Resume

As recently as about hundred years ago, astronomers thought that everything they could observe in the sky, i.e., the entire observable Universe, makes up one system – our Milky Way galaxy. Remarkable scientific progress since then has markedly changed our understanding, resulting in the nowadays well-established picture that billions of galaxies exist, which are the building blocks of the Universe. A typical galaxy is composed of hundreds of billions of stars, vast quantities of gas and dust, and also of dark matter, the nature of which remains one of the most important open questions in modern astrophysics. Today we also know that most (if not all) bigger galaxies in the Universe have other defining components lurking in their central regions – supermassive black holes (SMBHs). The episodic accretion of matter onto these mysterious objects, which are a million to a few billion times more massive than the Sun, often produces tremendous amounts of energy, within phenomena known as active galactic nuclei (AGN).

Active galactic nuclei

The discovery of AGN is often credited to Carl Seyfert, who in 1943 reported nuclear emission lines superposed on otherwise normal optical spectra of six extragalactic objects. His work, however, remained largely unnoticed, and its significance was only fully realized once radio astronomy developed with the conclusion of World War II. The subsequent partnership between optical and radio astronomers resulted in the identification of some of the most intense radio sources in the sky with known galaxies. Observers and theoreticians were quick to converge on the idea that accretion of interstellar matter onto a SMBH is likely what drives both the radio emission and the broad and narrow emission lines seen in optical spectra. The first radio surveys of the sky and Maarten Schmidt’s discovery of a distant quasar in 1963 eventually launched the studies of AGN into mainstream astronomy, where they have stayed ever since.

Active galactic nuclei are the most energetic objects in the Universe, emitting throughout much of the electromagnetic spectrum via both thermal and non-thermal processes. Within the well-established SMBH Paradigm, the "engine" of an AGN is the accretion of matter onto the SMBH, and its subsequent highly-efficient conversion into energy. In addition to the central massive black hole and the flat accretion disk, this paradigm (or
Figure 1: A schematic model of an active galactic nucleus (AGN). Note the strong radio jet in the case of the radio-loud AGN shown in the upper half of the figure. The model is taken from the work by Heckman & Best (2014).

AGN model) also features so-called broad- and narrow-line regions, an obscuring "torus", and in some cases collimated outflows, also known as jets (see Fig. 1 for a schematic diagram). The broad- and narrow-line regions are where the optical lines seen in AGN spectra originate from, and the jets are mainly powering the emission seen in the radio domain.

For historical reasons, but also due to the availability of instruments tuned to domains other than the optical and radio, a plethora of different AGN types exist in the literature, collectively constituting the so-called "AGN zoo". Several studies over the years have attempted to unite the different AGN types based on various properties. In brief, the two fundamental aspects that lead to different AGN types are the spin (and possibly mass) of the SMBH, and the efficiency of the accretion process. The former divides AGN into radio-loud (high spin/mass) and radio-quiet AGN, whereas the latter into radiative-mode (efficient accretion) and jet-mode AGN. A further division within the
radiative-mode AGN class may be understood in terms of orientation (i.e., viewing angle with respect to the central axis) effects. Central to this division is the obscuring "torus" of dust and gas, which results in Type 1 or Type 2 AGN, depending on whether or not it obscures the innermost AGN regions, respectively. The two radiative-mode radio-loud AGN types which can be successfully unified according to the orientation-based unified model, which are also the subject of this thesis, are called radio galaxies (Type 2) and radio-loud quasars (Type 1) (see Fig. 1).

**Star formation and the role of dust**

In addition to the nuclear activity, another fundamental physical process which determines the structure and evolution of (active) galaxies, is the transformation of gas into stars. It is known that the process of star formation, which largely competes for the same "fuel" as the AGN activity, requires dense environments relatively rich in cool molecular gas and dust, and as such occurs predominantly within giant molecular clouds. Depending on the amount of available material, and the prevailing conditions within a galaxy, the amount of star formation activity in a unit of time (also known as the star formation rate) can range over orders of magnitude, from close to zero in some elliptical galaxies, to moderate (one Sun-like star per year in our Galaxy) or prodigious star formation activity in some starburst galaxies. Research has shown that the stellar build-up of galaxies went through peak activity when the age of the Universe was between 2 and 6 billion years (redshift $1 < z < 3$), an epoch which coincided with that of the peak black hole growth,
i.e., AGN occurrence. This likely suggests that the two growth processes know about and possibly influence each other.

Due to the severe contamination from the AGN, the typical methods used to quantify the star formation activity, based on ultraviolet, optical, or even mid-infrared emission lines, fail to produce robust results in active galaxies. In such cases, thermal emission from dust is arguably the best tracer of the star formation activity. Astrophysical dust grains, which are mainly composed of carbon and intimately linked to the process of star formation, absorb the ultraviolet/optical emission from the newly formed hot stars, and re-emit in the far-infrared domain. In active galaxies, dust also features prominently in the "AGN torus", which subject to the considerably stronger AGN radiation field is heated to higher temperatures and emits mainly in the mid-infrared domain. Therefore, a crucial task in quantifying the star formation rate in active galaxies is the robust disentangling of the infrared emission due to star formation from that due to the AGN activity.

Given that the Earth’s atmosphere absorbs much of the infrared radiation from space, the infrared sky is best studied by telescopes which orbit Earth. Most recently, this was successfully achieved with the *Herschel Space Observatory* (Fig. 2), the largest infrared space telescope ever launched, with unprecedented sensitivity, spatial resolution, and wavelength coverage. Closing the gap between the mid-infrared *Spitzer* and submillimetre ground-based telescopes, *Herschel* provided "a new set of eyes" into the far-infrared domain, facilitating studies which revolutionized our understanding of star formation across cosmic time, particularly in distant active galaxies.

**This thesis**

We obtained *Herschel* observations, and used them in conjunction with data from a number of ground- and space-based instruments to systematically study the interplay between AGN and star formation activity in distant and massive active galaxies. The analyzed objects were selected from a complete sample of landmark radio galaxies and radio-loud quasars, also allowing us to test the orientation-based unified model of powerful radio-loud AGN. Our most important findings are highlighted below.

In Chapter 2, we demonstrated that about half of the targeted active galaxies have huge star formation activities, of order several hundreds of solar masses per year. These high-redshift starbursts may conveniently be referred to as "fireworks in the early Universe" (Fig. 3). In contrast with other literature studies, we found no clear evidence for universal suppression of star formation despite the powerful AGN activity which often exhibits an infrared luminosity comparable to that of the starburst. Moreover, we provided tentative evidence that the AGN activity may in some cases instead promote the formation of new stars, a finding which remains to be confirmed with further studies. *Herschel*’s superior spatial resolution allowed us to better isolate the infrared emission from our AGN host galaxies. In Chapter 3, we showed that the bright infrared emission, previously associated with one active galaxy from our sample, in fact mostly comes from nearby sources, and not from the active galaxy itself.
Strong arguments in favour of the orientation-based unified model of powerful radio-loud AGN, based on a wealth of multi-wavelength data, have been presented in the literature. Within this model, it is thought that powerful radio galaxies and radio-loud quasars are essentially the same objects, whose apparent differences can be understood in terms of viewing angle. Performing the first tests of the unified model in the largely unexplored far-infrared domain, in Chapter 4 we provided further evidence in support of this model. We found that the radio galaxies and quasars contained in our clean sample have remarkably similar far-infrared properties, but show clear differences in the mid-infrared domain. Both results are completely in line with the predictions of the unified model for these wavelength domains, confirming that the two particular radio-loud AGN types are manifestations of the exact same phenomenon.

Chapter 5 describes an ultraviolet-to-submillimetre study of a dozen Herschel-detected (i.e., far-infrared-bright) radio galaxy hosts. Using a newly-developed code, we computed a large variety of templates starting from physically-motivated assumptions and following the physics of stellar evolution, and used them in connection with current AGN models to estimate the properties of the stars present in the studied objects. We found that the available multi-wavelength observations are best represented by a view whereby, in addi-
tion to strong AGN activity in the mid-infrared, radio galaxy hosts have two distinct, a relatively young and a relatively evolved, stellar populations. The former dominates the emission in the far-infrared regime and the overall stellar luminosity, whereas the latter predominantly emits in the optical and near-infrared domains, and dominates the stellar mass in the active galaxies.

In stark contrast with the impressive multi-wavelength photometric observations is the lack of modern optical spectra of our sample active galaxies. In Appendix A, we presented a preliminary study of our ongoing efforts to overcome this limitation. We found that, due to the strong AGN activity, the typical ultraviolet emission lines present in radio galaxy spectra cannot be robustly used to quantify their star formation rates. The potential suitability of the C III]/He II line ratio as a diagnostic for the star formation activity remains to be systematically explored in a study involving more active galaxies. Finally, in Appendix B, we reported the Herschel photometry of supplementary radio-loud AGN, the properties of which are similar to those of the AGN studied in Chapter 2.

The results in this thesis highlighted the importance of studying the interplay between AGN and star formation activity in the distant Universe. Further leaps in our understanding of this symbiosis are to be provided by the highly-anticipated Atacama Large Millimeter Array, once operating in full capability.