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Gas, star formation and active nucleus: a thesis summary

ABSTRACT — In this thesis we studied the interplay between host galaxy and radio source in nearby radio galaxies. In every chapter we investigated different topics related to this issue, using various observational techniques. In this final chapter we combine the gained results in order to get a complete picture of the questions that we can answer with this thesis and of the questions that are raised for future research.

7.1 Results, chapter by chapter

First we will shortly summarise the most important results obtained from each chapter:

Chapter 2: Radio galaxy B2 0648+27

- The early-type host galaxy of B2 0648+27 contains $8.5 \times 10^9 M_\odot$ of H I, distributed in a large-scale ring with a diameter of 190 kpc. The optical light throughout the galaxy is dominated by a post-starburst young stellar population (YSP) of age 0.3 Gyr. Together with the presence of tidal features in deep optical imaging (Heisler & Vader 1994), this indicates that this system formed from a major merger event.

- There appears to be a large time-delay between the initial encounter of the progenitor galaxies and the onset of the starburst activity. This can be explained if the progenitor galaxies already contained a bulge.

- There is also a large time-delay between the merger/starburst event and the onset of the current phase of radio-AGN activity.

- The YSP detected in B2 0648+27 is massive enough to have given this system the appearance of an (Ultra-) Luminous Infra-Red Galaxy at the first epoch after the starburst event. At present, B2 0648+27 is in an evolutionary stage between an (U)LIRG and a normal early-type galaxy.
Chapter 3: $H\text{I}$ properties of nearby, non-cluster radio galaxies

- For 25% of the early-type host galaxies in our complete sample of nearby, non-cluster radio galaxies (compact + FR-I) we detect large-scale $H\text{I}$ structures in emission.

- These $H\text{I}$ structures are mostly large-scale disk- and ring-like structures, with diameters up to 190 kpc and masses up to $M_{H\text{I}} = 1.8 \times 10^{10} M_\odot$. These large-scale disks/rings have regular kinematics, although a varying degree of asymmetry is visible in these structures.

- The origin of these $H\text{I}$ disks/rings is likely related either to major mergers or to cold accretion of the IGM.

- The large-scale $H\text{I}$ disks/rings are old (several Gyr), much older than the current phase of radio-AGN activity. We do not find clear evidence for ongoing mergers.

- Despite the small-number statistics, the properties (detection rate, morphology and total mass) of these large-scale $H\text{I}$ structures are similar to the properties of large-scale $H\text{I}$ structures around radio-quiet early-type galaxies.

- We find a segregation in large-scale $H\text{I}$ mass content between compact sources and extended FR-I sources in the sense that galaxies with large amounts ($\gtrsim 10^9 M_\odot$) of $H\text{I}$ detected in emission all have a compact radio source, while none of the extended, lobe-brightened FR-I sources in our sample contain similar amounts of large-scale $H\text{I}$.

- $H\text{I}$ absorption results of our sample sources show that $H\text{I}$ can also be present in the host galaxies of extended FR-I sources, but at much lower amounts than we detect around the host galaxies of some of our compact sources.

Chapter 4: Stellar populations in our $H\text{I}$-rich radio galaxies

- There is no clear one-to-one correspondence between the stellar populations and the presence of a large-scale $H\text{I}$ disk or ring in our sample galaxies. Some of the $H\text{I}$-rich radio galaxies show a young (or better: intermediate age) stellar population, while others contain only an old population.

- In contrast to the young stellar population in B2 0648+27, the young stellar populations in some of the other $H\text{I}$-rich radio galaxies that we investigated are are typically a few Gyr old. This agrees with the old age of the large-scale $H\text{I}$ disks/rings in these sources. Only in the optical disk of B2 0722+30 there appears to be ongoing star formation.

- There is a correspondence between the morphological type of the host galaxy and the presence/absence of a young/intermediate age stellar population. The two true ellipticals in our sample contain an old stellar population, while a younger component is detected in the three S0s.

- The sources with the youngest stellar populations are the most luminous infra-red sources in our complete sample.
• The strength of the young/intermediate age stellar populations that we find in our radio galaxies suggests that the radio galaxies could have gone through a (U)LIGR phase at the epoch of the starburst event.

Chapter 5: H I in the powerful FR-I/FR-II radio galaxy NGC 612

• $1.8 \times 10^9 M_\odot$ of H I is detected in emission in NGC 612. Most of the gas is distributed in a rotating structure, although the large velocity distribution suggest that this gas has not (yet) settled.

• The H I distribution – together with the presence of a young stellar population – is consistent with the scenario that NGC 612 formed from a major merger event roughly 1 Gyr ago (although other scenarios cannot be ruled out)

• Tails of H I are seen towards three small, nearby companions, indicating ongoing interactions of these three companions with NGC 612.

• Very faint H I debris is detected over a distance of 400 kpc in between NGC 612 and NGC 619.

Chapter 6: Feedback – jet-driven outflows of neutral and ionised gas

• We detect fast outflows (up to $\sim 1000$ km s$^{-1}$) of neutral and ionised gas in the central few kpc of two nearby, powerful radio galaxies. The mass of the H I gas that we find in these outflows is about $100\times$ higher than the mass of the outflowing ionised gas.

• These fast outflows of neutral and ionised gas are likely driven by interaction of the radio plasma with the surrounding ISM. Despite the high energies that must be involved in a jet-ISM interaction, much of the outflowing gas remains, or becomes again, neutral. This puts serious constraints on the models of jet-ISM interactions.

• These newly discovered outflows of neutral gas are, at least at the lower end, comparable to outflows induced by starbursts in ULIRGs. They could therefore be an important feedback process in galaxy evolution.

7.2 Main topics, main results

Although every chapter gives a number of interesting results related to the gas, the stars or the active nucleus in nearby radio galaxies, the strength of this thesis lies in combining these results in order to get a more complete story about the evolution of radio galaxies. In Chapter 1 (Sect. 1.5) we defined five main topics related to this thesis. Here we will summarise what our results contribute to a better understanding of these topics:

\textit{Are mergers the main mechanism for triggering the radio-AGN activity in radio galaxies, or do other processes need to be considered?}

For the moderately powerful compact and FR-I sources that we studied in this thesis, we find no evidence for ongoing or recent ($<$ 1 Gyr) major merger events. A few of these galaxies
show indications of an old ($\gtrsim 1$ Gyr) merger event, derived from large-scale H\textsc{i} structures and the presence of a post starburst stellar population (although the only galaxy for which we unambiguously verified a major merger is B2 0648+27). Two of our radio galaxies contain a large scale H\textsc{i} disk/ring, but show no evidence that a starburst event occurred in the last several Gyr. There are also many nearby radio galaxies for which there is no indication of a past major merger event. Our results suggest that mergers could be related to the occurrence of radio-AGN activity in some radio galaxies, but not in all (as we will see below, this might be related to the type of radio source).

In case of a merger, what are the timescales involved regarding the triggering of starburst and radio-AGN activity?

For the cases where a gas-rich major merger occurred, there is a large time-delay between on the one hand the merger and starburst event and on the other hand the onset of the current episode of radio-AGN activity. This strongly suggests that secondary physical processes (such as bar formation, mergers of individual black holes, additional tidal perturbations, etc.) are required to trigger the radio source. The fact that the H\textsc{i} properties of our sample sources (mass, morphology and detection rate) are consistent with samples of radio-quiet early-type galaxies, suggests that radio-AGN activity is a short (perhaps recurrent) phase that could occur at some stage during the lifetime of most (maybe all?) early-type galaxies.

Are particular triggering-processes related to the morphological appearance of the radio source (e.g. FR-I vs. FR-II sources)?

We find evidence for a trend that galaxies with a large-scale H\textsc{i} disk/ring (in one case, B2 0648+27, confirmed to have formed from a major merger) all have a compact radio source, while none of the extended FR-I sources in our sample contain similar amounts of H\textsc{i}. An H\textsc{i} structure similar to those found around compact sources is also present around the powerful FR-I/FR-II radio galaxy NGC 612. This suggests that, while major mergers might be important for the triggering of the compact sources, as well as the FR-I/FR-II source in NGC 612, the extended FR-I sources might be triggered in another way. A similar conclusion was proposed by Heckman et al. (1986) and Baum et al. (1992), who argued from optical studies that mergers are important for triggering powerful FR-II radio sources, but that FR-I sources are likely triggered in an alternative way, for example through the stored rotational energy of the black-hole, or by a cooling flows. Recently, also Best et al. (2006) discussed feeding of moderately powerful radio sources through cooling of the IGM, in which feedback controlled episodic behaviour of the radio sources regulates the balance between cooling and heating of the gas in these systems.

Does the (re-)distribution of the ISM influence the radio source properties (e.g. compact vs. extended sources)?

We proposed several possible explanations for the segregation in large-scale H\textsc{i} mass content between the compact and extended radio sources in our sample. Based on the observational result in Chapter 3, the most likely explanation for this segregation is either that the radio jets ionise/heat the gas when they penetrate outward, or that the radio sources in the H\textsc{i}-rich systems do not grow into extended sources, either because they are frustrated by the ISM, or because their fuelling is inefficient. In Chapter 5 we show that NGC 612 both has a pow-
erful, extended FR-I/FR-II radio source, as well as a large-scale H I structure similar to the H I structures seen around some of our compact sources. This suggests that jet-ionisation is not a likely scenario for the observed trend, unless the FR-I sources in our sample are much more efficient in ionising/heating the gas than the more powerful radio source in NGC 612. Therefore, the segregation in large-scale H I mass content between the compact and extended radio sources in our sample is most likely related to the distribution of the (neutral) gas, both at large scales as well as in the central region of the radio galaxies. If a major merger created the H I-rich systems, possibly enough gas was funnelled into the central region in order to frustrate the radio source. Alternatively, non-steady fuelling of black hole may have caused the radio source to be switched off on a relatively short time-scale (or possible switched on and off recurrently). This could be the result of a complex gas distribution in the central region (created by the merger event), or of feedback by the AGN itself. As we saw in Chapter 6, powerful radio jets may drive out massive outflows of neutral and ionised gas from the central region. Although the compact radio sources from Chapter 3 are not as powerful as the two 3C sources studied in Chapter 6, it is nevertheless thinkable that the compact radio sources drive away their own gas supply, which turns them off before they can grow into extended sources. If FR-I sources are not triggered by mergers, but fuelled through a process of steady gas accretion (in which the gas supply is not terminated through feedback effects on such short time scales), they may have the time to grow far beyond the host galaxy.

What are the feedback effects of the radio source on the host galaxy?

The presence of a (powerful) radio source may have an important influence on the distribution of the ISM in radio galaxies. In particular in the case of a merger event, it is likely that there is a dense ambient ISM deposited in the central region of the galaxy. Feedback effects from the active galactic nucleus can have a major effect on the distribution of this ISM. Our results from Chapter 6 show that powerful radio jets can drive out gas from the central region in much larger amounts than so far expected. This is because most of the outflowing gas is in its neutral state and only a fraction of it is ionised. Taking into account these newly discovered neutral outflows, outflow rates due to jet-ISM interactions are of an order similar to stellar-wind driven outflows in starburst galaxies. The role of radio-AGN activity in galaxy evolution can therefore be much larger than often assumed.

7.3 Future outlook

Although this thesis has contributed to solving a number of fundamental issues related to the origin and evolution of nearby radio galaxies, there are also a number of questions raised for further research. Below we list the main questions and we shortly describe how to approach them in future projects:

- **How can large-scale H I disks/rings around early-type galaxies be formed?**

  Although Barnes (2002) showed that mergers can create large-scale H I disks or rings around early-type galaxies, it would be worth to investigate the observed H I disks/rings in more detail. By modelling the observed H I disks/rings that we find in some of our radio galaxies, it might be possible to gain a better insight in the formation of these structures, and in particular in the timescales involved. Also, although we concluded that at least in one case (B2 0648+27) the large-scale H I ring that we observe is the
result of a past merger event (given also the stellar content and the presence of very faint optical tails), this is not apparent for all other cases. It is important to study in more detail alternative mechanisms that may form large-scale H\textsc{i} disks or rings around early-type galaxies. For example, it would be worth to investigate in more detail whether the cold accretion scenario can indeed form very low-temperature H\textsc{i} structures that display regular rotation, and whether or not star formation is triggered during this process.

Beside this, it will be essential to study the optical morphology of the early-type host galaxies in more detail, in order to investigate the presence of optical tidal debris or a faint stellar disk in these systems. To investigate how long the H\textsc{i} structures that we detect may survive, it will be important to see if a low level of star formation (which we can not detect with our used method) is occurring locally in these disks (for example by taking UV observations of these H\textsc{i} disks/rings).

- **In what sense does the triggering mechanism of FR-I sources differ from that of the more powerful FR-II sources?**

  Although we do not find evidence for gas-rich mergers related to FR-I sources, our observations also do not provide evidence for an alternative triggering mechanism. It would be worth - if possible - to optimise future observations for tracing alternative triggering mechanisms of these FR-I sources, such as cooling flows, dry mergers or minor interactions.

  It is also necessary to study the more powerful FR-II radio galaxies. In this thesis we only imaged H\textsc{i} in one radio galaxy with FR-II properties (NGC 612). Although this source has H\textsc{i} properties different from the FR-I sources that we observed, it is impossible to draw general conclusions on the study of a single object. The fact that NGC 612 is has hybrid FR-I/FR-II radio source morphology complicates the comparison even further. On the other hand, also the powerful FR-II radio galaxies 3C 293 and 3C 305 (Chapter 6) have often been suggested to be related to a major merger. It is therefore necessary to image in H\textsc{i} a well defined sample of powerful FR-II sources.

- **What is the exact cause of the segregation that we find in large-scale H\textsc{i} mass content between compact and extended nearby radio sources?**

  First it will be important to distinguish between the various proposed scenarios for this segregation. Observations at other wavelengths can be useful in this respect. With optical narrow band imaging we can study the ionised gas, while X-ray observations can trace hot gas in and around our radio galaxies. This can be important tools to investigate the possibility of jet-ionisation or -heating. Deep optical imaging is necessary to look for optical peculiarities that could be related to a recent major merger event. CO observations can be useful to study the molecular gas, which often assembles in the centre of the galaxy during a gas-rich merger event (and which may also serve as fuel for starburst and AGN activity). Large amounts of molecular gas might therefore provide additional evidence of a past merger event and might also be important for frustrating the radio source. A detailed literature study of the available information at other wavelengths, together with new observations, would be a logical next step for further investigating our current sample of radio galaxies.
But more fundamental, does this trend relate only to the size of the source, or is it in fact related to the type of radio source? What is for example the case for more powerful FR-II sources and for powerful compact (GPS and CSS) sources? An extension of our sample, also with these more powerful radio sources, is necessary to investigate this in more detail.

- **How do the H\text{I} properties of radio-loud relate to those of radio-quiet early-type galaxies?**

  Although our H\text{I} study revealed no difference in H\text{I} properties between the host galaxies of radio-loud and radio-quiet early-type galaxies, larger samples with comparable sensitivity are necessary to derive more accurate statistics in order to verify this result (see also Sect. 3.6.4).

- **How can theory explain the neutral gas outflows?**

  The large amounts of neutral gas involved in jet-driven outflows that we find in two 3C radio galaxies are not obviously consistent with current theoretical models of jet-ISM interactions. As discussed in detail in Sect. 6.5.1 and 6.6.4, the high energies involved in jet-cloud interactions are thought to ionise the cloud material as it is being expelled, although rapid cooling might turn substantial amounts of gas back into its cold state. However, the magnitude of these predicted outflows of cold gas are much less extreme than the outflows of neutral gas that we observe. Now similar outflows are being detected also in other radio galaxies (Morganti et al. 2005), it is necessary to bring into line observations and theory on jet-ISM interactions. In this light it would be worth to investigate whether the physics of jet-ISM interactions can be constrained by our detected outflows of neutral gas.

### 7.3.1 Ongoing projects

We recently started two new projects, which are aimed at addressing some of the above mentioned issues. Here we describe them shortly:

**Neutral hydrogen in SDSS radio galaxies**

In collaboration with R. Morganti, P. Best, T. Heckman, T. Oosterloo and G. Kauffmann we are involved in a project to image in H\text{I} a sample of well defined types of radio sources (some of type FR-II) from the Sloan Digital Sky Survey (SDSS). The SDSS has a wealth of optical data (both imaging and spectroscopy) already available, which can be used to study for example the stellar content of these radio galaxies. Observations of these sources have recently been done with the Westerbork Synthesis Radio Telescope.

**Fast neutral outflows in radio galaxies: a major source of feedback in galaxy formation?**

In collaboration with C. Tadhunter and R. Morganti we are involved in a project to study the neutral optical absorption line NaID in nearby radio galaxies. This allows us to look for neutral outflows in radio galaxies, without having to rely on underlying radio continuum (as is the case for H\text{I} absorption). In principle, we can therefore look for neutral outflows in every radio galaxy and at every location within the galaxy where the optical continuum is strong.
enough. This may provide additional information about the exact driving mechanism of the outflows. Observations for this project have recently been completed successfully with the ISIS long-slit spectrograph at the WHT.

A similar study on the NaID line has been done by Rupke et al. (2002) in starburst galaxies. We will be able to compare our study of neutral outflows in radio galaxies with the outflow-studies of Rupke et al. (2002) in order to compare the relative contribution from the feedback induced by starbursts and that induced by radio sources.

7.3.2 Long-term outlook

Detailed knowledge about the interplay between the radio source and its host galaxy in the nearby universe (where we can study triggering and feedback processes in great detail), is vital for understanding radio galaxy evolution at high redshift. Our study of the neutral hydrogen gas and stellar populations in nearby radio galaxies could be useful for future projects with the next generation radio telescopes, such as the Low Frequency Array (LOFAR), the Atacama Large Millimeter Array (ALMA) and the Square Kilometre Array (SKA).

LOFAR

The Low Frequency Array (LOFAR), is a new-design radio telescope working in the low-frequency radio regime ($\sim 10 - 240$ MHz). LOFAR is being developed in a consortium led by ASTRON (Netherlands Foundation for Research in Astronomy) and is aimed to start operations in 2008. One of its main tasks will be to map the neutral hydrogen out to a cosmological redshift of $z \sim 11.4$. This will be the first instrument to study the neutral hydrogen gas from which the first stars and galaxies were formed, which lit up the universe during the so called epoch of reionisation. Besides this, LOFAR will also be used to look for the most distant radio sources and to trace H I in absorption against these sources. LOFAR will therefore give us a better insight in the both the neutral gas and powerful radio sources (and the interplay between them) in the Early Universe.

ALMA

The Atacama Large Millimeter Array (ALMA), currently under construction in the Atacama desert in Chile, is going to be the forefront instrument for studying cold molecular gas and dust in the universe. The ALMA array consists of movable dishes that can cover baselines between 150m and 12km and that have receivers working in the frequency range from 30 to 950 GHz. In its most extensive configuration, the instrument achieves sub-arcsec resolution. In its most compact configuration, it is sensitive to detect CO emission in normal galaxies up to $z \sim 3$ within 24 hrs of observations. Once completed in 2011, ALMA may be the perfect instrument to look for molecular gas in the central regions of large samples of radio galaxies in order to trace past merger events and to search for possible sites of star formation that may be embedded deep within these systems.

SKA

The Square Kilometre Array (SKA) is going to be the next generation super radio-telescope that, besides studying the formation of the Early Universe, will also allow a detailed mapping of H I emission in a large number of powerful radio galaxies. As already mentioned in Sect. 3.2, the largest disadvantage of imaging neutral hydrogen gas in emission in radio galaxies, is
that the current day telescopes are sensitive only to study the nearest radio galaxies (because sensitivity drops as $D^2$, with $D$ the distance to the galaxy). Since radio galaxies are sparse in the Local Universe, this means that we can only observe a limited sample. In particular the powerful radio galaxies of type FR-II, which are generally found at higher $z$, are very limited in number up to distances for which detailed H\textsc{i} imaging is feasible these days. SKA is going to be a revolutionary new-technology telescope, with an effective collecting area of 1 km$^2$, of which about half is concentrated within a central region of 5 km in diameter and the other half is spread across 150 stations that cover a distance of about 3000 km. This gives the SKA an unprecedented view (both in sensitivity and in spatial resolution) of H\textsc{i} gas in galaxies up to $z \sim 1.5$. This will allow for a very detailed study of the H\textsc{i} characteristics of all types of radio galaxies, as well as accurate statistical studies of H\textsc{i} in both radio-loud and radio-quiet early-type galaxies. At the moment SKA is in its design-study phase, and full operations are planned for 2019. Once SKA gets on-line, new H\textsc{i} studies will undoubtedly dramatically change our view of the Universe.

\textbf{Figure 7.1:} Artist impression of the Square Kilometre Array (SKA). In this concept the SKA consists of planar aperture arrays for the low frequencies combined with small, steerable dishes for the intermediate and high frequencies. The SKA will consist of multiple stations (100-200m in diameter) that are spread over 3,000 km and that, together, will have a total collecting area of 1 km$^2$. \textit{Credit: SKA – ASTRON}