The intriguing life of massive galaxies
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Revealing the origin of the cold ISM in massive early-type galaxies

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Abstract. Recently, massive early-type galaxies have shed their red-and-dead moniker, thanks to the discovery that many host residual star formation. As part of the ATLAS-3D project, we have conducted a complete, volume-limited survey of the molecular gas in 260 local early-type galaxies with the IRAM-30m telescope and the CARMA interferometer, in an attempt to understand the fuel powering this star formation. We find that around 22% of early-type galaxies in the local volume host molecular gas reservoirs. This detection rate is independent of galaxy luminosity and environment. Here we focus on how kinematic misalignment measurements and gas-to-dust ratios can be used to put constraints on the origin of the cold ISM in these systems. The origin of the cold ISM seems to depend strongly on environment, with misaligned, dust poor gas (indicative of externally acquired material) being common in the field but completely absent in rich groups and in the Virgo cluster. Very massive galaxies also appear to be devoid of accreted gas. This suggests that in the field mergers and/or cold gas accretion dominate the gas supply, while in clusters internal secular processes become more important. This implies that environment has a strong impact on the cold gas properties of ETGs.

Keywords. galaxies: elliptical and lenticular, cD – galaxies: evolution – galaxies: ISM – ISM: molecules – ISM: evolution – stars: mass-loss

1. Introduction

In order for early-type galaxies (ETGs) to fade and join this tight red sequence, it is thought that the fuel for star formation must be consumed, destroyed or removed on a reasonably short timescale (Faber *et al.* 2007). This should leave galaxies on the red sequence with little or no cold ISM, and thus no star formation. Evidence is mounting, however, that a reasonable fraction of ETGs do have cold gas reservoirs (e.g. Serra *et al.* 2012) and residual star-formation (e.g. Yi *et al.* 2005) . Young *et al.* (2011) have presented an unbiased census of the molecular gas content of the ATLAS^{3D} sample of nearby ETGs (Cappellari *et al.* 2011), and report that 22% of optically-selected, morphologically-classified ETGs have substantial molecular gas reservoirs (10^7–10^9 $M_\odot$ of H_2). If galaxies form in a hierarchical manner, then these observations pose a challenge to the standard view that ETGs join and remain on the red-sequence due to a lack of cold gas. One must either demonstrate that it is possible to create a tight red sequence without removing all of the cold ISM, or that galaxies can regenerate or acquire cold gas after becoming red.

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Various lines of enquiry suggest that the gas we detect in these galaxies is not left over from the progenitors that formed the ETG (e.g. Kuntschner *et al.* 2010). Unless the remnant gas can be made stable against star-formation this thus suggests that we are seeing regenerated or newly accreted gas. *Internal* gas return from stellar populations (dominated by mass loss from red giant branch, [post-]asymptotic giant branch stars and planetary nebulae; Parriott & Bregman 2008, Bregman & Parriott 2009) must be occurring in all ETGs at all times, at a rate depending on the number of stars present in each galaxy and its star formation history. One would thus expect many ETGs to have detectable molecular gas (assuming that some fraction of the hot gas reservoir does cool). Galaxies can also regain a cold ISM via *external* processes, such as (major and minor) mergers and/or cold mode accretion from the intergalactic medium.

Determining the dominant source of the cold ISM in ETGs is vital in order to understand their evolution. If stellar mass loss can build up molecular reservoirs, then galaxies can transform in isolation from spheroidal to disky systems, and perhaps even evolve back into the blue cloud (e.g. Kannappan *et al.* 2009). If however mergers are the dominant source of the gas, then star-formation episodes are likely to be short-lived.

Observationally the origin of the gas may be addressed by comparing the angular momentum of the ISM with that of the underlying stellar population. Because of angular momentum conservation stellar mass loss must produce gas that is kinematically aligned with the bulk of the stars which produced it, while material from external sources can enter a galaxy with any angular momentum. In this proceedings we report the result of our attempt to use the ATLAS^{3D} sample of ETGs to constrain the importance of externally acquired gas in this way (as presented in Davis *et al.* 2011). Here we show results comparing the kinematic misalignment of stars and ionised gas (from SAURON data; Cappellari *et al.* 2011). Identical results are found when one compares the stars and molecular gas (from CO interferometry with CARMA; Alatalo, *et al.* 2012). Ionised, atomic and molecular gas in local ETGs seem to be linked, always having similar kinematics and thus presumably sharing a common origin.

2. Results and Discussion

2.1. *Gas misalignments in the field and in clusters*

Figure 1 shows the measured kinematic misalignment between the stars and the ionised (and molecular) gas in the fast-rotating ATLAS^{3D} ETGs, split by environment. In the field ≈42% of galaxies have kinematically misaligned ionised gas. In many cases, fast-rotating galaxies with kinematically aligned molecular and ionised gas have HI distributions that again suggest an external origin for the gas. This suggests that mergers and accretion play a dominant role in supplying gas to field ETGs. However, in the Virgo cluster, the molecular and ionised material in fast-rotators is nearly always kinematically aligned with the bulk of the stars, pointing to gas supplied by purely internal processes.

We tentatively suggest that preprocessing in groups (see Section 2.2) may help to explain this environmental dichotomy. Merger-induced starbursts in groups and cluster outskirts could consume any kinematically misaligned molecular gas that is present, and leftover ionised material would be ram pressure-stripped. Once galaxies settle into a cluster or HI-poor group, external gas accretion and mergers are suppressed, allowing stellar mass loss to regenerate a kinematically aligned gas reservoir. It is possible that features such as bars and rings could funnel dust and gas lost by stars to the centre of the galaxy, or collect them together, and could explain the greater efficiency with which galaxies in dense environments must recreate their dense gas reservoirs. Alternatively, we could be detecting the remnant gas left over from the morphological transformation of

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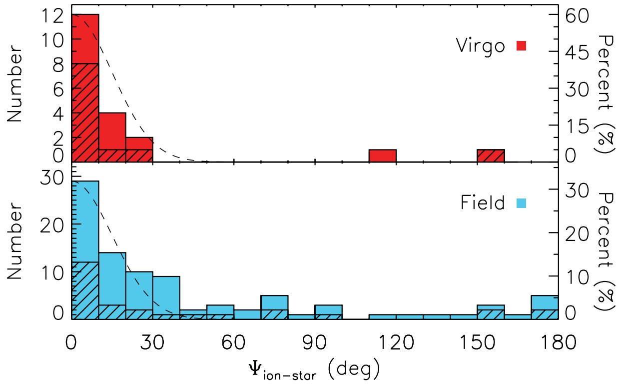

Figure 1. *Top:* Histogram showing the kinematic misalignment angle between the ionised gas and the stars for all fast-rotators in Virgo (from Davis *et al.* 2011). The hatched area indicates the number of galaxies in each bin that were also mapped in molecular gas. *Bottom:* As above, but for all field fast-rotators.

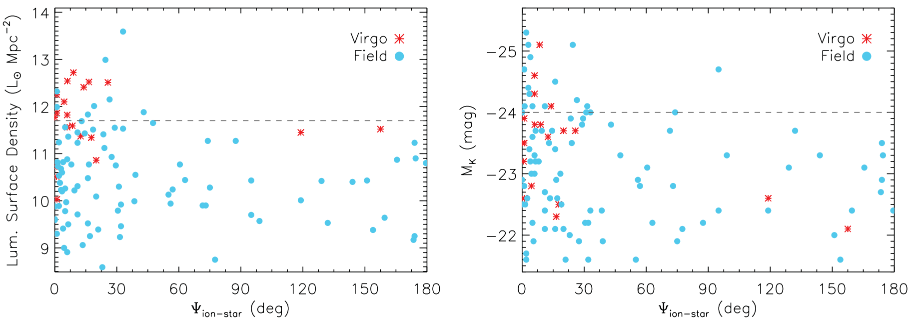

Figure 2. The kinematic misalignment angle between the ionised gas and the stars for fast-rotating ETGs, plotted against the local luminosity surface density (left), and the total absolute K_s-band magnitude (right; both from Davis *et al.* 2011). Virgo galaxies are plotted with red stars, and field/group galaxies with solid blue circles. The dashed line is a guide to the eye, at the suggested critical density/mass where essentially every galaxy becomes aligned. The error on each kinematic misalignment angle measurement is $\approx 15°$.

spiral galaxies into ETGs as they enter the cluster. Both of these possibilities, however, fail to explain why the detection rate of molecular gas (and the molecular gas mass fractions) are similar inside and outside of the Virgo cluster.

2.2. *The effect of group environments and mass*

Figure 2 shows that fast-rotators in dense groups, and with high masses also appear to always have aligned gas kinematics. Analysis (in Davis *et al.* 2011) suggests that these two effects are independent of each other. Thus both environmental and galaxy scale processes (e.g. AGN feedback, the ability for a galaxy to host a hot X-ray gas halo, and/or a halo mass threshold) must be at work, reducing the probability that cold, kinematically misaligned gas can be accreted onto these galaxies.

2.3. *Constraints from dust*

Figure 3 shows the dust to total gas (HI+H_2) ratio (from Crocker *et al.*, in prep), which seems to be systematically lower for ETGs with misaligned molecular gas. This supports a picture where the externally accreted gas comes from *minor* (rather than major) mergers (e.g. Kaviraj *et al.* 2011). Mergers with lower mass systems should result in the accretion

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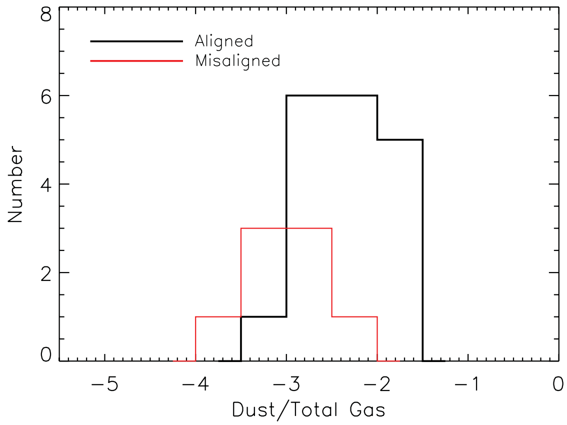

Figure 3. Histogram of the dust to total gas (HI+H_2) ratio (from Crocker *et al.*, in prep) for aligned and misaligned ETGs from the ATLAS^{3D} sample.

of lower metallicity gas, with a smaller dust content. Direct investigations of the gas phase metallicity itself are underway (Davis *et al.*, in prep), and should reveal if the dust-to-gas fraction in ETGs scales with gas-phase metallicity in the same way as in spiral galaxies.

2.4. *Future Prospects*

More work is clearly required to unambiguously determine the full importance of internal and external gas sources, and the role of environment and mass in the regeneration of gas reservoirs in ETGs. Equally important is understanding where stellar mass loss material goes in the 78% of ETGs that do not have cold molecular gas. It would be highly beneficial to extend the sort of kinematic analysis presented here to other clusters and groups, to see if the results reported here hold true in yet denser environments. The Fornax cluster in the southern hemisphere and the Coma cluster in the north are obvious nearby targets, which should become accessible with next generation facilities; e.g. the Large Millimeter Telescope (LMT) and the Atacama Large Millimeter/sub-millimeter Array (ALMA) in the millimetre, and instruments like KMOS/MUSE in the optical and infrared.

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