Star formation and AGN activity in distant massive galaxies
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Chapter 1

Introduction

Supermassive black holes (SMBHs), the black holes with masses of order millions to billions of solar masses, are ubiquitous in the Universe. It is nowadays assumed that every massive galaxy contains such an object in its very central regions. While the SMBH in our own Milky Way galaxy is virtually dormant, SMBHs in other galaxies may actively accrete matter, resulting in phenomena which classify these galaxies as active galaxies and their nuclei as Active Galactic Nuclei (AGN). Due to the immense power of such accreting systems, the AGN influence the galaxies in which they reside in various ways. Largely competing for the same resources (gas, dust) as those required for the SMBH growth, is the process of star formation (SF), which takes place on scales much larger than those of the central nucleus. Both the AGN and SF activity result in emission throughout much of the electromagnetic spectrum, and require a large wavelength coverage for a robust separation of their associated emission. This is particularly important in the rest-frame infrared domain, where dust emission powered by both activities dominates. The breakthrough Herschel Space Observatory provided sensitive observations in this hitherto largely unexplored domain, and combined with ancillary multi-wavelength data, these observations helped unravel the SF activity in galaxies hosting active nuclei, specifically in the more distant Universe.

1.1 Active Galactic Nuclei

The early beginnings of AGN physics are often linked to [Seyfert (1943)], who showed high-excitation nuclear emission lines superposed on a normal star-like spectrum in six galaxies, some showing broad and others only narrow emission lines. [Woltjer (1959)] pointed out that the observed emission requires a mass of a few $10^8 \, M_\odot$ within the central 100 pc of the galaxy, which [Salpeter (1964)] argued could be a black hole (as opposed to a hypermassive star) emitting mainly by accretion processes of a surrounding disk of gas. The development of radio astronomy after the conclusion of WWII, allowed [Baade & Minkowski (1954)] to identify Cygnus A, one of the most intense radio sources in the sky, with a known galaxy. The study of AGN, and extragalactic astronomy overall, was subsequently revolutionized with the first discovery of quasars and their identification
with very distant objects by Schmidt (1963).

1.1.1 The AGN model

Active galactic nuclei are the most energetic objects in the Universe. In combination with other observables (f.i. the size of the emission region), the energetics of AGN strongly link their existence to the so-called Supermassive Black Hole Paradigm. Within this well-established paradigm, the main components of an AGN are the SMBH, accretion disk, broad-line region, narrow-line region, obscuring torus, and jets. A schematic diagram depicting the typical AGN structure is shown in Fig. 1.1.

The central engine of an AGN is a compact, actively accreting SMBH, whose immensely strong gravitational field completely traps not only matter, but also light. The feeding of the black hole is achieved through an accretion disk, the flat structure of which is a consequence of the conservation of angular momentum of the infalling material (mainly gas and dust from the interstellar matter). The conversion of mass into energy within AGN may reach a very high efficiency of $\sim 10\%$, which is much higher than that reached when generating energy in interiors of stars ($\sim 0.7\%$). For example, powering a luminous AGN ($L_{\text{AGN}} = 10^{46} \text{ erg s}^{-1}$) with such high mass-to-energy efficiency requires a rate of accretion of only two Sun-like stars per year.

Strong ultraviolet/optical emission lines in AGN spectra is one of the most important characteristics of AGN. Depending on their linewidth, AGN emission lines are classified as either broad (exclusively permitted) or narrow (both permitted and forbidden) lines. The broad emission lines, which are essentially Doppler-broadened due to the high velocities ($>1000 \text{ km s}^{-1}$) of the emitting gas in the gravitational field of the black hole, are generated in the so-called broad-line region (BLR). Further out from the BLR, and characterized by lower gas densities and velocities ($\sim 100 \text{ km s}^{-1}$), is the narrow-line region (NLR), which produces the narrow emission lines in AGN spectra. On scales roughly between the BLR and NLR is a toroidal dusty obscuring structure, rich in molecular gas and dust, simply known as the AGN-torus. In some AGN orientations (see Fig. 1.1), the torus hides the broad-line region, which results in only narrow emission lines in their observed spectra. The torus and the jets (well-collimated outflows of material) will be addressed in more detail in the next sections.

1.1.2 The AGN zoo

The intrinsic variety within the AGN class, coupled with the advent of instruments covering previously unavailable wavelength domains, led to a plethora of AGN types, nowadays often referred to as the 'AGN zoo'. While there exists a significant overlap among (at least some) AGN types, retaining the various AGN names associated with their historical discoveries has occasionally led to some confusion in the AGN community. Therefore, in what follows I summarize the main properties of AGN, and describe the AGN types addressed in this thesis.

As recently reviewed by Heckman & Best (2014), depending on the physics of the accretion process, the AGN in the Universe may be split in two main categories: the so-
Figure 1.1: A schematic model of an active galactic nucleus in radiative-mode, published by [Heckman & Best (2014)]. The upper and lower halves of the model deal with radio-loud and radio-quiet objects, respectively.
called jet-mode and radiative-mode AGN. As the respective names suggest, the primary energetic output of jet-mode AGN takes the form of kinetic energy conveniently transported by two-sided, collimated outflows (i.e. jets), whereas that of radiative-mode AGN takes the form of strong electromagnetic radiation over a large wavelength range from X-rays to radio. This radiation is generated by sufficiently high accretion rates provided by an optically-thick, geometrically-thin accretion disk, a structure often replaced by a more geometrically-thick structure in jet-mode AGN, resulting in radiatively-inefficient accretion and launching of jets. Note that radio jets also occur in the radio-loud (see below) subgroup of the radiative-mode AGN. Selected properties of jet-mode and radiative-mode AGN, and of their typical host galaxies, are summarized in (Fig. 1.2). This thesis deals exclusively with radiative-mode AGN, also referred to as quasar-mode AGN in the literature.

In addition to exhibiting important differences in the energetics of the accretion, AGN show a wide range of radio-loudness, a fact that gives rise to the population of radio-quiet and radio-loud AGN. In practice, radio-loud AGN are those for which the ratio between radio (at 6 cm) and optical (at 440 nm) specific flux is greater than ten (e.g., Kellermann et al. 1989). These objects are about a factor $10^3$ to $10^4$ more luminous in the radio domain compared to their radio-quiet counterparts, and comprise about 10-20% of the total AGN population. Within the so-called spin paradigm by Wilson & Colbert (1995), the enormous radio luminosities characteristic for the radio-loud AGN population are produced by rapidly spinning (and possibly more massive) SMBHs, which may be the
1.2 Radio-loud AGN

The radio morphology of typical radio-loud AGN consists of a compact radio core, and a pair of jets terminating in so-called hot-spots and powering the radio lobes. Depending on whether the jets or lobes dominate the radio emission, Fanaroff & Riley (1974) split this AGN population in FRI and FRII types, respectively. Virtually all distant radio-loud AGN selected in flux limited radio surveys are powerful radio sources of FRII-like morphology with edge-brightened radio lobes. This classification is independent of radio size, which when taken into account leads to a further class of radio-loud objects, known as Gigahertz peaked-spectrum (GPS) and compact steep-spectrum (CSS) sources (e.g., O'Dea 1998). The widely accepted scenario is that the GPS (< 1 kpc) and CSS (< 30 kpc) sources are young radio sources, which would eventually expand into larger sources once their jets escape the interstellar matter of the galaxy in which they reside. A convenient and unique feature of radio-loud AGN is that, assuming a typical expansion speed for the radio jets, hence radio-source growth speed, their radio size provides a good idea about the age of the AGN episode.

1.2.1 The unified model of radio-loud AGN

While the two classifications presented in the previous section involve physical parameters (accretion power and black hole spin), a third observational classification of AGN is based on the orientation of the AGN with respect to the observer’s line of sight. Within the standard (orientation-based) unified model for radiative-mode AGN (e.g., Barthel 1989, Antonucci 1993, Urry & Padovani 1995), AGN are mainly divided in Type 1 (or unobscured) and Type 2 (or obscured) objects. In case of Type 2 AGN, a more equatorial line of sight ensures that the AGN-torus blocks the short-wavelength emission from the accretion disk and the surrounding broad-line region, structures which are easily accessed along a polar sight line in Type 1 objects. As a result, the typical optical spectrum of a Type 1 AGN has both broad and narrow emission lines on top of a bright continuum, whereas Type 2 objects’ spectra have only narrow emission lines on top of weak continua. In its simplest form, the orientation-based unified model makes a number of predictions concerning the emission from AGN (and the galaxies in which they reside) over a large wavelength range, most of which have repeatedly been confirmed using observations made with most space- and ground-based instruments (see Antonucci 2012, for a recent review). The radio-loud AGN in radiative-mode are called radio-loud quasars (Type 1) and radio galaxies (Type 2), and both types of objects feature prominently in this thesis. The fact that the torus largely hides the bright accretion disks surrounding the SMBH in radio galaxies presents a unique opportunity for studying the stellar properties in their (often massive) host galaxies.

1.2.2 The 3CR sample

Not surprisingly, a critical issue in any attempt to study orientation-dependent effects is the selection of AGN samples which are free of any bias with respect to orientation. In
practice, the only possible way to define meaningful unbiased samples is by selecting AGN based on the integrated low-frequency emission from their radio lobes, which essentially emit optically-thin and isotropic synchrotron radiation. One of the samples which meets these criteria, and is hence particularly well-suited for probing the unification of AGN, is the well-known Revised Third Cambridge Catalogue of Radio Sources (3CR, Bennett 1962; Spinrad et al. 1985). The 3CR sample is a complete, low-frequency (178 MHz), flux-limited ($F_{178\text{MHz}} > 10$ Jy) sample, containing the most powerful radio-loud AGN in the Northern hemisphere. While the lower redshift end of this sample includes a mixture of both efficiently and inefficiently accreting black holes, its $z > 1$ counterpart contains exclusively radiative-mode AGN. The complete (64 objects) $z > 1$ 3CR sample of quasars and radio galaxies, which has been observed with virtually all major space- and ground-based instruments, is the main focus of this thesis.

1.2.3 The SEDs of radio-loud AGN

The spectral energy distributions (SEDs) of radio-loud AGN (Fig. 1.3) provide evidence for a number of distinct spectral components, reflecting both the AGN activity and the stars in their host galaxies (e.g., Miley & De Breuck 2008). At the shortest (X-ray) and longest (radio) wavelengths, the typical SED of a powerful radio-loud AGN is completely...
1.3: Star formation in galaxies

The rest-frame mid-infrared wavelength domain (5-40\(\mu\)m) is often dominated by thermal emission from AGN-heated warm dust, which is located in the torus region. A number of either static or hydrodynamic models for the infrared emission from AGN-tori, often with completely different assumptions and parameters, are available in the literature – yet the details of the torus dust distribution are not fully known (recently reviewed by Netzer 2015). Theoretical considerations suggest that the dust within the torus is arranged in clumps instead of being smoothly distributed, in line with what has been inferred from mid-infrared interferometric observations of a couple of nearby AGN (e.g., Hoenig 2013). As expected from the orientation-based unified model of radio-loud AGN, the emission from the hot dust in the innermost torus regions may be obscured in the case of radio galaxies.

If SF takes place within the AGN host galaxy, the longer-wavelength emission from dust in the outermost regions of the torus blends with the emission from cool dust which is heated by the newly formed stars. In the literature, this spectral component is either represented with a modified blackbody component with a fixed emissivity index, or with observed or simulated starbursts. Similar considerations are applicable also for old stars which have been produced during the complete star formation history of the AGN host galaxy. Radio-loud AGN are often found in massive early type galaxies, which are consistent with being initially formed at high redshift (e.g., Rocca-Volmerange et al. 2004).

In addition to the stellar emission from both old and young stars, additional components driven by the AGN activity further complicate the disentangling of the SED in the UV/optical domain of radio galaxies. The high-\(z\) radio galaxies\(^1\) studied in this thesis, often show a pronounced alignment between their UV/optical and radio morphology (e.g., McCarthy 1993; Dickson et al. 1995). This so-called ‘alignment effect’ has been interpreted as a combination of jet-induced star formation, nebular emission, and emission from the accretion disk which has been scattered off dust particles in the polar regions of AGN.

1.3 Star formation in galaxies

1.3.1 The physics of star formation

The transformation of gas into stars determines the structure and evolution of galaxies, and as such is one of the most fundamental processes studied in astrophysics. It is nowadays established that the formation of new stars takes place within giant molecular clouds – dense regions rich in relatively cool molecular gas – and that it involves the complicated physics of turbulence, self-gravity, and magnetic fields (e.g., McKee & Ostriker 2007). Note that for all but the closest galaxies, the process of star formation may only

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\(^1\) The strong power-law thermal emission from the accretion disk in radio-loud quasars (Type 1) precludes any studies of their host galaxies.
be studied in a global sense, using galaxy-integrated light measurements.

The recent availability of large multi-wavelength surveys presented unique possibilities for studying the amount of star formation (also known as star formation rate (SFR)) over much of the history of the Universe. These studies revealed that the stellar build-up of galaxies increased gradually during the early Universe, and went through its peak activity\(^2\) at redshifts between \(z \sim 3\) and \(z \sim 1\), after which it rapidly declined towards the Universe of today (e.g., Madau & Dickinson 2014). Additionally, such studies illustrated that the SFRs of the majority of galaxies correlate well with their stellar mass content over a large range in stellar mass up to a redshift of \(z \sim 2.5\), shaping what is known as the 'main-sequence' of galaxies (e.g., Elbaz et al. 2011; Rodighiero et al. 2011). This tight relation suggests that the efficiency with which gas is converted to stars is similar throughout much of the history of the Universe. A small fraction of galaxies, conveniently named starburst galaxies, are located significantly above the main-sequence. In the local Universe, these objects almost exclusively are (ultra)luminous infrared galaxies ((U)LIRGs), associated with merging systems (Sanders & Mirabel 1996). While the discussion above holds for galaxies with clear signs of SF activity, there exists a relatively large population of galaxies, f.i., the massive early-type galaxies in the local Universe, which show no signs of current SF activity.

A number of diagnostic methods of the star formation activity have been introduced in the literature, among others including the ultra-violet (UV) and far-infrared (FIR) continuum, and either recombination (e.g., H\(\alpha\)) or forbidden ([OII]) emission lines (see e.g., Kennicutt & Evans 2012, for a detailed review). However, in galaxies hosting active nuclei, all but the FIR thermal continuum are severely affected by the AGN-driven emission. Given that the contrast between the typical AGN and star-forming galaxy SED is largest in the infrared, the dust continuum emission has been exploited as the default tracer of star formation within the AGN community, particularly in light of the Herschel observations which allowed for robust subtraction of the emission from AGN-heated dust in the torus. Other objects for which the FIR dust luminosity provides straightforward measure of their SFRs are the (U)LIRGs, in which copious amounts of dust may completely obscure the star formation activity in the UV/optical domain. Estimating SFRs based on the dust luminosity in the literature usually relies on the crude calibration provided by Kennicutt (1998).

### 1.3.2 The role of dust

As already hinted above, the dust plays a prominent role in the physics of galaxies despite contributing a mere 1% (or less) of their total mass. Astrophysical dust grains, predominantly carbonates and silicates, are primarily formed in the later stages of the evolution of massive stars when they either expel their outer regions (asymptotic giant branch stars), or violently explode in supernovae. Being mixed in almost all phases of the ISM, dust carries out the extinction (i.e. absorption and scattering) of light and catalyses the formation of molecules, in particular molecular hydrogen – the most abundant molecule in the Universe. While its presence in giant molecular clouds makes

\(^2\) As I describe in later sections, the \(1 < z < 3\) period coincides with the heyday of the black hole growth in the Universe.
it intimately linked to the process of star formation, dust also emerges in the AGN-torus, where its obscuration effects give rise to the Type 1/Type 2 AGN dichotomy. Dust grains absorb the UV/optical light from astrophysical sources like stars and AGN, and given their temperature (10-100 K in star-forming regions; 300-1500 K in AGN-tori) they re-emit the incident light in the rest-frame infrared. In particular, the emission from AGN-heated dust peaks in the mid-infrared (20 - 40 µm), and that of star-formation-heated dust in the far-infrared (50 - 100 µm) domain. The latter coincides with the spectral coverage of the Herschel instrument, whose advent revolutionized our understanding of star formation across cosmic time.

1.3.3 The Herschel Space Observatory

The Herschel Space Observatory (Pilbratt et al. 2010), with its unprecedented combination of sensitivity and spectral coverage, closed the gap between the shorter-wavelength Spitzer and longer-wavelength domains covered by ground-based telescopes, providing a new window of the dusty, obscured Universe, specifically towards high redshift. During its four-year mission (2009-2013), Herschel (Fig. 1.4) executed a mixture of pointed and imaging surveys in the far-infrared/submillimetre domain, using both imaging instruments on board: PACS (at 70, 100, and 160 µm) and SPIRE (at 250, 350, and 500 µm), producing a wealth of legacy data to be analysed in years to come. The 38-hours Herschel observations which this thesis is largely based on, come from the Guaranteed Time project The Herschel Legacy of distant radio-loud AGN (PI: Barthel).
1.4 The AGN/SF connection

The huge energetic output from the AGN may severely affect the general conditions in the hosting galaxy. While AGN are intriguing objects in their own right, it is this connection to their host galaxies which receives the most attention in the astrophysical literature.

Over the last twenty years, several tight correlations between the mass of the central SMBH on one hand, and various properties of the host galaxy on the other, were presented in the literature (reviewed by Kormendy & Ho 2013). One of the most notable examples is the strong correlation between the mass of the SMBH and the velocity dispersion of the host galaxy’s bulge (Fig. 1.5), known as the $M_{\text{BH}} - \sigma$ relation (e.g., Ferrarese & Merritt 2000, McConnell & Ma 2013). Similarly, other properties of the host also scale with the black hole mass, and these include the mass of the bulge (Magorrian et al. 1998) and its luminosity (McLure & Dunlop 2002). These strong scaling relations, together with the evidence that the AGN and SF activities peaked at $z \approx 2$ (Fig. 1.5), suggest an intimate link between the growth of the black hole and that of its stellar bulge.

1.4.1 Feedback effects

Predictions about the luminosity function (i.e., the volume density of galaxies as a function of their luminosity) from theoretical, dark-matter-only simulations significantly overestimate the number of massive galaxies in the local Universe. To overcome this overproduction of big galaxies in simulations, researchers introduced the concept of AGN feedback, and more specifically the negative feedback. At least two modes of negative feedback are discussed in the literature. The first involves the direct suppression of star formation by the AGN activity (i.e., quenching mode), and the second involves the regulation of the cooling of the available gas which could otherwise coalesce to form new stars (i.e., maintenance mode). Although negative feedback has been studied extensively both via observations and cosmological simulations, it is not yet clear how efficiently energy (heating) and momentum (pressure) are coupled to the AGN host galaxy’s ISM, and which feedback mode dominates.

Besides negative feedback, another AGN feedback effect working in the opposite direction has also recently received much attention in the literature. Within the framework of this so-called positive feedback, a radio jet propagating through an inhomogeneous ISM may also trigger new episodes of star formation within the AGN host galaxy. While such jet-induced star formation has been directly supported by only a limited number of observations at low and high redshift, high-resolution hydrodynamical simulations show that the pressure confinement of the ISM associated with the jet activity can lead to a significant increase of the host galaxy’s SFR. Positive feedback has repeatedly been considered as one of the mechanisms responsible for shaping the alignment effect observed in powerful radio galaxies. Even though the negative and positive effects function in the opposite direction, they are not necessarily contradictory, and may operate in the same host galaxy, though on different time-scales or in different locations.
1.4: The AGN/SF connection

Figure 1.5: The co-evolution of the black hole and stellar bulge growth. Left: the $M_{\text{BH}} - \sigma$ relation by McConnell & Ma (2013); right: black hole and stellar bulge growth over cosmic time, published by Shankar et al. (2009).
1.4.2 AGN/SF symbiosis

The triggering of the AGN and SF activity requires that sufficient material is available, and that for the former, this material is funnelled to the central SMBH losing practically all of its angular momentum. One mechanism through which this can be achieved, which cosmological simulations indicate is the prime mechanism for galaxy growth, is the process of merging between galaxies. Note that due to the relatively low accretion rates required to sustain the AGN, a merger involving a relatively gas-poor component (i.e., dry merger) could power the AGN activity without initiating substantial SF activity. When signatures for mergers are clearly observed, for example in the case of powerful intermediate-redshift radio galaxies (e.g., Tadhunter et al. 2011), the onset of the starburst and AGN activity does not seem to proceed along a single well-defined evolutionary sequence. In other words, AGN in mergers may be triggered simultaneously with the main starburst episode, but also significantly before or after the starburst. The triggering of low-to-moderate-luminosity AGN is less understood, with several morphological studies (e.g., Kocevski et al. 2012) concluding that major mergers are unlikely to trigger most of the AGN activity. While minor mergers with less discernible morphological features cannot be ruled out, other secular processes such as tidal disruptions or disk instabilities are likely responsible for the triggering of the majority of AGN activity.

In general, Herschel studies of star formation in AGN host galaxies over a large luminosity and redshift range suggest that AGN are mostly hosted by star-forming galaxies on the main-sequence, with properties typical for their redshift (see Lutz 2014 for a thorough review). While the importance of major mergers in the black hole and galaxy growth appears to be limited at $z < 1$, major mergers cannot be conclusively excluded at the high-$z$ Universe, where their physical properties could be entirely different (e.g., Caputi 2014).

1.5 This thesis

In this thesis, we follow a multi-wavelength approach to identify and quantify the energetics of the AGN and SF activity in complete samples of massive galaxies undergoing well-understood AGN episodes. The main questions addressed in this thesis are as follows:

- What is the level of SF activity in the hosts of (some of) the most powerful distant radio-loud AGN?
- How is the energetics of the SF activity compared to that of the AGN activity, and is there evidence for feedback effects in this AGN population?
- Does the orientation-based unified model of radio-loud AGN hold in the rest-frame infrared domain?
- What are the properties of the stellar populations in hosts of radio-loud AGN?
- What triggers the SF activity, and where does it take place?

\footnote{Merger events may be major or minor. The mass ratio between the merging components for the former and latter is 1:1 and about 1:5, respectively.}
Chapter 2 presents a comprehensive study of the SF properties of the massive host galaxies of the complete \( z > 1 \) 3CR sample of powerful radio-loud quasars and radio galaxies. Combining mainly Herschel and Spitzer photometric data, we perform an SED analysis to decompose the observed IR SEDs into AGN- and SF-related components. This approach employs clumpy torus models from the library of Hönig & Kishimoto (2010) and typical modified blackbodies to account for the AGN-heated warm dust and young-star-heated cold dust emission, respectively. From the individual SEDs, we create median SEDs for the two types of objects, and assess their overall similarities and differences. We quantify the IR SF and AGN activities of 3CR host galaxies, and place these results in the context of the negative feedback scenario. We compare the SF properties of 3CR hosts to inactive galaxies with similar physical properties, and discuss the issue of positive feedback by connecting the measured SFRs to the duration of the AGN activity, measured from radio imaging. Finally, we implement a stacking procedure to study the average properties of \( z > 1 \) 3CR host galaxies individually not detected with Herschel.

Color-color diagrams represent a simple, yet powerful way to investigate SED shapes. In Chapter 3, we create rest-frame color-color diagrams for the \( z > 1 \) 3CR radio-loud quasars and radio galaxies, with the goal to test the orientation-based unified model for radio-loud AGN, which postulates that these two AGN types are intrinsically the same objects but viewed along different angles. We consider different combinations of infrared colors which not only serve as orientation-invariants and orientation-indicators for the radio-loud AGN population, but also probe the relative importance of the SF and black hole activity in AGN host galaxies. For the latter we also explore typical star-forming galaxies and hosts of the more common radio-quiet AGN, with properties comparable to those of the 3CR hosts.

Our rich dataset facilitates detailed studies of individual objects from the complete 3CR sample. Chapter 4 presents a study of the radio-loud quasar 3C 318, which was considered as one of the most intrinsically luminous infrared sources in the Universe (SFR \( \sim 2000 \, M_\odot \, \text{yr}^{-1} \), Willott et al. 2007). Benefiting from the superior spatial resolution of Herschel (compared to that of previous telescopes with partly overlapping wavelength coverage) we show that much of the infrared emission attributed to 3C 318 in fact is not associated with 3C 318’s host. We use optical spectroscopy and ancillary multi-wavelength photometric data to uncover the nature of this excess infrared emission, after which we quantify the emission from 3C 318’s host, and accurately measure its SFR.

To constrain the physical properties (mass, age, metallicity) of the stellar components present in the high-\( z \) 3CR radio galaxy hosts, in Chapter 5 we opt for synthetic stellar templates in place of the modified blackbodies adopted in Chapter 2. We generate the stellar templates using the newly-developed evolutionary code PÉGASE.3 (Fioc & Rocca-Volmerange, in prep.), and use them in conjunction with state-of-the-art AGN-torus models (Siebenmorgen et al. 2015) and recent HST observations, to fit the UV-to-submm SEDs of a dozen radio galaxy hosts with all-round good-quality photometric (and in a few cases Spitzer spectroscopic) data. Among other things, we use this dataset to study the torus-starburst connection and to correlate the starburst ages to the duration of the AGN episodes in these selected radio galaxy hosts. Finally, we investigate the relative importance of non-stellar contribution to the UV/optical SEDs of some radio galaxy
hosts, which might be related to the alignment effect observed in high-z radio galaxies.

Optical spectroscopy of radio-loud AGN has the potential to provide further constraints on the properties of the SF activity in their host galaxies. Appendix A presents a preliminary analysis of several optical spectra of radio galaxies obtained with Keck, whereby we investigate various rest-frame UV emission lines in the extracted one-dimensional spectra. Finally, in Appendix B, we report Herschel photometry and IR SEDs of selected radio-loud AGN (mainly quasars) from the 4C catalogue, which were observed to extend the redshift range of the 3CR sample presented in Chapter 2 to slightly longer redshifts ($z < 3$).