An IFS study of Low-Powered Radio Galaxies

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Chapter 1

Introduction

For millennia, Man has turned his gaze skyward in awe and wonder at the heavens and wondered at the processes that processes that drive structure on the colossal scale of galaxies and galaxy clusters. As physicists we conduct experiments to better out understanding of the processes and laws that control the universe; an old joke goes that as astronomers, our experiment has already been conducted for us, it's called The Big Bang: our job is to use it to test the theories and laws of physics. Indeed, astronomy is a unique opportunity to test our knowledge as scales and limits that are not attainable here on Earth.

The most successful cosmological description of the universe is the dark energy (represented by L), cold dark matter (LCDM) coupled with inflation. This describes how the current state of the universe (69% Dark Energy (currently best described with a scalar field), 26% cold dark matter (a matter-like species which only interacts gravitationally), $\sim$5% ordinary baryonic matter and <0.003% radiation, complete with deep gravitational potential wells in which galaxies and galaxy clusters have formed) has evolved from an infinite and random spacetime 'foam'. Quantum fluctuation within this 'foam' cause region to form which has the corrected conditions for inflation to occur: this includes a quantum scalar field with a sufficient energy density to dominate the region. This field cause the exponential expansion of space at superluminal speeds. Quantum fluctuations are rapidly expanded to beyond the scale of the horizon (distance that a massless particle can travel within the age of the universe). At this point they become frozen in as perturbation to the density profile of the universe (any perturbations prior to the start of inflation are stretched so thin that they can be considered completely negligible). Once the energy density of the inflationary field becomes too low, inflation ends, radiation dominates and the expansion slows to subluminal speeds. As the horizon expands at the speed of light, the density perturbations re-enter the horizon (smallest first), providing seed for the gravitational collapse of dark matter. This process has hardwired hierarchical growth of structure (where the smallest structures, small galaxies, form first, which then coalesce into large galaxies, which form groups, clusters and eventually super-clusters) into the cosmos.

Having said that, we have said nothing the materials that we can directly observe: baryonic matter and radiation. Baryonic matter is far more complicated than dark matter and thus when we observe galaxies we see far more structure than simply smooth halos which it is believed that dark matter mostly exists as. The large plethora of shapes of galaxies are summed up in the Hubble Diagram. However, recent studies have shown that we cannot completely classify a galaxy by its morphology only (though some broad trends with morphology do exist). A more physical representation might be by color: Baldry et al. (2004) showed that galaxies exist within two distinct regions (known as the blue cloud and red sequence) on a color–magnitude plot. These represent galaxies that are actively star forming with a population of young stars (which are bluer) and galaxies which have had their star formation quenched and are made up of older stars (which are redder). Since magnitude can be considered a proxy for stellar mass (the mass-light ratio of galaxies does vary but not by much) and the underlying physics is a color–mass relation. This is shown in figure 1.1. These two classes roughly follow the Hubble diagram: spirals tend to exist in the cloud, while elliptical and lenticular (S0s) galaxies (which are collectively known as Early-type galaxies (ETGs)) mostly exist in the red sequence. This thesis has a particular focus on ETGs for reasons described below and more a detailed description of the our current understandings of ETGs is given in section 1.1.

Given their low star formation rates, ETGs are dominated by old stars, while spirals are dominated by young stars. The reasons for this dichotomy is a major part of modern astrophysics. ETGs are often the most massive galaxies: they clearly must have undergone substantial star formation in their early history. They either must have run out of fuel for forming stars or have undergone some process which is preventing star formation. Many have been observed to contain large reservoirs of cold (molecular) gas, the material from which stars are formed, meaning that we must favor the latter.

Many studies now point to the fact that most (if not all) galaxies contain a supermassive black hole at the center. Many studies also show that there are correlations (known as scaling relations) between the properties of the central black hole and the host galaxy despite orders of magnitude differences between the sphere of gravitational influence of the black hole and the size of the host galaxy.

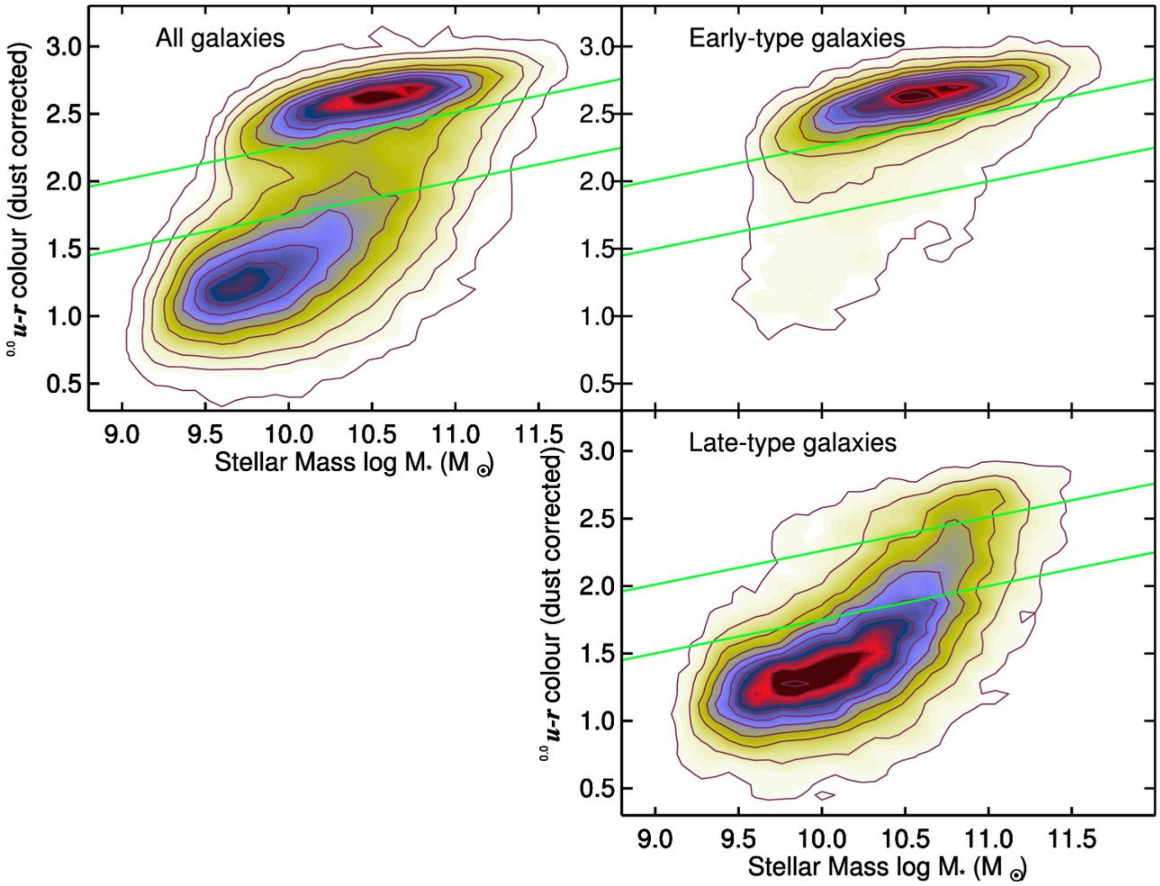

Figure 1.1: A reddening-corrected color–mass diagram showing the distribution of ETGs and LTGs on the color–mass plane with the red sequence, blue cloud and dividing green valley labeled. Figure courtesy of Schawinski et al. (2014)

Many galaxies contain a bright point source at the center. These are known as Active Galactic Nuclei (AGN) and in extreme cases these can outshine the combined starlight of the host galaxy. AGN are understood to be the result of accretion of the inter-stellar medium (ISM) onto the central black hole and the energy emitted by the AGN is generally invoked to explain the scaling relationships between the black holes and their host galaxies as well as the quenching of star formation. This process is known as AGN feedback.

AGNs are very varied, however much work has been done on a single unified model of AGNs, where the differences between individual observations can be explained by differing orientations of the AGN. The Unified Model by Antonucci (1993) describes AGN as made up of up to five components or regions surrounding the central black hole: (i) immediately around the black hole is an accretion disk. Surrounding this is (ii) a dust obscuring structure which is torus in shape. This blocks a side-on view of the black hole and accretion disk. Radiation from the accretion disk ionizes (iii) the region immediately above and below the disk. This emits in the optical regime with characteristic broad lines and gives rise to its name: the broad-line region (BLR). The BLR is also obscured by the torus. Above this is (iv) the narrow-line region (NLR), an area of more ordered and less ionized gas. Finally, a small proportion of AGN contain (v) jets of plasma traveling at relativistic speeds out from th e poles of the accretion disk (the exact orientation of the jet may well also be dependent of the orientation of the spin of the black hole, though this remains an unknown). The nature of the jet is explored in more detail below. AGN viewed side-on, with the black hole, accretion disk and BLR obscured by the torus are known as Type 2 AGN, while AGN viewed face-on, sometime viewing directly down the jet, are known as Type 1. A schematic the unified model is shown in figure **??**

Despite the unification of the many observed morphologies of AGN, it is becoming increasingly clear that AGNs exist in two different modes, Radiative and Jet-mode, raising speculation about differing mechanisms and possibly fuel sources for each. More detail on both modes can be found in section 1.2.

Many galaxies also emit in the radio, although most are extremely faint. These galaxies are known as radio galaxies (RGs) and most radio emission is attributed to synchrotron emission (the broader term of free-free emission is sometimes used in the literature) from the jet within an AGN. However, Nyland et al. (2016) notes that at the very faint end, there may be some contamination of samples from galaxies consistent with circumnuclear star formation. There is broad consensus within the literature that the most powerful RGs are the product of gas rich (wet), major mergers

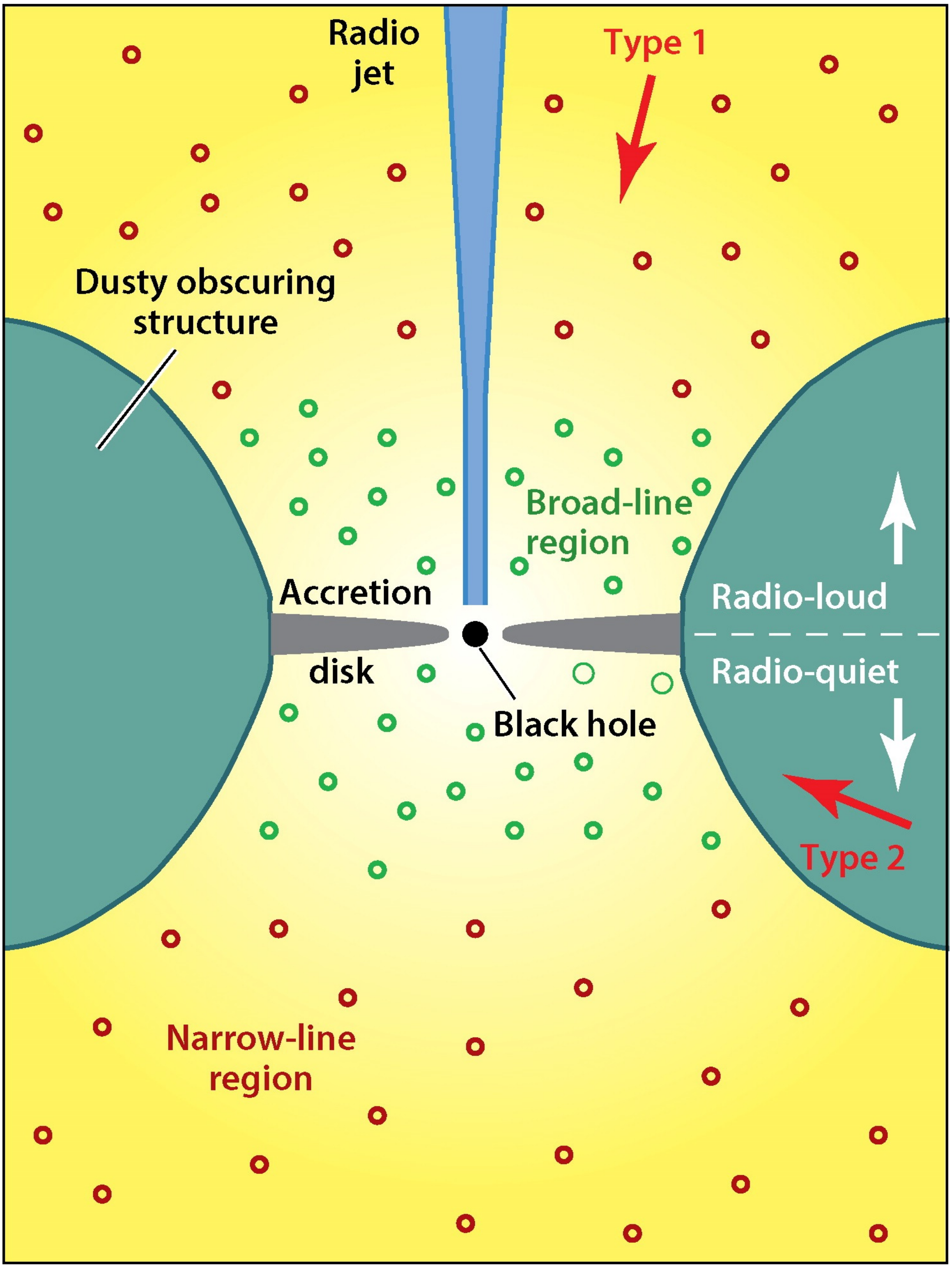

Figure 1.2: A schematic of the unified model of AGN. The primary source of radiation is the accretion disk. This in tern ionizes both the broad-line and the narrow-line regions. A dust torus obscures a side-on view (Type 2 AGN), while a jet sometimes occurs from the poles of the disk. Figure courtesy of Heckman & Best (2014)

of galaxies (a major merger is defined as a ratio in mass closer than 3:1 between progenitor galaxies). These AGN tend to be extremely luminous: indeed despite clearly containing a very powerful jet, they are mostly radiative mode AGN. These RGs form a very small minority of the RG population and hence are not representative. Heckman & Best (2014) presents evidence that most RGs are fueled through secular processes. Exploring the nature and origin of the fuel, as well as the mechanism of accretion and effect of the resulting AGN feedback forms the basis of this thesis.

The rest of this chapter will cover the background required to study the RG population. Firstly, since RGs are mostly found in ETGs we will cover our current understanding of ETGs. This is mostly a summary of the recent Integral Field Spectroscopy (IFS) surveys including Atlas3D, MaNGa, MASSIVE, SAMI and Califa. This can be considered a setting out of the control sample for our later investigations. After this we will give a more detailed summary of the current state of our understanding of AGN. This will include covering RGs.

1.1 Early Type Galaxies

In this section we mostly summarize Cappellari's excellent review of IFS studies of ETGs (Cappellari, 2016).

1.2 Active Galactic Nuclei

Much of this section, makes use of the review by Heckman & Best (2014) and the references therein, and we would point readers in the direction of this review if more detail is required.

This section will first look at the different global parameters that can be measured for AGN. After this the two different modes (radiative and jet modes) will be explored.

1.2.1 AGN parameters

1.2.1.1 Bolometric Luminosity

Perhaps the most basic property of any AGN is it's total (bolometric) luminosity. Given the non-spherically symmetric nature of the unified model of AGN, estimating the bolometric luminosity can be a non-trivial task, particularly for obscured (Type 2) AGN.

1.2.1.2 Black Hole Mass

Thanks to scale relations, measuring the black hole mass, $M_{\rm BH}$ is relatively simple. In this work we use the mass – stellar velocity dispersion, σ_* relation (M-s) from McConnell & Ma (2013):

$$\log\left(\frac{M_{BH}}{M_\odot}\right) = 8.32 + 5.64\log\left(\frac{\sigma_*}{200\mathrm{km\,s^{-1}}}\right) \tag{1.1}$$

1.2.1.3 Eddington Ratio

The Eddington ratio, $L/L_{\rm Edd}$, is the ratio of the Bolometric Luminosity to the maximum luminosity the AGN could possibly achieve while still in hydrostatic equilibrium (the Eddington limit), $L_{\rm Edd}$. The Eddington limit for pure ionized hydrogen is:

$$\frac{L_{\rm Edd}}{L_\odot} = \frac{4\pi G m_p c}{\sigma_T}\frac{M_{\rm BH}}{M_\odot} = 3.3\times 10^4 \frac{M_{\rm BH}}{M_\odot} \tag{1.2}$$

where m_p is is the mass of proton and σ_T is the Thomson scattering cross-section for an electron on a proton (the ratio σ_T/m_p is the opacity of a plasma).

1.2.2 Radiative Mode

Radiative mode AGN are thought to show actively growing black holes as accreted matter falls directly into the event horizon. They are typically radiatively efficient with Eddington ratios of 1-100%. This can also drive powerful interstellar winds, capable of terminating star formation and thus moving a galaxy from the blue cloud to the red sequence.

1.2.3 Jet Mode

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