (2005), this methodology can significantly overestimate the flux and velocity dispersion of the measured emission lines. Extensive simulations show that the new procedure is much more accurate and appears to be superior to previous ones, allowing us to detect emission down to an equivalent width of 0.1 Å.

3 Distribution of the ionised gas

The distribution of the ionised gas in our sample shows diverse morphologies. In general the distribution follows that of the stars, although there are several cases where the situation is much more complex (i.e. filaments, rings, spiral arms, lanes).

The incidence of ionised-gas emission in our sample is 75%. Seven galaxies show only weak traces of emission, and there are five cases with no detection. By morphological type, lenticular galaxies display a slightly higher content of ionised gas than elliptical galaxies (83% versus 66%). Similar percentages were found when the sample was divided according to environment (83% field, 66% cluster). One important remark is that the fraction of galaxies with clearly detected emission in the Virgo cluster drops to only 55% (10/18), with just 3/9 ellipticals showing the presence of gas. The incidence of ionised-gas shows no correlation with either luminosity or the presence of a bar in the galaxy. The detection rates found for our sample are in good agreement with those of Macchetto et al. (1996), who found emission in 85% of the lenticular and 68% of the ellipticals in their sample.

In Figure 2, we present maps of the stellar and ionised-gas distribution and kinematics for four of the 48 galaxies in our sample. NGC 2974 reveals a fast rotating gas disk co-rotating with respect to the stars. Despite the regular appearance of the ionised-gas distribution, the equivalent width (EW) map of the [O III] line (see Fig. 2) highlights the presence of an inner ring and two spiral arms that extend all the way out to the limits of our field-of-view (see Krajnović et al. 2005a for a detailed analysis of this galaxy using SAURON data). A similarly regular case is that of NGC 4526, although in this case the ionised gas is confined to a well defined, fast rotating disk in the central kpc of the galaxy. NGC 2768 is a well-known galaxy where the distribution of the ionised-gas appears to be perpendicular to that of its stellar counterpart (i.e. polar-ring, Fried & Illingworth 1994; Bertola et al. 1992). The SAURON [O III] EW map shows that the gas distribution has a filamentary morphology along the galaxy minor axis. The gas distribution in NGC 4278 displays a peculiar integral-sign pattern that is closely followed by the gas velocity field. The stellar and gas kinematics appear to be misaligned by increasingly wider angles, as they twist in opposite directions towards the outer parts of the field-of-view.

4 What powers the observed nebular emission?

Diagnostic diagrams of [O III]/Hβ vs [N II]/Hα (Veilleux & Osterbrock 1987; Kauffmann et al. 2003) have been used extensively in the past to investigate the trigger of the ionisation of the gas (i.e. AGN, star-formation). Many scenarios have been invoked to explain the presence of ionised gas in early-type galaxies: central AGN, hot (10^7K) gas (Sparks et al. 1989; de Jong et al. 1990), young stars (Shields 1992), post-AGB stars (Binette et al. 1994), or shocks (Dopita & Sutherland 1995). Within the wavelength range delivered by SAURON only the Hβ and [O III] lines can be used for this purpose. Despite this limitation, the [O III]/Hβ ratio serves as a good indicator to locate regions where emission is due to young stars and also to trace variations of the ionisation mechanisms within a single galaxy.

Regions displaying low [O III]/Hβ ratios (i.e. $\leq$1) are usually interpreted as indicative of star-formation (Ho et al. 1997). However, higher ratios (i.e. $>$1) could still indicate star-formation if the metallicity of the gas is sufficiently high (Veilleux & Osterbrock 1987). Additionally other mechanisms can lead to high ratios. Since it is unlikely that the metallicity of the ionised gas varies abruptly within galaxies (unless there has been some recent accretion of material), large variations across maps of the [O III]/Hβ ratio are more likely to be produced by changes in the ionisation mechanism rather than changes in the metallicity.

Figure 2 shows the [O III]/Hβ ratios for the galaxies discussed in Section 3. The [O III]/Hβ ratio maps clearly reveal the presence of radial gradients and substructures in the ionisation properties of the gas in the four galaxies. The ratio is moderately high in NGC 2768, NGC 2974, and NGC 4278, while it is very low in NGC 4526. In this last galaxy, the location of the low [O III]/Hβ values corresponds to the location of a prominent dust disk (as shown in the unsharp-masked image), and suggests ongoing star formation. In this respect, there seems to be a clear link between the ionised structures found in the [O III]/Hβ maps with those seen in the [O III] equivalent width and kinematic maps (i.e. ring in NGC 2974, or integral-sign pattern in NGC 4278).

The remaining sample of 44 galaxies also displays a great diversity of [O III]/Hβ ratios within galaxies, but also across the sample. This suggests that either there are many mechanisms at play in the ionisation of the gas, that the metallicity of the ionised gas is very heterogeneous in those galaxies, or both.

5 Relation between gas and dust

In order to study the dust distribution and compare it with that of the ionised gas we have generated unsharp-masked images using archival *Hubble Space Telescope* images. We found that, consistent with previous results, dust generally follows the ionised-gas distribution (Goudfrooij et al. 1994; Tomita et el. 2000; Tran et al. 2001). The opposite situation is not always true, as we have found galaxies with clear presence of emission with no traces of dust in the unsharp-masked images. As found by previous authors (Ho et al. 2002), regular dust distributions generally are associated with smooth velocity fields, however the lack of regular dust lanes does not imply the presence of irregular kinematics.

The four cases presented in Figure 2 display a wide range of dust morphologies that correlate in different degrees with the structures seen in the distribution of the ionised gas. The prominent dust disk in NGC 4526 traces closely the distribution of the gas. The ring-like structure and spiral arms in NGC 2974 are also followed by dusty structures at the same locations. The dust morphology is less defined in NGC 2768 and NGC 4278, but still suggests an orientation for the dust that is similar to that of the gas distribution.

6 The Origin of the ionised gas

The measurement of misalignments between the kinematics of the gaseous and stellar components in early-type galaxies has often been used to determine the relative importance of accretion events and the internal production of gas through stellar mass-loss (e.g. Bertola et al. 1992). The orientation of the dust relative to that of the stars has also served this purpose (e.g. van Dokkum & Franx 1995). In order to quantify the presence of decoupled gaseous components in our sample and to investigate their dependence on environment, we have measured the mean misalignment between the stellar and ionised gas using *kinemetry*, a generalisation of surface photometry to the higher-order moments of the line-of-sight velocity distribution of galaxies (Krajnović et al. 2005b).

In Figure 2 (solid line) we show the distribution of the average misalignments for the galaxies in our sample of 48 galaxies with sufficiently extended emission. The distribution of values appears to be skewed towards small misalignments. However, the fact that there is still a significant fraction of galaxies showing mild to strong misalignments suggests that the ionised gas has not a purely internal origin (in which only small misalignments are expected). The overall shape of the distribution remains unchanged when the sample is divided into elliptical and lenticular galaxies. No dependency is found on neither environment nor galaxy luminosity. We do, however, find a strong dependence on apparent flattening of the galaxy

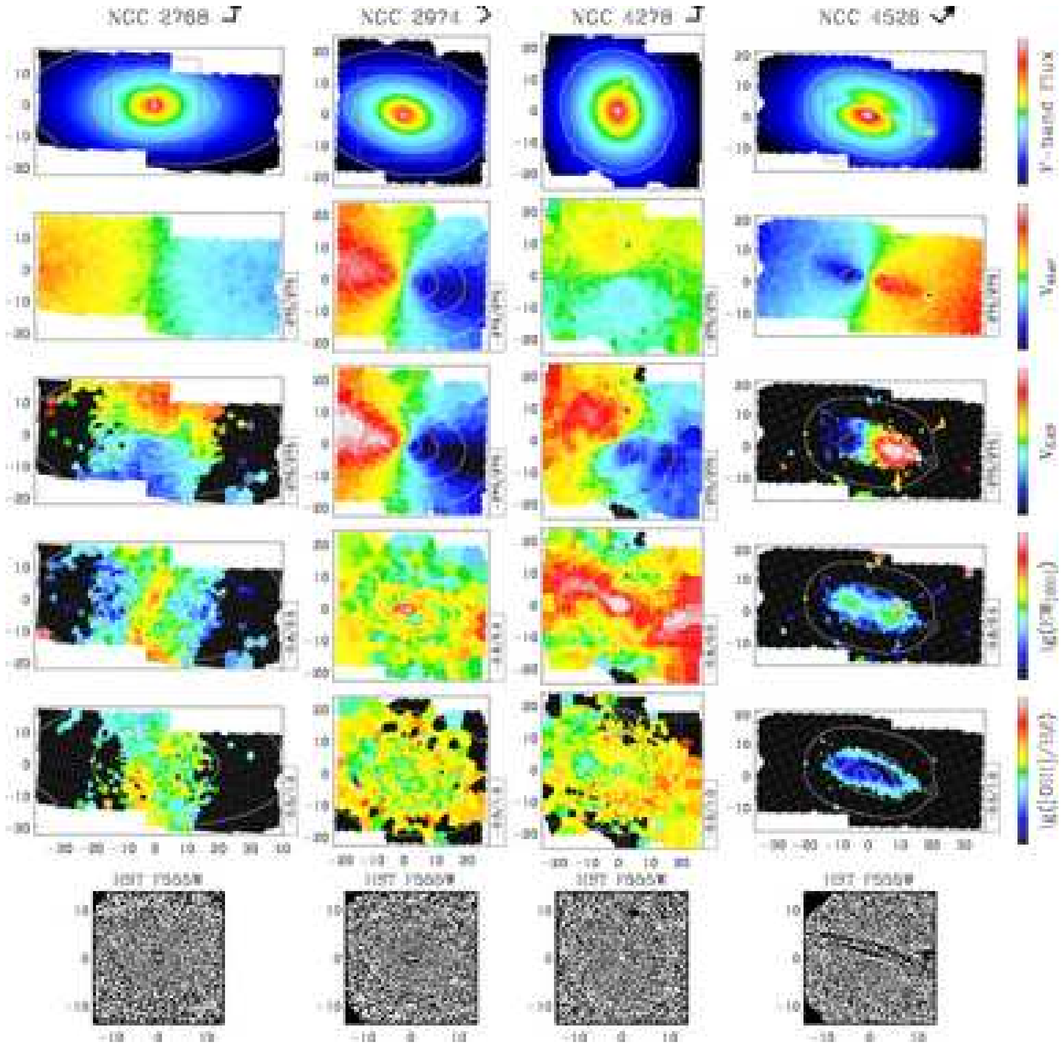

Fig. 1. SAURON maps for 4 galaxies representative of the gas properties in the 48 E and S0 galaxies surveyed by the SAURON project (Sarzi et al. 2005). From top to bottom: i) the reconstructed total intensity, ii) the stellar velocity, iii) the ionised-gas velocity, iv) the equivalent width of the [O III] emission line in Å (in log units), v) the value of the [O III]/Hβ ratio (also in log units), and vi) unsharp-masked images obtained from HST observations. The cuts levels are indicated in the box at the right-hand side of each map. The grey boxes on the top figures indicate the field-of-view of the HST images in the last row. Notice how the gas distribution can vary from galaxy to galaxy, and how the kinematic major axis of the ionised gas deviates from that of the stars. The [O III]/Hβ ratio maps clearly reveal the presence of radial gradients and substructures in the ionization properties of the gas. The low [O III]/Hβ values corresponding to the dust disk in NGC 4526 suggest ongoing star formation.

(see Fig. 2, bottom panel). It appears that the distribution of misalignments of the most flattened objects accounts for the observed excess of co-rotating over counter-rotating gas and stellar systems in the whole sample. The roundest objects (ϵ <0.2) display a more uniform distribution. This result suggests that rotational support might be important to explain the observed dependence.

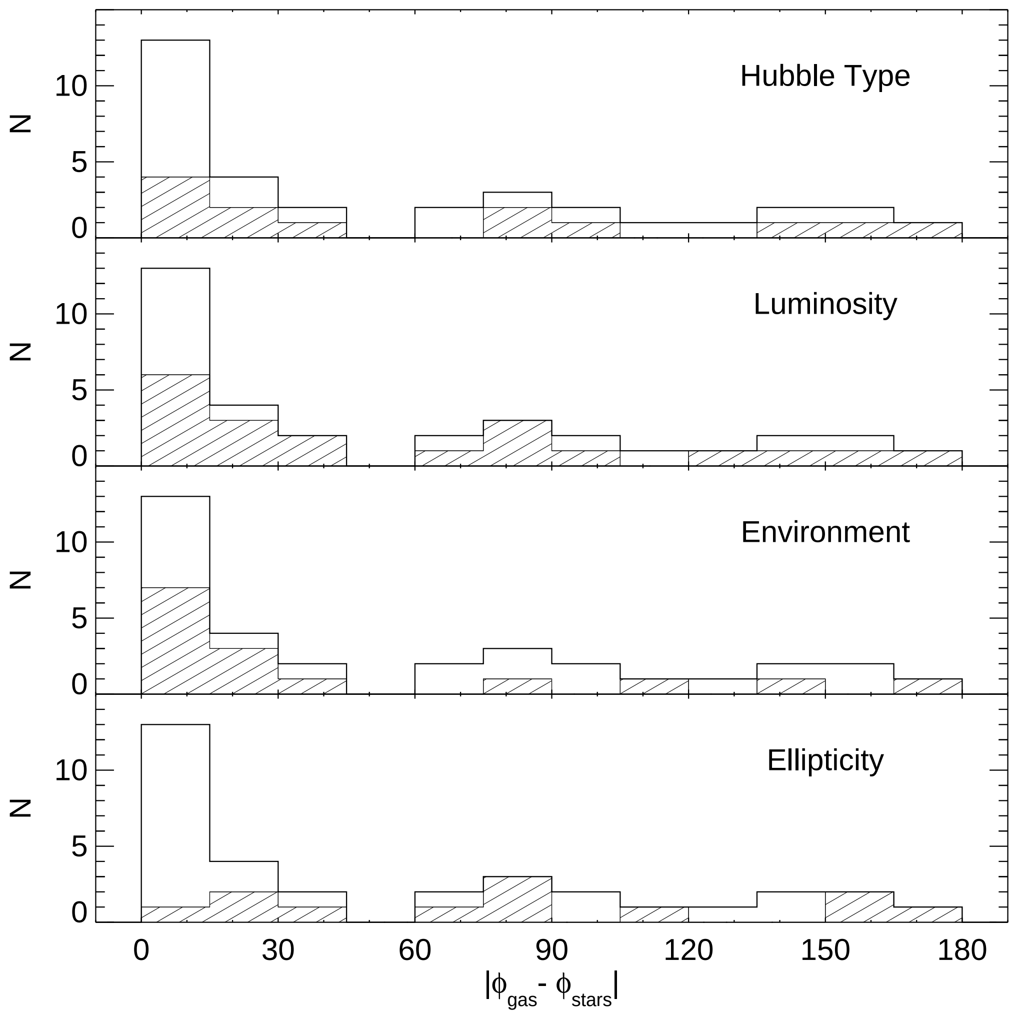

Fig. 2. Distribution of misalignments between the kinematic stellar and gaseous axes. In all panels the solid line represents the distribution of misalignments for the 48 E and S0 galaxies. The shaded areas in the different panels represent (from top to bottom): ellipticals, galaxies brighter than $M^*_B = -19.7$ mag (Efstathiou, Ellis & Peterson, 1988), field galaxies, and roundest galaxies ($\epsilon \leq 0.2$).

7 Concluding remarks

We have presented some examples of the morphological and kinematical state of the ionised gas in a representative sample of early-type galaxies using data from the SAURON spectrograph at the 4.2m William Herschel Telescope. The results of our analysis reveal a wide range of morphological, but also kinematical structures. It also shows that there must be several mechanisms responsible for the ionisation of the gas, not only across galaxies, but also within galaxies. The presence of dust is common in our sample and is usually accompanied by gas emission. Finally, we studied the distribution of misalignments between the stars and gas in our sample, and conclude that the origin of the ionised gas cannot be purely internal or external.

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