Connecting stars and ionised gas with integral-field spectroscopy

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Abstract

Using integral-field spectroscopy, the `SAURON` survey has shown that early-type galaxies, once thought to be essentially devoid of gas, commonly show ionised gas emission found with a rich variety of distributions and kinematics, ranging from very uniform disks or rings, and large-scale twisted structures, to flocculent and irregular streams. Such variety is missed in conventional long-slit spectroscopy, and integral-field spectroscopic data allow accurate removal of the underlying stellar continuum compared with imaging surveys, giving very low detection limits. Moreover, spectral data can simultaneously provide the stellar kinematics and populations as well as the emission-line properties. We investigate the connection between the stellar and gas properties using integral-field spectroscopy from `SAURON`, `OASIS` and `GMOS`,

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and find that, although some global trends exist, the connection between the stellar population parameters and the gas properties is in some cases puzzlingly unclear.

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1 Introduction

Over the past decade, it has become clear that not only do a significant fraction of early-type galaxies contain appreciable quantities of dust and gas (e.g. Macchetto et al., 1996), but that the amount and nature of this material plays a very significant role in the formation and evolution of these systems (e.g. Bekki & Shioya, 1997). Whilst it was once reasonable and computationally necessary to consider early-type galaxies as purely stellar systems born of collisionless processes, it is now clear that the degree of dissipation during mergers, and subsequent conversion of gas to stars, has a profound effect on the morphology and internal dynamics of early-type galaxies (Cox et al., 2006). The introduction of gas to the system (through mergers or accretion from the environment) and its evacuation (via stellar winds, super novae and nuclear activity) are crucial aspects of any modern model of galaxy evolution, but the mechanisms which control these processes are still poorly understood.

Observationally, accurately characterising the gas content of galaxies is extremely challenging. Gas can be present in a number of co-existing phases, each producing different observables from the radio to X-ray domains. Moreover, often a number of observables and/or assumptions are required to determine the physical properties such as mass, temperature and chemical abundance. Coupling this with the generally complex distribution of gas within galaxies, it is not surprising that many open questions remain.

2 The `SAURON` Survey

One such question is on the relationship between the gas found in early-type galaxies and the stars that dominate their visible morphologies. As part of the `SAURON` survey (de Zeeuw et al., 2002), we have measured the emission-line properties of a representative sample of nearby early-type galaxies (Sarzi et al., 2006, see also Sarzi et al., this volume). For this sample of both field and

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cluster elliptical and lenticular galaxies, a remarkable 75% of galaxies show clear evidence of emission. This fraction is highest for the field and lenticular classes, although the differences between classes are generally small.

One of the most striking features of the `SAURON` data is the variety of structures found in both the distribution and kinematics of the ionised gas. Figure 1 shows some illustrative examples.

NGC 2768 appears as a regular, flattened galaxy, with a faint dust lane along its minor axis, visible as a distortion of the isophotes in the reconstructed image. The [OIII] equivalent width map reveals an extended and distorted region of ionised gas that follows this dust lane, and from the velocity map, can be seen to rotate around the galaxy major-axis, perpendicular to the stars.

NGC 2974, on the other hand, shows a very regular, large-scale gas disk that co-rotates with the stars. In this apparently regular case, however, the equivalent width map reveals a complex structure of spiral arms connected to a ring, surrounding an elongated central bar (see also Emsellem, Goudfrooij & Ferruit, 2003; Krajnović et al., 2005; Jeong et al., 2006).

NGC 4278 also shows a large-scale coherent distribution but with a smoothly twisting [OIII] velocity field that is itself misaligned to the stellar rotation field. This ionized gas structure appears to connect to a similarly aligned structure observed in neutral hydrogen, existing on very large scales (Morganti et al., 2006).

Finally, **NGC 4526** exhibits a spatially distinct disk of gas (and dust) that closely corresponds to a fast-rotating sub-component of the stellar velocity field. Both are more flattened and rapidly rotating than the rest of the galaxy. It appears that material has settled into a cold disk component, which is subsequently forming stars.

3 Global connection between stars and ionised gas

From the examples shown in Figure 1, it is clear that the distribution and kinematics of the gas and stars can vary greatly between galaxies. Using the `SAURON` velocity maps, Sarzi et al. (2006) quantified the relative kinematic alignment of the stars and gas. From this study it was found that flattened galaxies with a high level of rotational support tend to have well-aligned gaseous and stellar kinematics, while slowly rotating and round (in projection) galaxies showed a wide range of misalignments (see also Sarzi et al., this volume). This would imply that gas is more tightly connected to the evolution of fast-rotating galaxies, either as an internal product of stellar evolution, or as a residual of the

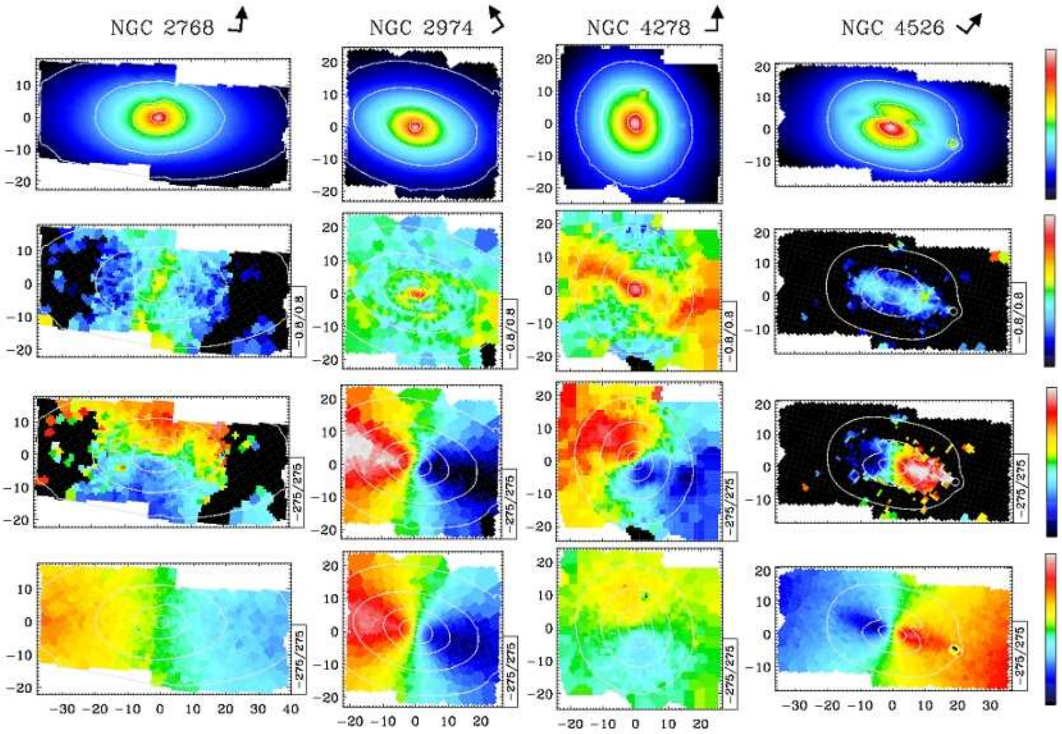

Fig. 1. Examples of `SAURON` maps. *Top row*: reconstructed image from integrated spectra. *Second row*: equivalent width of [OIII]. *Third row*: mean velocity of [OIII]. *Fourth row*: mean stellar velocity. From Sarzi et al. (2006).

external material involved in forming a large portion of the stars themselves (or both).

If the ionised gas is connected to a recent evolutionary phase of the stellar component, one would expect to see a relation between the gas content and stellar age. Stellar age is measured as the (luminosity-weighted) mean of an integrated population, and therefore it is the relative mass-fraction of old and young stars that determines the 'age' we measure, not the time of the last formation event. Related to this, we must normalize the absolute gas mass by the galaxy stellar mass. A giant elliptical may have a larger absolute gas mass than a lenticular galaxy with one hundredth of the stellar mass, but if this represents only 0.1% of the elliptical's total mass, converting it to stars will have a negligible impact on the luminosity-weighted mean age of the integrated population.

Figure 2 shows the luminosity-weighted mean stellar age versus the 'specific' ionised gas mass (i.e. normalized by the stellar mass, in this case the dynamical, or virial, mass), presented in Emsellem et al. (2006). The circle and 'spindle' symbols indicate slow- and fast-rotating galaxies, respectively. We do not find a tight relation, but there is certainly a clear trend for galaxies with larger specific gas masses to have younger mean ages. We also find that all but

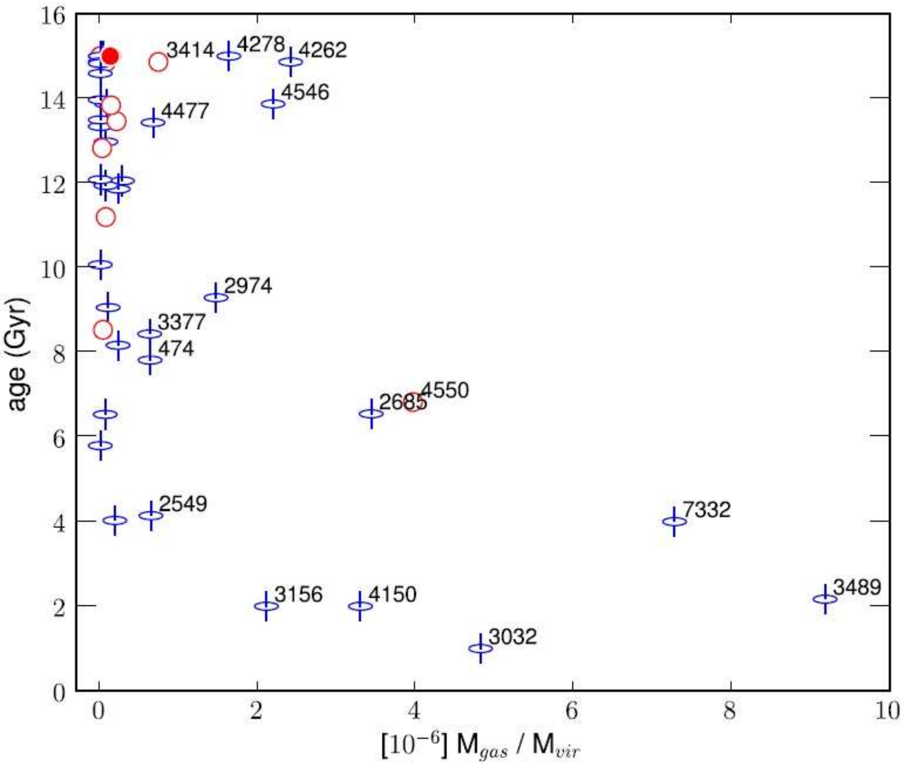

Fig. 2. Luminosity-weighted mean stellar age versus the specific ionised gas mass (ionised gas mass normalized by the virial mass) within the `SAURON` field of view. Circles indicate slow-rotating galaxies; ‘spindles’ represent fast-rotating galaxies; filled circles show galaxies consistent with zero rotation. See Emsellem et al. (2006) for details of this classification.

two galaxies with appreciable ionised gas content are fast-rotators, supporting the idea that gas processes play an important role in forming these flattened, rotating galaxies. Interestingly, for a subset of these `SAURON` galaxies, Morganti et al. (2006) do not find such a clear trend considering the relative mass of neautral hydrogen with mean stellar age, or a connection with the stellar dynamics.

There are a number of reasons not to expect a tight relation between the stellar age and ionised gas fraction. Firstly, the ionised gas flux can arise both from young star-forming regions, or from shock-excitation, which may not be directly related to recent star formation, e.g. by an active nucleus or novae. From the `SAURON` spectra alone, we do not have sufficient diagnostic lines to discriminate these two processes. Secondly, the time-scales of star formation may vary between galaxies, giving different mean stellar ages for the same relative gas fraction. Finally, in the case of gas entering the system as a distinct accretion event, this may happen multiple times over the lifetime of a galaxy and with varying magnitude, giving a non-trivial relationship between the gas we see now, and the integrated population.

4 Case studies: NGC 3032 and NGC 4150

We may expect the complication of time-scales between the current gas content and the luminosity-dominant stellar population to be less apparent for galaxies with young ages, since one may reasonably expect that the ionised gas traces the reservoir of material used to form those young stars. Here we examine two of the galaxies with youngest mean stellar ages in the `SAURON` sample: NGC 3032 and NGC 4150.

4.1 NGC 3032

This galaxy has the youngest luminosity-weighted stellar age of the `SAURON` sample. An unsharp-masked *HST* image reveals a spiral dust structure with star-forming knots in the main body of the galaxy, a region where the mean stellar age is only 1 Gyr (McDermid et al., 2006). There is also ionised gas detected at the same position, and one would perhaps expect this to trace the same star-forming material, thus sharing the distribution and kinematics of the dominant young stars. However, as Figure 3 shows, within the `SAURON` field, the stellar and gas rotation velocity maps (from Emsellem et al., 2004; Sarzi et al., 2006, respectively) are actually *counter-rotating* (in projection).

Zooming-in on the central regions of the stellar velocity field with the higher spatial resolution `OASIS` data reveals that, in fact, the central 2 arcseconds harbour a kinematically decoupled component (KDC) not seen in the lower spatial resolution `SAURON` data. This KDC has a more similar kinematic orientation to the gas than the outer parts. Moreover, the KDC is co-spatial to a sharp increase in the Hβ Balmer absorption line-strength, corresponding to a decrease in the mean stellar age to below 0.5 Gyr (McDermid et al., 2006).

For this galaxy it seems that the ionised gas does indeed trace a reservoir of star-forming material, but the star-formation is only apparent within the central few hundred parsecs of the galaxy. The link between the gas and the KDC can be made both from their shared kinematic orientation, and the very recent formation of the stars.

It is somewhat unexpected that the ionised gas in the outer regions is decoupled from the young stars at the same (projected) positions. This galaxy appears rather face-on ($\epsilon \sim 0.1$), making it difficult to know whether the stars and gas rotate in the same plain. However the relatively low apparent gas rotation velocity (and dispersion, not shown) would be roughly consistent with a disk observed at the corresponding inclination (20-30°) for a galaxy of this mass. It may be that this gas is indeed participating in the star-formation along the spiral dust lanes apparent in the *HST* image, but that these young

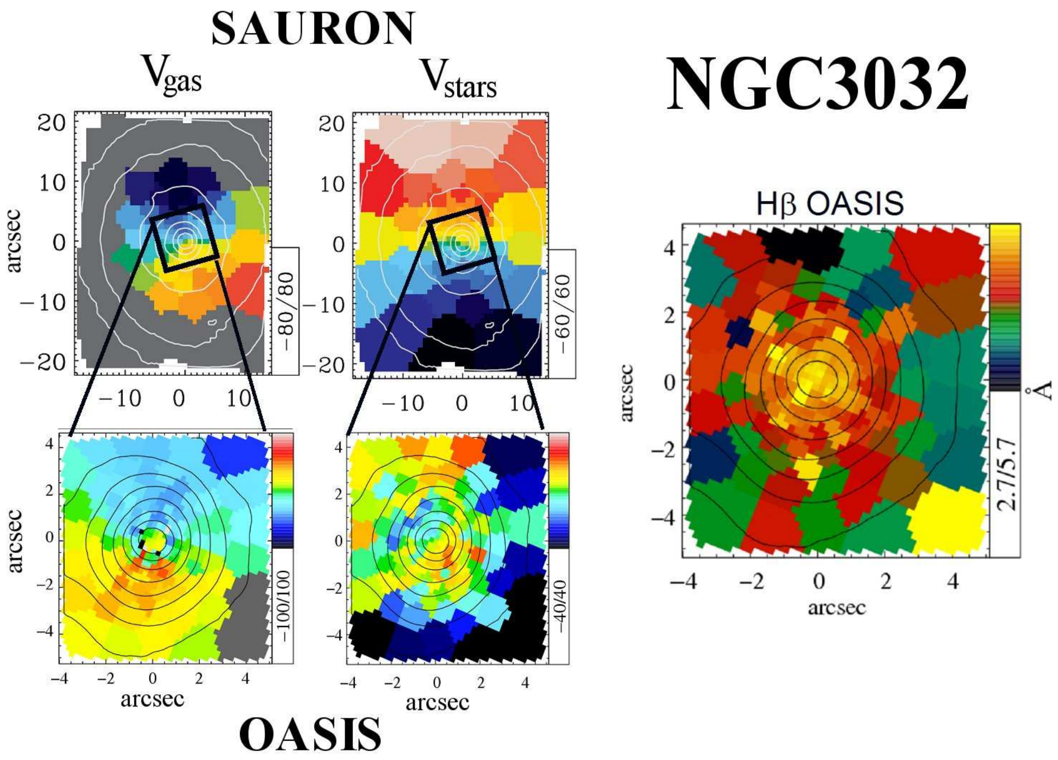

Fig. 3. *Top left:* `SAURON` measurements of the gas and stellar rotation velocities (V_{gas} and V_{star} respectively). *Bottom left:* Corresponding measurements of the central regions with higher spatial resolution, using `OASIS`. *Right:* Hβ absorption line strength measured with `OASIS`.

stars do not contribute sufficient light to influence the mean stellar velocity. Further modelling is required to establish this.

4.2 NGC 4150

This galaxy is also amongst the objects with the youngest mean stellar age in the `SAURON` sample, with a global age (measured within 1 effective radius) of 2 Gyr. Unlike NGC 3032, the `SAURON` stellar and gas rotation fields (from Emsellem et al., 2004; Sarzi et al., 2006, respectively) are co-rotating, and so one can naively assume that this gas is linked to the reservoir of material for star-formation in this galaxy.

Like all the galaxies in the `SAURON` sample with young global ages, within the central few hundred parsec of NGC 4150, there is a distinctly young population, giving a sharp increase in the observed Hβ absorption line strength and a corresponding decrease in the mean age from 2 to less than 1 Gyr. At the same location, and just visible from the `SAURON` data, there is a stellar KDC. Zooming in to the central regions, this time using the `GMOS` integral-field spectrograph on Gemini, the stellar KDC is clearly revealed. The ionised

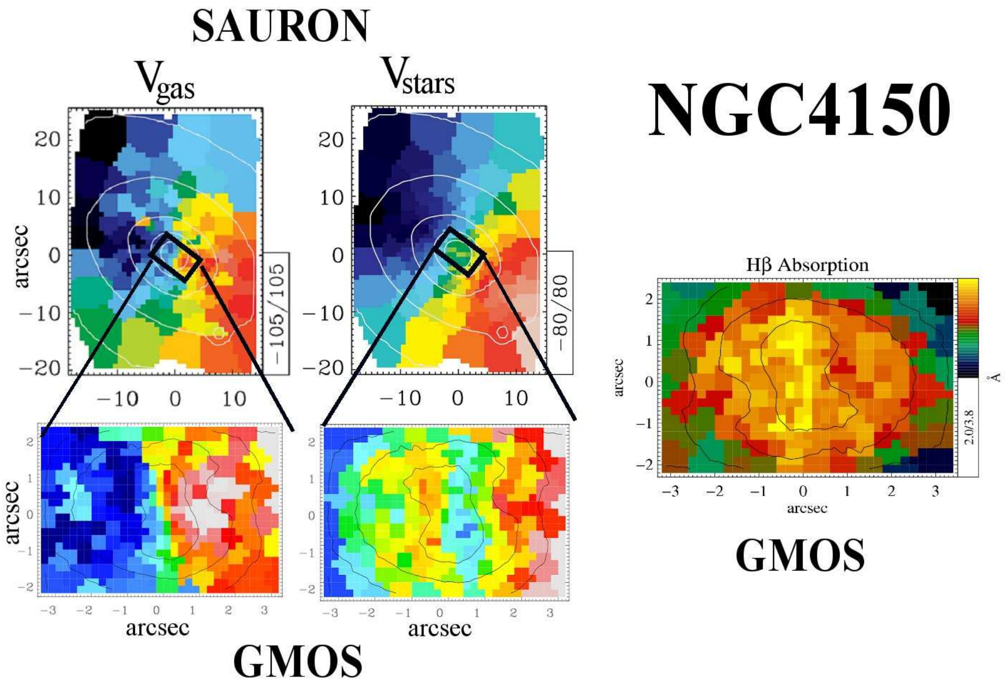

Fig. 4. As for Fig. 3 but for NGC 4150, where `GMOS` was used to observe the central region.

gas, however, in the same region remains co-rotating with the outer parts. In contrast to NGC 3032, the ionised gas seems completely decoupled from the youngest stars in the system, that have only quite recently formed.

5 Conclusions

We have explored the connection between the stellar and ionised gas content of early-type galaxies, to try to understand the origin and fate of the gas, and its influence on the stellar component of these galaxies. We have made use of integral-field spectroscopy, a uniquely powerful tool for this task, since it can simultaneously provide not only the ionised gas flux at faint levels, but also the stellar kinematic and population properties. Moreover, only with two-dimensional coverage is it possible to appreciate the rich complexity of structure found in both stellar and gas components. We have shown the power of discovery that improved spatial resolution can bring, and that by coupling wide-field, low spatial resolution and narrow-field, high spatial resolution integral field spectroscopy one obtains a more accurate picture of how a galaxy works.

A global trend exists that galaxies with higher ionised gas content (relative to their stellar mass) tend to be younger than those without much gas. This suggests a direct link between the observed ionised gas and the (luminosity-weighted) mean stellar population. Investigating this further, we presented two galaxies with young (1-2 Gyr) mean stellar populations. In one case, NGC 3032, we find that the ionised gas is kinematically linked to the youngest stars (0.5 Gyr) in the central few hundred parsecs of the system, but is decoupled to stars that are slightly older (1 Gyr) and further out (kiloparsec scales). In the case of NGC 4150, we find the opposite behaviour, where the youngest stars (also in a KDC within the central few hundred parsec) are counter-rotating to the ionised gas. These two cases demonstrate that the apparent global connection between the stars and gas is not necessarily directly related to the near-instantaneous processes currently acting on the galaxy, but to the general interplay of gas accretion and star formation over the lifetime of the galaxy.

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