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On the origin and fate of ionised-gas in early-type galaxies: The SAURON perspective

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Abstract

By detecting ionised-gas emission in 75% of the cases, the SAURON integral-field spectroscopic survey has further demonstrated that early-type galaxies often display nebular emission. Furthermore, the SAURON data have shown that such emission comes with an intriguing variety of morphologies, kinematic behaviours and line ratios. Perhaps most puzzling was the finding that round and slowly rotating objects generally display uncorrelated stellar and gaseous angular momenta, consistent with an external origin for the gas, whereas flatter and fast rotating galaxies host preferentially co-rotating gas and stars, suggesting internal production of gas. Alternatively, a bias against the internal production of ionised gas and against the acquisition of retrograde material may be present in these two kinds of objects, respectively. In light of the different content of hot gas in these systems, with slowly rotating objects being the only systems capable of hosting massive X-ray halos, we suggest that a varying importance of evaporation of warm gas in the hot interstellar medium can contribute to explain the difference in the relative behaviour of gas and stars in these two kinds of objects. Namely, whereas in X-ray bright and slowly rotating galaxies stellar-loss material would quickly evaporate in the hot medium, in X-ray faint and fast rotating objects such material would be allowed to lose angular momentum and settle in a disk, which could also obstruct the subsequent acquisition of retrograde gas. Evidence for a connection between warm and hot gas phases, presumably driven by heat conduction, is presented for four slowly rotating galaxies with Chandra observations.

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1. Introduction

Over the years, a number of imaging and spectroscopic studies have contributed to end the preconception about early-type galaxies as consisting of simple stellar systems (see Goudfrooij, 1999, for a review). Yet, if it is now accepted that elliptical and lenticular galaxies often contain dust and display nebular emission, a number of questions still remain unanswered. What is the origin of the interstellar material in early-type galaxies? Is it material lost by stars during their evolution or does it have an external origin? And what is its fate? Does it cool down to form stars or does it become hot, X-ray emitting gas? Furthermore, what powers the observed nebular emission? Is it a central active nucleus? Is the warm ($\sim 10^4$ K) gas ionised by the hot ($\sim 10^7$ K) gas through heat conduction (e.g., Sparks et al., 1993)? Is the gas ionised by stars; young or old (e.g., post-AGB)? Or is it excited by shocks, as also proposed for low-ionisation nuclear emission-line regions (Dopita and Sutherland, 1995).

The SAURON integral-field spectroscopic survey (de Zeeuw et al., 2002) has not only further demonstrated that early-type galaxies often display nebular emission, but also shown that such emission comes with a variety of morphologies, kinematic behaviours and line ratios, which suggests a rather complex picture for the origin, fate and ionisation of the gas. Using a new procedure that simultaneously fits both the stellar spectrum and the emission lines, Sarzi et al. (2006 hereafter Paper V) could indeed measure Hβ, [O III]λλ4959,5007, and [N I]λλ5198,5200 emission lines down to equivalent width values of 0.1 Å, uncovering extended emission in 75% of the 48 elliptical and lenticular galaxies in the SAURON sample. Across these objects, the gas emission is found in disks, in filamentary structures, along lanes, or in rings and spiral arms. The ionised-gas kinematics is rarely consistent with simple coplanar circular motion, and generally display coherent motions with smooth variation in angular momentum. Finally, a considerable range of values for the [O III]/Hβ ratio is observed both across the sample and within single galaxies, which, despite the limitations of this ratio as an emission-line diagnostic, suggests that a variety of mechanisms is responsible for the gas excitation in E and S0 galaxies.

This paper will focus primarily on the origin and fate of the ionised gas in early-type galaxies. In Section 2 we will discuss clues from the relative kinematic behaviour of gas and stars in early-type galaxies, whereas in Section 3 we will consider some suggestive facts concerning the hot-gas content of the elliptical and lenticular galaxies in the SAURON sample. Finally, we will draw our conclusions in Section 4.

2. Clues from the kinematic decoupling between gas and stars

The distribution of the values for the misalignment between the angular momenta of gas and stars 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).

If the origin of the gas is external and gas is acquired from random directions, an equal number of co- and counter-rotating gaseous and stellar systems should be found, with a more or less pronounced fraction of objects with gas in polar orbits depending on the intrinsic shape of early-type galaxies (Steiman-Cameron and Durisen, 1982). On the other hand, gas that is internally produced will rotate in the same sense of its parent stars and only co-rotating gas and stars should be observed. In both cases, projection effects and the presence of triaxial systems will lead to observe also intermediate values for the kinematic misalignment, beside 0°, 90° and 180°. Overall, however, if the gas has an external origin the resulting distribution for the kinematic misalignments should be *symmetric* around 90°, with an equal number of counter- and co-rotating gaseous and stellar systems, whereas if the origin of the gas is internal the distribution of kinematic misalignments should be *asymmetric*, with values mostly between 0° and 90°. Using the early-type galaxies that in the SAURON sample display clear stellar rotation and well-defined gas kinematics, in Paper V we have found a distribution for the gas-star kinematic misalignments that is inconsistent with the prediction of either of these simple scenarios. As the top panels of Fig. 1 show, half of the objects display a kinematic decoupling that implies an external origin for the gas, but the number of objects consistent with co-rotating gas and stars exceeds by far the number of counter-rotating systems, suggesting that internal production of gas has to be important.

The distribution of values for the kinematic misalignment between stars and gas does not depend on Hubble type, galactic environment, or galaxy luminosity (Paper V, but see also Fig. 2 of Falcón-Barroso et al., 2006a). It does, however, strongly depend on the apparent large-scale flattening of galaxies. Fig. 1 shows that the roundest objects in our sample ($\epsilon \leqslant 0.2$) present a more symmetric distribution of kinematic misalignments than flatter galaxies, which instead host predominantly co-rotating stellar and gaseous systems. Since for random orientations fairly round galaxies are likely to be almost spherical and hence supported by dynamical pressure, rather than by rotation, the degree of rotational support could also be important to explain the observed dependency on galaxy flattening. In Emsellem et al. (2007) we assess the level of rotation support adopting a quantity, λ_R, that is closely related to the specific angular momentum of a galaxy. In the SAURON sample, galaxies with $\lambda_R \leqslant 0.1$ form a distinct class characterised by little or no global rotation and the presence of kinematically decoupled cores. Opposed to such slowly rotating objects are galaxies that either display faster global rotation or that are consistent with being systems supported by rotation that are viewed at small inclinations. Fig. 1 shows the distribution of kinematic misalignments between gas and stars in fast and slowly rotating galaxies according to the criterion of Emsellem et al. (see also

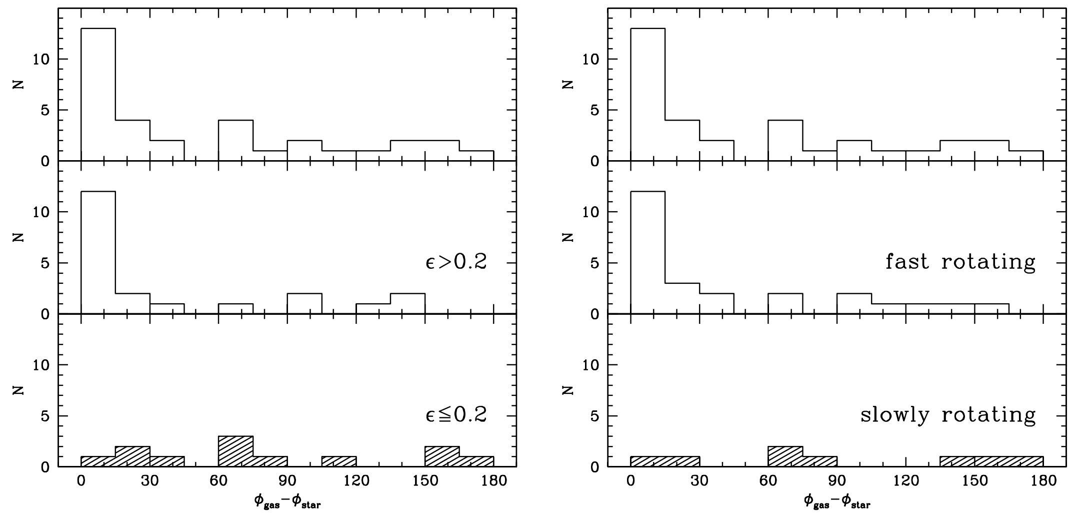

Fig. 1. Distribution of the values for the kinematic misalignment between stars and gas for SAURON early-type galaxies with clear stellar rotation and well-defined gas kinematics. The distribution corresponding to all the SAURON galaxies satisfying these conditions is shown in both top panels, whereas the middle panels show the misalignments distribution only for flatter and fast rotating objects (on the left and right, respectively) and the lower panels only for rounder and slowly rotating systems (on the left and right, respectively). Adapted from Sarzi et al. (2006).

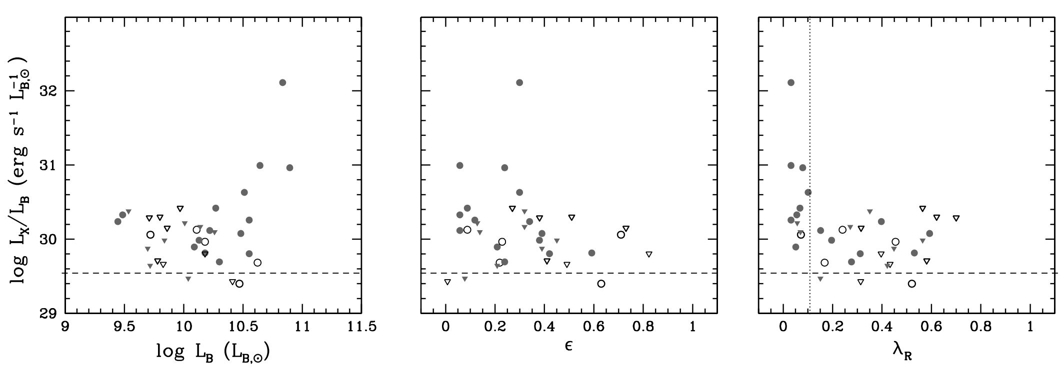

Fig. 2. X-ray properties of SAURON early-type galaxies. From left to right the X-ray luminosity L_X, normalised to the total blue-band luminosity L_B, is compared to L_B, the flattening ϵ and the degree of rotational support as traced by the λ_R parameter of Emsellem et al. (2007). L_X values (circles) or upper-limits (triangles) are ROSAT and Einstein measurements from the compilation of O'Sullivan et al. (2001), except for NGC 524 and NGC 5813, which were taken from Pellegrini (2005) and Böhringer et al. (2000), respectively. These data cover three-quarters of the SAURON early-type sample. Filled and open symbols show elliptical and lenticular galaxies, respectively. In each panel, the horizontal dashed line shows the normalised X-ray luminosity expected from stellar sources (O'Sullivan et al., 2001). Notice the tight segregation of objects with high-L_X/L_B to the region with $\lambda_R < 0.1$ – only slow-rotators can retain massive X-ray halos.

McDermid et al., 2006 for an illustration of these two kinds of objects). Consistent with our expectations, the two distributions are remarkably different, as in the case of flat and round objects.

According to the previous first-order assumptions these results suggest that external accretion of gaseous material is less important than internal production of gas in flat and fast rotating galaxies, whereas rounder and slowly rotating objects would acquire their gas more often. Such an interpretation is quite puzzling, however, for there is no obvious reason why early-type galaxies would acquire or produce more or less gas depending only on their apparent flattening or level of rotation support. The flat and fast rotating objects plotted in Fig. 1 do not live in a different environment than the round and slowly rotating systems, and except for a few cases, all objects share old and evolved stellar populations (Kuntschner et al., 2006).

This leads to consider alternative explanations for the observed distribution of values for the kinematic misalignment between gas and stars, starting from the assumption that all early-type galaxies can both acquire and produce gaseous material. In this framework, what is needed are mechanisms that would favour the accretion of prograde over retrograde material in flatter and fast rotating galaxies, and remove or hide the gas internally produced in rounder and slowly rotating objects.

For instance, a pre-existing indigenous gaseous disk could obstruct the acquisition of material with anti-parallel angular momentum. This appears to be the case of late-type galaxies where indeed counter-rotating gaseous and stellar systems are very seldom observed (see Falcón-Barroso et al., 2006b and Ganda et al., 2006, for a SAURON view on early- and late-type spiral galaxies, respectively, and Bertola and Corsini, 1999, for a review on the phenomenon of counter-rotation). On the other hand, the presence of a massive halo of hot, X-ray emitting gas could render undetectable in the visible spectrum the gas shed by stars as this evaporates in the hot gaseous medium (e.g., Mathews, 1990).

3. Clues from the X-ray properties

Following the previous considerations, it is interesting to note that early-type galaxies display dramatically different behaviours when it comes to their X-ray luminosity L_X.

Indeed, whereas in faint elliptical and lenticular galaxies X-ray binary stars can account for the observed X-ray fluxes, the brightest early-type galaxies tend to display truly extended and massive halos of hot, X-ray emitting gas (e.g., Fabbiano et al., 1992). This can be appreciated when L_X is compared to the blue-band luminosity L_B, as L_X–L_B at low-luminosities and L_X–L_B^2 for $L_B \gtrsim 3\times10^9 L_{B,\odot}$ (e.g., O'Sullivan et al., 2001). The scatter in the L_X–L_B diagram is very large, however, and has been the subject of many investigations (see Mathews and Brighenti, 2003 for a review). In particular, (Eskridge et al., 1995a; Eskridge et al., 1995b) found that S0s and flat Es show lower X-ray luminosities than rounder elliptical galaxies of the same optical luminosity, which prompted theoretical studies concerning the rôle of intrinsic flattening or rotation in producing different L_X at a given L_B (Ciotti and Pellegrini, 1996; Brighenti, 1996).

Fig. 2 shows, for the SAURON early-type galaxies with global X-ray luminosity measurements, L_X/L_B *versus* L_B, ϵ and λ_R. Consistent with previous studies, also in the SAURON sample the brightest X-ray halos are exclusively found around the brightest and roundest objects, although there are also galaxies with $\epsilon \gtrsim 0.3$ and $L_B \gtrsim 3\times10^{10} L_{B,\odot}$ that exhibit normalised X-ray luminosities consistent with stellar sources (dashed line). On the other hand, when L_X/L_B is compared to the λ_R parameter it is quite remarkable not only that high L_X/L_B values are found solely in galaxies with $\lambda_R < 0.1$, i.e. the slow-rotators, but also that the previously mentioned round or bright objects with faint normalised X-ray luminosities turned out to be fast rotators. In other words, λ_R works better than the apparent flattening or the total luminosity of a galaxy in separating objects with or without extended X-ray halos.

The presence of massive halos of hot, X-ray emitting gas in rounder and slowly rotating galaxies could explain why a conspicuous number of co-rotating gaseous and stellar systems is not observed in this class of objects, since the stellar-loss material would be efficiently removed from the observed ionised-gas component of the interstellar medium.

The conduction of heat from hot to warm medium can be observed when the warm recipient is material that has been recently acquired and that comes with sufficient column density. Owing to X-ray images with high spatial resolution, evidence for such interaction was presented by Trinchieri and Goudfrooij (2002) and Sparks et al. (2004) as they revealed a striking spatial coincidence between regions with ionised-gas emission and specific features in the hot gas distribution in the giant elliptical galaxies NGC 5846 and NGC 4486, respectively. Sparks et al. (2004) also show that where hot and warm emission coincide the temperature of the hot gas is lower than in the surrounding regions, as expected in the presence of a heat sink.

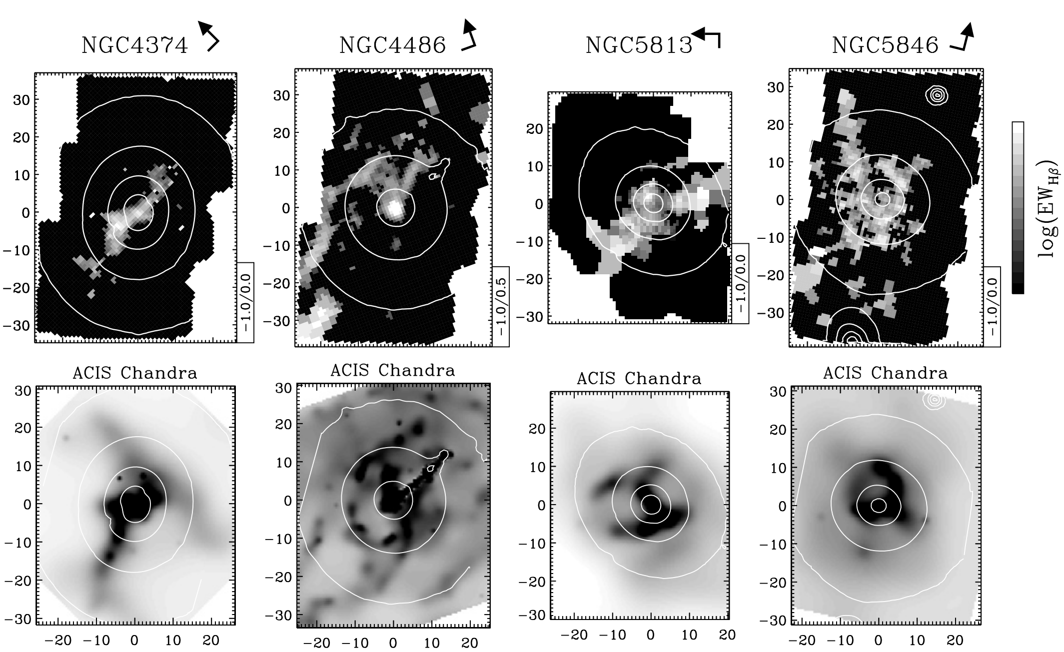

Fig. 3. Warm *versus* hot gas emission in four slowly-rotating SAURON galaxies. The top panels show the equivalent width of the Hβ line, in Å and on a logarithmic scale, whereas the lower panels show smoothed maps for the X-ray emission observed with Chandra, in arbitrary units. Except in only few regions, nebular emission is usually associated to X-ray emitting features. For NGC 4486 and NGC 5846, this connection was already discussed by Sparks et al. (2004) and Trinchieri and Goudfrooij (2002), respectively

Here we bring two additional examples of such interaction. Fig. 3 compares the distribution of the ionised-gas emission with that of the hot, X-ray emitting gas for the four slowly-rotating galaxies with the brightest X-ray halos in the SAURON sample, which include NGC 5846 and NGC 4486. Except in only few regions, we found that the Hβ emission is usually associated to X-ray emitting features in the Chandra images.

If the fate of stellar-mass loss material in slowly-rotating galaxies is to join the hot component of the interstellar medium, we suggest that in the presence of a much less significant hot medium the stellar ejecta may have the time to collide, loose angular momentum, and settle on the galactic plane. As such a gaseous disk could obstruct the subsequent acquisition of retrograde gas material, the absence of bright X-ray halos in fast-rotating galaxies would contribute to explain the excess of objects with co-rotating gas and stars and the relative shortage of counter-rotating gaseous and stellar systems. Additionally, if the hot interstellar medium is heated primarily by the dissipation of the kinetic energy of the stellar ejecta, it is likely that part of the stellar angular momentum is transferred to the hot gas. Although their existence remains controversial (Hanlan and Bregman, 2000; Diehl and Statler, submitted for publication), rotating X-ray halos would exert larger ram-pressure forces on material that is accreted with opposite angular momentum to the stars and the hot gas, thus further obstructing the accretion of retrograde material.

4. Conclusions

Starting from our finding that 75% of the SAURON early-type sample galaxies show ionised-gas emission, and armed with the new tool of Emsellem et al. to assess the level of rotation support in galaxies, we have explored different venues for the origin and fate of the gas in these systems. In particular, we have focused on the puzzling finding that round and slowly rotating objects generally display uncorrelated stellar and gaseous angular momenta, whereas flatter and fast rotating galaxies host preferentially co-rotating gas and stars. At face value this result suggests that external accretion of gaseous material is less important than internal production of gas in flat and fast rotating galaxies, whereas rounder and slowly rotating objects would acquire their gas more often. There are however no obvious reasons to support this view, in particular because these two kinds of galaxies inhabit similar galactic environments.

Assuming that all early-type galaxies can produce and acquire gaseous material, we have therefore considered the possibility that other mechanisms could obstruct the acquisition of counter-rotating gas in flat and fast rotating galaxies and remove or render undetectable the stellar-loss material in round and slowly rotating objects. Given the potential role of interaction between different phases of the interstellar medium, and building on past findings that S0s and flat Es show lower X-ray luminosities than rounder elliptical galaxies of the same optical luminosity, we have compiled X-ray luminosity measurements for our sample galaxies and found that only the objects classified as slowly rotating on the basis of integral-field observations can retain massive halos of hot gas.

In light of the different content of hot gas in slow and fast rotating galaxies, we have suggested that the different importance that evaporation of warm gas in the hot interstellar medium has in these galaxies can contribute to explain the difference in the relative behaviour of gas and stars in these two kinds of objects. Namely, whereas in X-ray bright and slowly-rotating galaxies stellar-loss material would quickly join the hot medium and escape detection as ionised-gas, in X-ray faint and fast-rotating objects such material would be allowed to lose angular momentum and settle on a disk, which could also obstruct the further acquisition of retrograde gas. Thus, the evaporation of stellar ejecta in the hot medium and the obstructing action of an indigenous disk would explain the relative shortage of co-rotating and counter-rotating gaseous and stellar systems in slow and fast rotating galaxies, respectively.

We note that the fast-rotating objects with the largest values for the specific mass of ionised gas, that is, the ionised-gas mass normalised by the virial mass of the galaxy, tend to have a more uniform distribution for the gas-star kinematic misalignments, consistent with an external origin for their gas. Among the fast-rotating objects with ionised-gas mass fractions above 2×10^{-6}, three have co-rotating gaseous and stellar systems, one shows gas in polar orbits, and four display retrograde gas motions. A larger specific mass of ionised gas may reflect the need for sufficiently large amounts of gas in order to overcome the obstructing action of an indigenous disk, or simply the triggering of additional sources of ionisation, such as shocks or star formation. As regards the latter, McDermid et al. (this volume, their Fig. 2) indeed find younger stellar population embedded in these objects.

A quantitative assessment of the relative importance of evaporation in the hot interstellar medium and of dissipative processes, as well as more constraints on the amount of cold gas at both small and large scales (from CO and HI observations), will be needed to confirm the picture proposed in this paper.

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