Chapter 1

Introduction

1.1 Background

The vast majority of galaxies in the universe have emission properties dominated by their constituent stars. Some objects, however, have significant non-stellar emission components. For instance, galaxies with substantial internal obscuration and star-formation, like M82, are over-luminous in the infrared. Other objects are found to have an unusually bright nucleus, which emits copious amounts of radiation over a broad range of wavelengths, often out-shining the rest of the galaxy in the process. These galaxies are said to harbor an Active Galactic Nucleus (AGN), and form the topic of this thesis. Current thinking holds these AGN's to be massive ($10^{7-9} M_\odot$) black holes, which accrete matter through a disk-like structure (the accretion disk). Radiation from this accretion disk produces the observed optical and UV radiation, while the dust around the nucleus (presumably shaped as a torus of dense clouds) absorbs and re-radiates part of this energetic radiation in the infrared. Depending on the relative orientation of the torus towards the observer and the exact make-up of the AGN, one observes a plethora of different objects, ranging from quasars, BL Lacs, QSO's to radio galaxies. All these objects may be different manifestations of the same kind of nuclear engine.

For reasons not fully understood, some AGN emit strongly at radio wavelengths, while others do not, or do so at a level 3 orders of magnitude lower. This lead to the classification of radio-loud versus radio-quiet AGN. The optically most luminous type of radio-quiet object is the QSO (quasi stellar object), which is completely dominated by its nuclear emission. Recently using the Hubble Space Telescope (HST), the faint underlying galaxies have been imaged directly (e.g., Lowenthal et al. 1995, Taylor et al. 1996, Bahcall et al. 1997). These radio-quiet AGN reside both in elliptical and spiral hosts. The less luminous Seyfert galaxies are usually associated with spirals.
Based on the relative orientation of its central engine to the observer, these Seyferts can be sub-classified as type I to II, depending on the presence (or absence) of broad emission lines and strong continuum radiation (cf. Antonucci 1993). These broad emission lines are produced by Doppler shifts due to the high orbital motion (~10,000 km s⁻¹) of clouds close to the black hole. A direct view of these clouds is blocked by an obscuring torus in the type II's. Narrower lines are produced further out (up to about 1 kpc), where the clouds are moving more slowly.

Unlike the radio-quiet AGN, the radio-loud AGN are uniquely found to reside in elliptical hosts, which, however, are frequently observed to have peculiar substructure (cf. Chapter 8). The main types of these radio luminous AGN are distinguished by their radio morphology. Following Fanaroff & Riley (1974), a radio source is defined as belonging to the first or second class (FR I vs. FR II) based on whether more or less than half of the total radio emission¹ emanates from inside a region half its total angular extent. This effectively means FR I objects are dominated by the nuclear region, fading away at larger radii, whereas FR II objects have prominent emission features at the extremities of their radio extent (cf. Bridle 1984, Baum et al. 1995). This thesis mainly deals with these lobe dominated FR II radio sources.

1.2 Radio Source Evolution

Historically, the FR I and FR II distinction was applied to large (at least several arcseconds) radio sources, due to the resolution limit of the radio telescopes available at the time. The definitions of FR I and FR II have no restrictions of angular or physical size – the categories are just a morphological classification. With an increase in angular resolution, especially after the very long baseline interferometry (VLBI) experiments became feasible, previously unresolved sources turned out to have morphologies remarkably similar to the already well studied large-scale radio sources (see Fig. 1.1). Because of this slow and gradual technological advance, sources have been classified and assigned names, which are, with hindsight, less than fortunate. If we focus on the FR I, or lobe-dominated, type sources, we can distinguish the Gigahertz Peaked Spectrum (GPS), Compact Steep Spectrum (CSS), and the large-scale FR II radio sources. Typical GPS, CSS, or FR II sources have exactly the same appearance, but they have very different size scales. In principle, all these sources could be classified as FR II sources on the basis of morphology, while, in practice, these classes were named on the basis of their radio spectral properties long before this became apparent. GPS sources are smaller than 1 kpc, CSS sources are between 1 and 20 kpc, and FR II's are larger than 20 kpc. If we compare these sizes to galactic structures, GPS's radio structure is within the extent of the Narrow Line Region² (NLR), CSS sources are sub-galactic in size, and FR II sources have expanded beyond the confines of the galaxy.

Once this morphological similarity was established, evolutionary scenarios were

¹ at 178 MHz
² The region close enough for the central engine to effectively photo-ionize the ambient gas into line-emission. This can be up to a few kpc in some sources. The NLR should not be confused with the Broad Line Region (BLR), which is much closer to the AGN.
put forward by a number of people (e.g., Carvalho 1985; Hodges & Mutel 1987; De Young 1993; Fanti et al. 1995; Begelman 1996; Readhead et al. 1996a, 1996b; Bicknell, Dopita, & O'Dea 1997; O'Dea & Baum 1997). Radio sources are proposed to evolve along the GPS — CSS — FRII sequence. The radio lobes are over-pressurized cocoons of hot gas and plasma which are continuously fed by the jets. A more or less constant expansion speed is obtained due to the balance between pressure and ambient density decline as the source expands (Readhead et al. 1996a,b). This concept leads to a problem with the relative number densities of these objects observed in the universe. For a linear expansion rate with time, the larger objects evolve more slowly in size, since the fractional expansion rate is inversely proportional to physical size. This means that the large FRII sources should be far more prevalent than the small GPS sources. This is not the case. About 10% of the powerful radio galaxies are GPS, whereas based on size, one would expect ~0.1% of the total population, a discrepancy of 2 orders of magnitude (O'Dea & Baum 1997). This has a few implications. Perhaps the initial assumption of constant expansion rate is wrong, and GPS sources initially advance slower than FRII sources, although this seems unlikely (Readhead et al. 1996a, 1996b). Alternatively, the majority of GPS sources may never evolve into larger sources but instead stay confined to their small size. A third possibility is that the GPS sources do evolve into CSS's and FRII’s, but they decline significantly in radio luminosity as they increase in size (Fanti et al. 1995, O'Dea & Baum 1997); in this way almost all GPS sources would be included in a flux limited sample, but only a few of their resulting FRII’s. This effect artificially inflates the fractional GPS content. In this third scenario, due to the radio luminosity decline, the progenitors of the FRII’s that are included in flux-limited samples must have been extremely luminous, but
also very rare GPS sources (0.1% of the total FR II population) – on the order of one in the whole sky. The fact we currently do not observe such an object is consistent with this.

1.3 Thesis Project

The aim of this thesis is to study the origin and nature of powerful extragalactic radio sources, with emphasis on understanding the connections between compact, possibly young sources, and the large-scale radio galaxies. Since we already know the radio morphological properties to be almost identical, we focus on the underlying host galaxy. The study of this galactic environment into which the radio source is expanding enables us to distinguish between the various proposed scenarios. For instance, a dense cocoon of gas and dust that some modelers propose to confine the GPS sources will have different extinction properties compared to FR II sources, in which no such medium exists (because the radio source successfully expanded). These differences are best studied in the (near) infrared, where they would give rise to distinct color properties. If, on the other hand, GPS sources do evolve all the way into FR II sources, we expect the physical properties of the underlying host galaxies of GPS and FR II sources to be similar. The typical life-times for these radio structures are on the order of 10^7-10^8 year, significantly shorter than the stellar evolutionary timescale of a few Gyrs. The radio structure therefore expands inside a well evolved stellar system, and if we ignore the instantaneous effects of radio–ISM interaction (like the alignment effect\(^3\)), the overall emission properties of these systems should be identical. Provided the proper instrumentation, these effects can be verified.

The Hubble Space Telescope (HST) has made it possible for the first time to match radio and optical angular resolutions (at ~50 milli-arcseconds), enabling detailed examination of the optical and near-infrared morphologies of the host galaxies of these radio sources, as well as investigating the effect the expanding radio plasma has on its ambient gaseous medium. Where appropriate, we augmented our space-based data by ground-based imaging and spectroscopy.

1.4 Thesis Outline

Before one can consider including a suitable radio source into a comparative sample, a few basic facts have to be established. First of all, what is the optical counterpart to the radio structure? Given the faint nature of the high redshift hosts, this is a far from trivial question. Once properly identified, we need to know the redshift of the source as well, since quantities like absolute luminosity and size scale with redshift. The fraction of sources without identification or redshift determination was especially large among the compact GPS sources. In Chapter 2 we report on our identification and redshift program to resolve this problem with the GPS sample in preparation for the comparisons undertaken in subsequent chapters.

Chapter 3 discusses the radio properties of these GPS sources. It also tests whether differences exist between GPS galaxies and quasars (GPS sources optically associated

\(^3\) The observed spatial correlation between the optical and radio morphologies. Radio plasma shock-ionizes ambient gas into optical line-emission, cf. Chapter 5.
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with quasars). The next two chapters (4 and 5) deal with HST broad-band and line-emission imaging of CSS sources. With these data the interaction between the radio plasma and its ambient medium can be investigated. Under the free expansion model, significant levels of interaction are expected in GPS and CSS sources. The GPS class is too small to be successfully resolved by HST; the CSS's, on the other hand, have the ideal angular size for this kind of study (a few arcseconds). Also, the radio structure has not yet expanded beyond the confines of the host galaxy.

Chapters 6 and 7 report on our ground-based near-infrared imaging program. Host galaxies of GPS, CSS, and FR II galaxies are compared on their morphologies and color properties, and results are tested against the predictions by the various evolutionary scenarios. Furthermore, comparisons with stellar synthesis models are presented. Chapter 8 improves on this by discussing HST NICMOS data, also on a sample of GPS, CSS, and FR II sources. A summary of the main results and possible future projects are given in Chapter 9.