The intriguing life of massive galaxies
Proceedings IAU Symposium No. 295, 2012
D. Thomas, A. Pasquali & I. Ferreras, eds.

doi:10.1017/S1743921313005279

Origin and Ionization of the Warm Ionized Gas in Massive Early-type Galaxies

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Abstract. Most early-type galaxies are not devoid of cold and warm gas. The origin and ionization of this gas reveal the intriguing ongoing evolution of these galaxies. In most cases, the warm ionized gas shows emission-line spectra similar to low-ionization nuclear emission-line regions (LINERs). Their ionization mechanism has been hotly debated. We will present evidence from line ratio gradient that rules out AGN and shocks as the dominant ionization mechanism, and suggests the ionizing sources follow the stellar density profile. Hot evolved stars are the favorite candidates but bring new puzzles.

This finding allows us to obtain a gas-phase metallicity calibration in these early-type galaxies, using the line emission. We will show how the metallicity of the warm gas depends on stellar mass and stellar age, and what it tells us about the origin of the warm gas in these galaxies.

Keywords. galaxies: elliptical and lenticular, cD, galaxies:ISM, stars: AGB and post-AGB

1. Introduction

Massive early-type galaxies have old stellar populations and are not actively forming stars. The most massive ones among them have stopped growing over the past 7 billion years. The shape difference between galaxy luminosity function and the halo mass function also requires a lower star formation efficiency in massive haloes. However, simulations suggest the dark matter haloes should still accrete more gas and this gas should cool and turn into stars if there were no additional heating. Also, the recycled gas from stellar evolution could also provide fuel for star formation. What is the fate of the accreted gas and the recycled gas? For the interstellar medium of these massive early-type galaxies, one important probe that has been under-utilized is the warm ionized gas.

The majority of massive early-type galaxies contain warm ionized gas which display optical line emission in their spectra. This has been known since the 1980s with long slit spectroscopy surveys (Phillips *et al.* 1986, Kim 1989, Buson *et al.* 1993, Goudfrooij *et al.* 1994, Macchetto *et al.* 1996, Zeilinger *et al.* 1996). It has been confirmed with integral field spectroscopy surveys, such as SAURON (Sarzi *et al.* 2006) and ATLAS3D (Davis *et al.* 2011). From these observations, we know that the warm ionized gas is spatially extended and can extend to kpc scales (Sarzi *et al.* 2006). Where does this gas come from? Does it come from stellar mass loss? Is it newly accreted gas? Or is it cooled from the hot X-ray-emitting gas? We would be able to tell its origin if we could measure the metallicity of the gas. However, such a metallicity calibration is not yet available, because the ionization mechanism is unsettled. In this contribution, we describe a new constraint on the ionizing source of the gas and explore a gas-phase metallicity calibration.

2. Ionization Sources

The line ratios displayed by the warm gas in most early-type galaxies satisfy the criteria of Low-ionization Nuclear Emission-line Regions (LINERs, Heckman 1980) on all major line-ratio diagnostic diagrams. It has been hotly debated what source ionized the gas. There are multiple ionization mechanisms that can produce the same kind of line ratios. These include photoionization by a central AGN (Ferland & Netzer 1983, Halpern & Steiner 1983, Groves *et al.* 2004), photoionization by hot evolved stars, such as post-AGB stars (di Serego Alighieri *et al.* 1990, Binette *et al.* 1994), collisional ionization by fast shocks (Dopita & Sutherland 1995), photoionization by hot X-ray emitting gas (Voit & Donahue 1990, Donahue & Voit 1991), conductive heating or turbulent mixing (Sparks *et al.* 1989). Therefore, determining the ionization mechanism requires other information.

What is going to distinguish AGN and stellar sources is the gradient in certain line ratios that are sensitive to the ionization parameter. AGN and distributed stellar sources will produce different flux density profiles. Given a fixed density profile, they will produce different ionization parameter profiles. By measuring the spatial gradient in a line ratio that is sensitive to ionization parameter, we can distinguish the AGN photoionization scenario and the distributed stellar ionizing sources convincingly.

Currently available IFU surveys or long-slit spectroscopy either cover too small a wavelength range or do not have sensitivity on the outskirts of a galaxy. We therefore turn to the SDSS survey and use the aperture effect to measure the spatial gradient. SDSS used an angular aperture of 3". The same angular aperture corresponds to a larger physical scale at larger distances. By selecting the same population of galaxies at all distances, we can statistically study the spatial distribution line emission and line ratio gradient. We select only red-sequence galaxies on a color-magnitude diagram and build a volume limited sample with $0 < z < 0.1$. We remove dusty-star-forming galaxies by rejecting 30% of galaxies that have the lowest D4000 in each redshift bin. This way we sample the same population of galaxies at all redshifts. With such a sample, we found that the median [O3]/[S2] ratio among the 25% brightest Hα emitter in each redshift bin is fairly flat with scale, which rules out AGN as the ionizing source and strongly favors a distributed ionizing source that follows the stellar density profile (Yan & Blanton 2012). See Figure. 1.

Additionally, the stellar photoionizing model has a prediction about luminosity dependence. Since bright early-types have slightly shallower profiles than faint early-types, they should produce different ionizing flux profiles and different line ratio gradients. By separating the sample according to broadband luminosity, we verified the prediction using the real data. This strongly suggests that the ionizing source is spatially distributed like the stars.

To evaluate the likelihood of the shock ionization and turbulent mixing models, we measured the temperature of the gas in coadded spectra. We selected galaxies from the above mentioned sample, but limited in redshift $0.06 < z < 0.15$ for which the median line ratio varies very slightly with the redshift (i.e. aperture). We excluded the 3% strongest line emitter among them so that the line ratio is not dominated by any galaxies hosting AGNs. We separated the resulting sample according to [N2]/[O2] ratio which is a metallicity indicator of the gas. We removed the stellar light in the resulting stacked spectra and were able to measure the $[N\ II]$ λ5755 line. The $[N\ II]$ 6584/5755 ratio yields a temperature measurement of $15,000K$ for the low-metallicity sample and $8,000K$ for the high-metallicity sample. These temperatures are consistent with the photoionization but are inconsistent with shock models or turbulent mixing models.

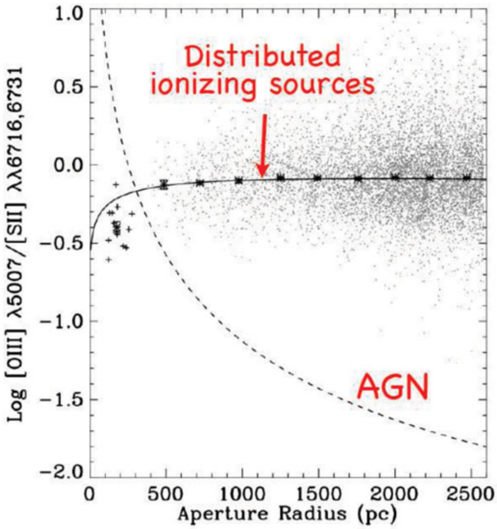

Figure 1. [O III]/[S II] ratio as a function of aperture size for a volume-limited sample of non-star-forming line-emitting red galaxies, most of which have LINER-like emission line ratios. Asterisks indicate median values in each bin. Crosses are for the Palomar sample of Ho, Filippenko & Sargent (1997). Grey points are from SDSS. The curves show the model predictions for photoionization by an AGN (dashed) or by distributed ionizing sources following the stellar density profile (solid). Assuming the line ratio profile in all of these galaxies are similar to each other and the warm gas density profile follows that of the hot X-ray gas, then the median trend suggests the gas is ionized by a population of hot evolved stars. However, this urgently needs to be verified in individual galaxies and with direct warm gas density measurements.

3. Gas-phase Metallicity in Early-type Galaxies

Given that the gas is ionized by stars, we can now derive a gas-phase metallicity calibration using CLOUDY spectral synthesis code (Ferland *et al.* 1998). For the input ionizing spectrum we use a 13 Gyr-old simple stellar population from Bruzual & Charlot (2003), assuming solar metallicity and a Chabrier initial mass function. We assume a gas density of 200 cm^{-3} and the default solar abundance pattern stored in CLOUDY except for Nitrogen. Because Nitrogen is a secondary element in the high metallicity regime, the N/O abundance ratio increases with Oxygen abundance. We adopt the scaling provided by Vila Costas & Edmunds (1993). We vary the ionization parameter from $10^{-4.5}$ to 10^{-2} and the metallicity (Z) from $0.0625Z_{\odot}$ to $4Z_{\odot}$. Fig. 2 left panel shows the resulting grid in [O III]/[O II] vs. [N II]/[O II], overplotted with a sample of dust-free, non-star-forming galaxies from SDSS. We can see that the [O III]/[O II] ratio provides a good proxy for ionization parameter and the [N II]/[O II] ratio provides a good proxy for metallicity.

Using the calibration derived, we measure the Oxygen abundance for these massive galaxies and plot them as a function of their stellar mass in the right panel of Fig. 2. We compare them with the star-forming galaxies sample from Tremonti *et al.* (2004). The metallicies in these galaxies are slightly lower than those in star-forming galaxies with the same mass. This indicates that the gas cannot simply be residual gas left over from past star formation. At least it has to be diluted by infalling gas. We also see a hint of a mass-metallicity relation among early-type galaxies, the origin of which will be investigated further.

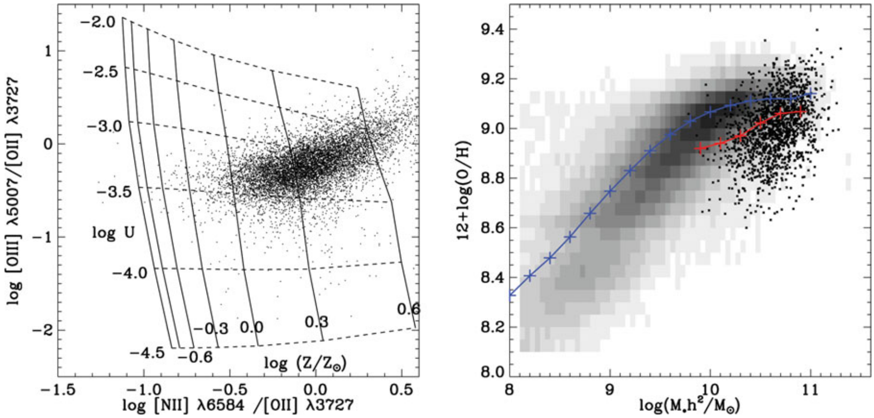

Figure 2. Left: [O III]/[O II] vs. [N II]/[O II] for a grid of CLOUDY models with different ionization parameter and metallicity. Overplotted are a sample of passive red galaxies from SDSS that have a Balmer decrement consistent with zero extinction. Right: Oxygen abundance in non-star-forming red sequence galaxies as a function of stellar mass. The red galaxies are denoted by dark points. The background grey scale indicate star-forming galaxy from Tremonti *et al.* (2004). The large colored crosses indicate the median in each stellar mass bin for passive red galaxies (red crosses) and star-forming galaxies (blue crosses).

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