Tracing the Ancestry of Galaxies
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Molecular Gas and Star Formation in Local Early-Type Galaxies

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Abstract. The molecular gas content of local early-type galaxies is constrained and discussed in relation to their evolution. First, as part of the ATLAS$^{\rm 3D}$ survey, we present the first complete, large (260 objects), volume-limited single-dish survey of CO in normal local early-type galaxies. We find a surprisingly high detection rate of 22%, independent of luminosity and at best weakly dependent on environment. Second, the extent of the molecular gas is constrained with CO synthesis imaging, and a variety of morphologies is revealed. The kinematics of the molecular gas and stars are often misaligned, implying an external gas origin in over a third of the systems, although this behaviour is drastically diffferent between field and cluster environments. Third, many objects appear to be in the process of forming regular kpc-size decoupled disks, and a star formation sequence can be sketched by piecing together multi-wavelength information on the molecular gas, current star formation, and young stars. Last, early-type galaxies do not seem to systematically obey all our usual prejudices regarding star formation, following the standard Schmidt-Kennicutt law but not the far infrared-radio correlation. This may suggest a greater diversity in star formation processes than observed in disk galaxies. Using multiple molecular tracers, we are thus starting to probe the physical conditions of the cold gas in early-types.

Keywords. ISM: evolution, ISM: kinematics and dynamics, ISM: molecules, galaxies: elliptical and lenticular, cD, galaxies: evolution, galaxies: ISM, galaxies: kinematics and dynamics

1. Introduction

Early-type galaxies (ETGs), comprising ellipticals and lenticulars (E/S0s), are generally considered “red and dead”, with the bulk of their stars homogeneously old, slightly less so at the lower masses and in the field (e.g. Thomas et al. 2005). This is clearly an oversimplification, however, and residual star formation is still present in at least 30% of local ETGs. This is easily quantified with near-ultraviolet imaging, particularly sensitive to even small amounts of star formation (e.g. Yi et al. 2005), but is also clearly detected through optical absorption lines (e.g. Kuntschner et al. 2010).

In this paper, we study the properties of the molecular gas in ETGs, the fuel for star formation, through the ^{12}CO(1-0) line. We focus on the complete, volume-limited sample of 260 local ETGs from the ATLAS$^{\rm 3D}$ survey ($M_K < -21.5$ mag; Cappellari et al. 2011), as well as results from its predecessor (`SAURON`; de Zeeuw et al. 2002).

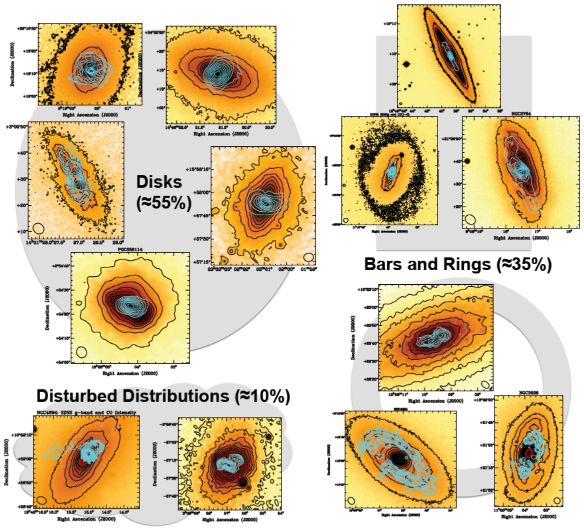

Figure 1. Mosaic showing CO distributions (solid blue lines) overlaid on optical images (colours and solid black lines) for selected sample galaxies. A range of morphologies is observed.

2. Molecular gas properties

In Young et al. (2011), we present a complete CO single-dish survey of the ATLAS^{3D} sample carried out with the IRAM 30m telescope. With a sensitivity of 3 mK T_{a}^{*} per 30 km s^{-1} channel ($\approx 3\times10^{7}$ $M_{\odot}$ of molecular hydrogen at the median distance), the main result is a surprisingly high detection rate of 22%. Equally important, detections are present throughout the so-called red sequence, formed of objects with presumably low specific star formation rates. The molecular gas masses span the range 10^{7}–10^{9} $M_{\odot}$, and both the detection rate and the molecular-to-stellar mass ratios are independent of luminosity and most structural and dynamical parameters probed. There is however a clear dependence on the specific stellar angular momentum (as quantified by the λ_{R} parameter; Emsellem et al. 2007), in the sense that slow-rotating galaxies are deficient in molecular gas, and a possible weak dependence on environment for fast-rotating galaxies.

We have strived to obtain follow-up interferometric line-imaging of all CO detections, first with BIMA and PdBI, and now with CARMA (Alatalo et al., in preparation). Figure 1 shows a subset of the nearly 40 galaxies observed so far, and it illustrates the range of distributions detected. CO is generally centrally-concentrated, with central disks, bars, rings, and occasional disturbed morphologies. A careful comparison with the spiral galaxies of the BIMA-SONG survey (Regan et al. 2001) reveals that while the CO extent is generally smaller in an absolute sense in ETGs, the extent distributions are identical once scaled by a characteristic size (effective radius, scalelength, isophotal diameter, etc).

Taking full advantage of the three-dimensional nature of the `SAURON` optical integral-field data *and* the CO synthesis observations, we can compare the kinematics of the stars, ionised gas, and molecular gas (Fig. 2; Davis et al. 2011). The kinematic major axes of the stars and molecular gas are aligned in about 2/3 of the CO-detected galaxies, implying that the molecular gas is consistent with an internal origin (e.g. stellar mass loss) in 2/3 of the cases overall, while it must have an external origin (e.g. external accretion, minor merger) in at least 1/3 of the cases (some of the kinematically-aligned gas can also have an external origin). Crucially, these statistics are strongly dependent on environment. The stars and molecular gas are nearly always kinematically-aligned in

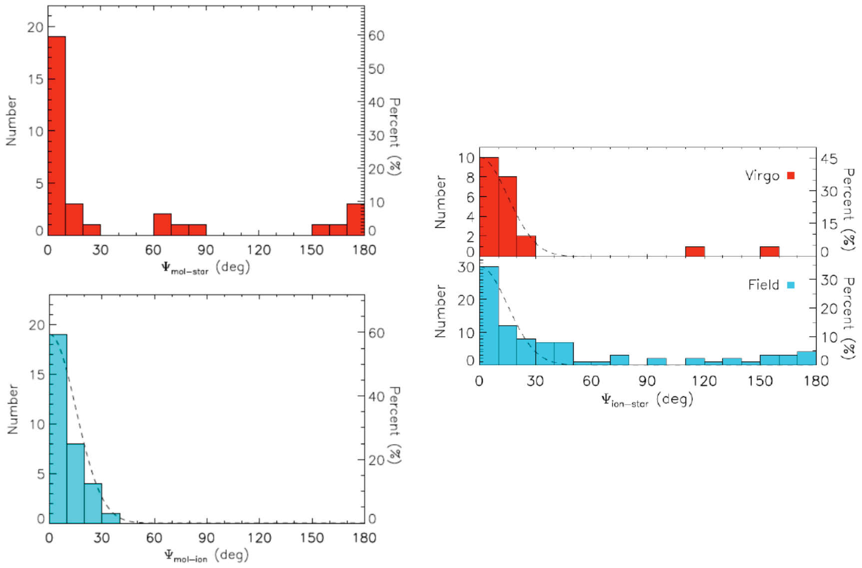

Figure 2. *Top-left:* Kinematic misalignment distribution between the stars and molecular gas. About 1/3 of the objects are misaligned. *Bottom-left:* Kinematic misalignment distribution between the ionised and molecular gas. The two gas phases are always aligned. *Right:* Kinematic misalignment distribution between the ionised gas and stars, for fast-rotating galaxies in the Virgo cluster (top) and in the field (bottom). The galaxies are nearly always aligned in Virgo but show a range of misalignments in the field. Adapted from Davis et al. (2011).

clusters (here Virgo), while about half the galaxies are misaligned in the field. This implies that external accretion of gas is very important in the field but is possibly totally shut down in clusters. Interestingly, the ionised and molecular gas are always kinematically-aligned, so that they must share a common origin. As our ionised gas detection rate is much higher, our conclusions are put on a much firmer basis by the ionised gas.

3. Star formation

Comparing our molecular gas maps with the `SAURON` data in a spatially-resolved way, the molecular gas appears to be forming young central disks in a number of objects (Crocker et al. 2011). This is revealed by fast-rotating decoupled central stellar components, depressed stellar velocity dispersions, ionised gas emission with [OIII]/Hβ line ratios typical of star formation, enhanced Hβ absorption, etc. However, this is not always the case. Molecular gas is sometimes associated with [OIII]/Hβ line ratios more typical of those expected from evolved stellar populations, and occasionally no sign of a young stellar population is detected at all.

As ETGs are also (on average) significantly different dynamically from disk galaxies (e.g. Q parameter), it is clear that they represent a different and unique environment in which to probe star formation, both its usual tracers and possible causal relations. After carefully accounting for internal extinction, we find that the Kennicutt-Schmidt relation and a constant star formation efficiency (relating the surface density of molecular gas to that of star formation) are both consistent with the data. However, the far infrared (FIR)-radio continuum correlation is not satisfied, with too many FIR-bright galaxies (Fig. 3), and different infrared star formation tracers do not agree, perhaps implying significant dust heating from non-star formation sources.

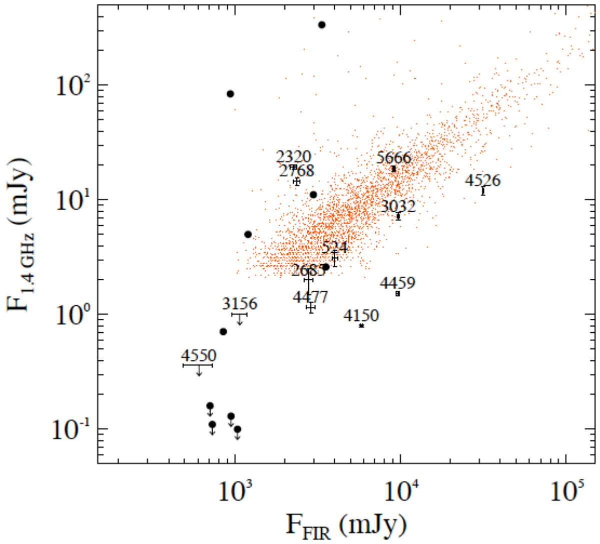

Figure 3. Far infrared-radio continuum (1.4 GHz) correlation of the `SAURON` ETGs (black dots) compared to that of the galaxies in the Uppsala General Catalogue (red dots; mostly disk galaxies). Black dots with error bars are CO-detected and preferentially lie on the FIR-bright side of the relation. Adapted from Crocker et al. (2011).

Understanding possible differences in the star formation processes of ETGs requires a good knowledge of the physical conditions in the interstellar medium. We have thus started a programme to constrain the opacity, column density, volume density, temperature, and other parameters of the cold gas in our sample galaxies, using multiple molecular line tracers (e.g. ^{13}CO, HCN, HCO$^+$). Preliminary results indicate occasionally enhanced ^{13}CO and suppressed HCO$^+$ (Krips et al. 2010; Crocker et al., in preparation).

Observing molecular tracers other than ^{12}CO is challenging with the current generation of instruments, but with its vastly improved sensitivity and angular resolution, ALMA will both broaden and increase the pace of discoveries. It will also allow to probe trends as a function of both lookback time and environment. Herschel will similarly improve our understanding of the gas (atomic, ionised and molecular) and dust associated with the molecular gas, in particular the dust-to-gas ratio.

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