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Recent Star Formation in Nearby Early-type Galaxies

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Abstract. Motivated by recent progress in the study of early-type galaxies owing to technological advances, the launch of new space telescopes, and large ground-based surveys, we attempt a short review of our current understanding of the recent star formation activity in such intriguing galactic systems.

1. Introduction

Early-type galaxies represent one of the biggest challenges to our understanding of galaxy formation and evolution, in particular as far as their star formation history is concerned. Studies of the nearby galaxy population can provide useful clues to solving this problem, by setting tight constraints on the level of their most recent star formation activity. Traditionally, early-type galaxies used to be regarded as simple and old stellar systems mostly devoid of gas or dust. By the turn of the century, however, evidence was already mounting that a substantial fraction of elliptical and lenticular galaxies do show conspicuous gas and dust reservoirs (e.g., Goudfrooij et al. 1994; Macchetto et al. 1996, and references therein), and the presence of younger stellar components (e.g., Trager et al. 2000, and references therein). In recent years, tremendous progress has been made in uncovering the recent star formation history of early-type galaxies, owing in particular to the advent of new technologies such as integral field spectroscopic units or more sensitive receivers at radio and mm frequencies, to the launch of space observatories such as *GALEX* and *Spitzer* allowing us to probe wavelength domains otherwise inaccessible from the ground, and to large spectroscopic campaigns such as the Sloan Digital Sky Survey (SDSS). In this paper we attempt to review such recent efforts, without any pretence of completeness. We will first focus on detailed studies of the stellar populations of early-type galaxies at different wavelengths, in particular with the SAURON integral-field unit in the optical, and with *GALEX* and *Spitzer* in the UV and mid-IR (MIR) domain (Sect. 2). We will then turn to the reservoirs of neutral, molecular, and ionized gas in nearby elliptical and lenticular galaxies, and consider evidence for ongoing star formation in them (Sect. 3). Finally, we will consider some results based on the analysis of a large sample of early-type galaxies with SDSS data (Sect. 4) and conclude by discussing how all these findings could connect with each other (Sect. 5).

2. Stellar Population Studies and Evidence of Recent Star Formation

2.1. The Optical—SAURON Results

Many studies have shown that early-type galaxies are not exclusively formed by old stars (e.g., Thomas et al. 2005, and references therein). The SAURON survey of early-type galaxies (de Zeeuw et al. 2002) has further allowed us to find the location of different stellar sub-populations, in particular of young stars, and to link such structures to the photometry and kinematics of early-type galaxies. Using maps for the strength of the Hβ, Mg*b* and Fe 5015 absorption lines in a representative sample of 48 early-type galaxies in H. Kuntschner et al. (in preparation), we reinforce previous indications that the integrated stellar populations of most elliptical galaxies display old stellar ages whereas lenticulars exhibit a wider spread of ages, and likewise for galaxies in clusters compared to objects in a lower density environment. Very young stars, less than ~ 2 Gyr old, are found to dominate the entire SAURON field in four objects in the SAURON sample, whereas in the remaining galaxies the young populations appear to be either distributed in extended disks or to cluster towards the center. In fact, such young nuclear populations are also likely to have formed in small stellar disks, since the presence of young stars in the center correlates very well with that of small (less than $\sim$500 pc) stellar components that are kinematically distinct from the rest of the galaxy (McDermid et al. 2006).

The connection between stellar ages and kinematics extends also beyond the central regions. In Emsellem et al. (2007) we assess the overall level of rotational support in a galaxy adopting a quantity, $\lambda_{\rm R}$, that is closely related to the specific angular momentum of a galaxy. In the SAURON sample, galaxies with $\lambda_{\rm R} \leq 0.1$ form a distinct class characterized by little or no global rotation and the presence of kpc-scale 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 (see also the contribution by Falcón-Barroso, this volume, p. 227, for an illustration of these two kinds of objects). All SAURON galaxies that formed stars recently (which amount to 25% of the sample and include either objects with luminosity-weighted mean ages below 6.5 Gyr or with young disks and nuclei), are fast rotators, whereas slow rotators do not show evidence of secondary star formation events. In fact, beside the presence of young disks and nuclei, fast rotators can also display extended, Mg*b*-enhanced structures that appear to be flatter than the stellar isophotes (Kuntschner et al. 2006). Although not obviously younger than the rest of the galaxy, such stellar sub-components most likely originated in a secondary star formation event, consistent with the finding that fast rotators host dynamically distinct stellar components characterized by large angular momentum and radial anisotropy, as observed in stellar disks (Cappellari et al. 2007).

2.2. The UV—*GALEX* Results

Although the strength of optical absorption lines such as those probed by SAURON can provide sensible constraints on the presence of younger stars when compared to the predictions of *single* stellar population models, deriving the mass and age of young stellar components from line strength indices alone is an exercise that is fraught with degeneracies. In this respect probing the UV light allows us to weigh and date even a relatively small fraction of very young stars, since the UV output of a stellar population varies dramatically over the first few hundred Myr of its history. In particular, whereas the far-UV (between 1350 and 1750 Å) light is also sensitive to the radiation from old hot helium-burning horizontal branch stars, the near-UV radiation (NUV, between 1750 and 2750 Å) traces particularly well the presence of young stars.

The potential of such UV information to constrain the age and fraction of young stars of early-type galaxies has recently been shown by Jeong et al. (2007), who combined UV observations from *GALEX* with ground-based optical imaging for the E4 galaxy NGC 2974. They find a blue NUV–optical color indicative of the presence of very young stars, less than 500 Myr old, both near the center and in an outer ring. The star formation rate and mass fraction of young stars peaks in the outer ring, reaching $2 \times 10^{-3}\, M_{\odot}\, \mathrm{yr}^{-1}\, \mathrm{kpc}^{-2}$ and 0.1% respectively, whereas, overall, 1% of the stars in NGC 2974 formed in the last 500 Myr. Using the mass model of Krajnović et al. (2005), Jeong et al. also show that the location of the outer UV ring, as well as those of the central rings traced by the [O III]$\lambda\lambda 4959, 5007$ emission in the SAURON data for this galaxy, are consistent with the positions of orbital resonances that would be induced by the presence of a rotating large scale bar, which is driving the observed star formation in these regions. As most of the early-type galaxies in the SAURON sample are being observed with *GALEX*, it will be interesting to see how many more objects will exhibit evidence of recent star formation in UV light, as in the case of NGC 2974.

2.3. The Mid-IR—*Spitzer* Results

At the opposite end of the optical spectrum, MIR observations provide an alternative way to investigate the stellar populations of early-type galaxies. The MIR spectra of passively evolving stellar populations are affected by the presence of mass-losing giant stars, in particular AGB stars. The dusty envelopes of these stars re-radiate the heat received from their parent stars in a characteristic broad region between 9 and 12 μm, mostly due to silicate grains. As a stellar population ages, the photospheric MIR continuum fades less quickly than the circumstellar 10 μm emission, so that the relative strength of the silicate features can be used to trace the age of the population.

The advent of *Spitzer* has recently allowed to detect routinely the 10 μm circumstellar emission in early-type galaxies, leading for instance Bressan et al. (2006) to confirm that 82% of their Virgo cluster galaxies have been passively evolving since their formation. Bregman, Temi, & Bregman (2006) find that early-type galaxies generally show old MIR-inferred ages even when an optical analysis based on absorption line strengths indicates relatively young luminosity-weighted mean ages. Although these results seem at odds with the larger fraction of SAURON galaxies with evidence of recent star formation, we need to keep in mind that both these MIR studies concentrated only on the brightest end of the local early-type galaxy population, and that the MIR age estimates are still subject to a severe age–metallicity degeneracy (Bressan et al. 2006).

3. Gaseous Reservoirs and Evidence of Ongoing Star Formation

If stellar population studies provide evidence of recent star formation in nearby early-type galaxies, we also ought to find gas reservoirs capable of fueling such activity before and while star formation occurs. Furthermore, the detection of molecular gas and of emission from H II regions should correspond to the presence of the youngest stars.

3.1. Neutral Gas

A number of shallow H I surveys have shown already that early-type galaxies can have massive (up to $10^{10}\,M_\odot$) and very extended (up to 200 kpc in size) disks of neutral hydrogen (e.g., Oosterloo et al. 2002, and references therein). Such investigations could only detect the most H I-rich galaxies, however, which prompted Morganti et al. (2006) to set out to explore the complete H I mass distribution of early-type galaxies, starting from the representative SAURON sample. So far, neutral gas has been found in 70% of the 12 *field* galaxies initially observed by Morganti et al. (2006), with masses between a few times $10^6\,M_\odot$ and just over $10^9\,M_\odot$. The neutral material in these objects also seems to be connected to the ionized gas observed by SAURON in the optical regions, since all galaxies where H I is detected also contain ionized gas, whereas no H I is found in galaxies without ionized gas. Additionally, in the most gas-rich systems the neutral and ionized material display similar kinematics. Considering that the presence of ionized gas may not always lead to star formation (see Sect. 3.3), these early results suggest that sufficient material to explain the observed amount of recent star formation could be generally present around early-type galaxies, and that gas accretion does not happen exclusively in peculiar early-type galaxies.

3.2. Molecular Gas

In order to form stars, gas ultimately has to cool and condense, leading also to the formation around dust grains of molecules such as carbon monoxide. Similarly to the case of H I, a number of CO emission surveys (e.g., the compilation by Bettoni, Galletta, & García-Burrillo 2003) have revealed that early-type galaxies can show substantial amounts of CO emission, which generally traces regularly rotating molecular disks (e.g., Young 2002, 2005). More recently, Combes, Young & Bureau (2007) have followed up with single-dish observations 43 out of the 48 early-type galaxies in the SAURON sample, detecting CO emission in 28% of them. This fraction is somewhat smaller than previously reported, but this is because Combes et al., contrary to earlier studies, also surveyed bright early-type galaxies that have a relatively lower molecular gas content. All galaxies with CO emission show evidence of recent star formation in their central regions from SAURON or OASIS data, and have radio continuum to far-IR flux ratios that further support the case for ongoing star formation. In fact, the CO-rich SAURON early-type galaxies appear to extend the well-known relation between the star formation rate surface density and the surface density of H_2 by two orders of magnitude down in star formation rate.

In addition to mm observations, the MIR domain provides additional ways to trace even tiny amounts of star formation activity, in particular through the detection of emission from polycyclic aromatic hydrocarbon (PAH) features (e.g., Kaneda, Onaka, & Sakon 2005). Although most investigations with *Spitzer* have focussed on the brightest end of the early-type population, the first results are nonetheless promising. For instance, Bressan et al. (2006) find evidence of recent star formation in 12% of their Virgo cluster sample, whereas Panuzzo et al. (2007) succeed in quantifying the epoch ($\sim$200 Myr ago) and intensity (adding in average $\sim 1\, M_\odot\ \mathrm{yr}^{-1}$) of the recent star formation event in the central regions of the SB0 galaxy NGC 4435, adding just about 1.5% of the stellar mass in these regions.

3.3. Ionized Gas

Optical nebular emission has traditionally been used to trace the warm ($\sim 10^4$ K) component of the interstellar medium and identify star formation in H II regions. Ionized gas emission in early-type galaxies is generally quite weak, however, so that its detection requires a careful subtraction of the stellar continuum.

By introducing a novel technique to address this issue, in Sarzi et al. (2006) we could reach down to a detection limit of just 0.1 Å for the equivalent width (EW) of the emission lines and detect extended ionized gas emission in 75% of the early-type galaxies in the SAURON representative sample, confirming that these systems contain gas more often than not. Although the limited SAURON wavelength range does not allow an extensive line diagnostic analysis, very low [O III]/Hβ line ratios nonetheless suggest ongoing star formation in at least four objects, or 8% of the sample. In fact, that stars are forming in these galaxies is proven also by the finding of disk-like gas kinematics, regular dust morphology, young stellar populations, and molecular gas in all of them. Interestingly, very young stars, CO emission, and even PAH features (K. Shapiro, private communication) can be found in objects where the warm gas displays very high [O III]/Hβ ratios (see, e.g., NGC 3489 and NGC 3156 in Sarzi et al. 2006). This finding suggests that as ionized gas in early-type galaxies is also subject to different sources of excitation than O stars, it may not always be a good tracer of star formation, in particular if this occurs at a low level. On the other hand, all the SAURON early-type galaxies with compelling evidence of ongoing star formation share relaxed gas kinematics, displaying in particular small gas velocity dispersions.

This common kinematic characteristic is found exclusively in fast rotators in the SAURON sample, however, suggesting that not all early-type galaxies are equally likely to form stars. In particular, the spatial correlation with the hot ($\sim 10^7$ K) X-ray emitting phase of the interstellar medium (Sarzi et al. 2007, and references therein) suggests that the fate of ionized gas in the most massive and slowly rotating early-type galaxies is to evaporate into the hot medium rather than to condense and form stars (see also Nipoti & Binney 2007, for a quantitative analysis). Preventing star formation in the most massive objects consistently over time through the interaction with the X-ray gas could explain the low frequency of CO and PAH detection in these systems (Sect. 3.2), and is in agreement with the notion that the most massive galaxies also host the oldest stellar populations.

4. Results from Larger Volumes

If the previous efforts show with tremendous detail that a substantial fraction of nearby early-type galaxies is, or has recently been, forming stars, such local studies can only offer a sketchy picture of the recent star formation history of early-type galaxies in the local Universe. Large surveys such as the SDSS, on the other hand, allow us to investigate much larger numbers of early-type galaxies, although generally offering only the integrated photometric and spectroscopic properties of these objects.

Some of the most dramatic results in this subject have been obtained by combining the SDSS optical photometry with NUV images obtained with *GALEX*. Out of 39 bright early-type galaxies from the sample of Bernardi et al. (2003), Yi et al. (2005) found six objects with NUV—r-band colors consistent with the formation in the last Gyr of stars amounting to approximately 1–2% of the stellar mass. Kaviraj et al. (2007) considerably extended Yi et al.'s first exercise to analyze a sample of $\sim$2100 morphologically selected early-type galaxies from the SDSS with $z < 0.11$, finding that at least $\sim$30% of their objects had formed between 1 and 3% of their mass in the last Gyr, mostly between 300 and 500 Myr ago. In an even larger effort, Schawinski et al. (2007) have compiled a catalog of $\sim$16 000 morphologically selected early-type galaxies with redshift between $0.05 < z < 0.10$ and SDSS, *GALEX* and 2MASS photometric and spectroscopic data, finding not only similar fractions of galaxies with recent star formation, but also that $\sim$4% of their early-type galaxies are currently forming stars based on their emission line ratios.

The recent work of Graves et al. (2007) further complements these studies. Yi et al. (2005) and Kaviraj et al. (2007) concentrated on red-sequence objects without strong emission to avoid AGN contamination in the UV light, whereas Schawinski et al. (2007) include galaxies with a broader range of optical colors and with gas emission but conservatively deemed as quiescent objects without reliable Hα, Hβ, [N II]$\lambda\lambda$6548, 6583, and [O III] emission. Graves et al. (2007) investigate more closely the red-sequence early-type galaxy population with gas emission, by including objects with relatively fainter gas emission as long as they display Hα and [O II]$\lambda\lambda$3726, 3729 lines that indicate LINER-like emission,[1] or alternatively, which firmly exclude ongoing star formation. With such a sensitive distinction between galaxies with or without ionized gas Graves et al. (2007) find that red-sequence galaxies with LINER-like emission show integrated stellar populations that are invariably younger than their quiescent counterparts, except at the brighter and more massive end of the red-sequence where galaxies show no sign of recent star formation.

5. Conclusions

How do all these findings combine together? Is it possible to draw a consistent picture of the recent star formation history of local early-type galaxies based both on the detailed study of the closest galaxies and on the analysis of integrated properties for much larger samples? Unfortunately, the answer is not quite yet.

Starting with the fraction of early-type galaxies that are presently forming stars, at first glance the fact that 8% of the SAURON sample displays [O III]/Hβ line ratios consistent with emission from H II regions would seem in reasonable agreement with the finding that 4% of the objects in the SDSS sample of Schawinski et al. (2007) display the same behavior. We have to keep in mind, however, that the SAURON sample is a representative but *incomplete* sample of the nearby early-type population, in which fainter galaxies are particularly underrepresented. As star formation could be more common in these systems than in more massive galaxies (Sect. 3.3), the true fraction of early-type galaxies with emission associated with H II regions could be much higher than presently found by SAURON. Similarly, the fraction of star-forming early-type galaxies estimated from more complete SDSS samples should also be regarded as a lower limit, since the SDSS spectra can only detect the most intense of starbursts. For instance, considering an EW of 0.8 Å for the faintest lines detected in the SDSS data, only one of the 48 SAURON galaxies has sufficiently strong emission within $1\,R_\mathrm{e}$ (corresponding to the typical physical area subtended by the SDSS fibers) to be detected as one of the star-forming early-type galaxies of Schawinski et al. (2007).

As regards the presence of younger stellar components in early-type galaxies, it is reassuring that Schawinski et al. (2007) and Kaviraj et al. (2007) estimate fractions of galaxies that are presently forming stars ($\sim$4%), and that contain populations younger than a few 100 Myr ($\sim$30%), respectively, which are consistent with each other given the different timescales traced by the nebular and NUV emission. On the other hand, it is less clear how well the mass fractions and ages of the young stellar components derived by *GALEX* and SDSS data agree with the SAURON observations. Consider the fact that just 1% of 500 Myr old stars embedded in a 10 Gyr old population induces an increase of $\sim$1 Å in the strength of the Hβ absorption line. Only 10% of objects in the SAURON sample have a global (within $1\,R_\mathrm{e}$) Hβ line strength that exceeds by 1 Å that observed in the oldest objects. Although the discrepancy with the 30% fraction reported by Kaviraj et al. (2007) could be reconciled considering that more

[1]That is, characterized by low ionization emission, as in the case of the low ionization nuclear emission regions first identified by Heckman (1980).

SAURON objects show evidence of recent star formation (up to 25%, Sect. 2.1), until the mass and age fraction of these young subcomponents is determined for a sufficiently complete sample of nearby galaxies it will remain hard to ascertain whether such SAURON objects correspond to the galaxies that experienced recent star formation according to analyses based on *GALEX* and SDSS data.

Despite these uncertainties, it is clear that with the exception of the most massive objects most early-type galaxies have undergone some degree of recent star formation. The gas reservoirs fueling such activity can now be detected with relative ease, and new techniques have been developed to analyze data from different passbands to better constrain the star formation history of galaxies. The biggest challenge ahead is still to quantify more precisely the extent of such star formation activity and its impact in shaping the observed structural and dynamical properties of these systems. In fact, it is precisely to address these and other questions that we have recently started a complete integral field survey of the nearby early-type galaxy population, nicknamed ATLAS^{3D}, which will be complemented by single-dish mm-band observations and by deep multiwavelength optical imaging.[2]

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[2]Details can be found at http://www-astro.physics.ox.ac.uk/atlas3d/.

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Discussion

Beckman: 1) Where are the various components distributed (CO, H I, S I, etc.)? 2) You should be able to check the origin of the gas and stars, i.e., to distinguish extrinsic from intrinsic origin, via the metallicities of both stars and gas.

Sarzi: 1) The H I reservoir generally extends to very large radii but it is not necessarily confined to the galaxy outskirts, as it often extends to the central regions as well. Molecular gas and SF regions are generally more concentrated but high resolution studies for the CO are still limited and *GALEX* UV observations have revealed tidally triggered SF also in the outer regions of early-type galaxies.

Kennicutt: With star formation being such a common property of elliptical galaxies one would expect them to host Type II supernovae. Do you know whether they have been observed in ellipticals?

Sarzi: Good point! I will double check.

Marc Sarzi.