Spectroscopy and nuclear dynamics of starburst galaxies
Vermaas, L.

1 Introduction

1.1 Starburst galaxies

The term ‘starburst’ denotes a period of star formation at a very high rate. In a normal spiral galaxy, star formation occurs in the spiral arms with a rate of $\sim 1 M_{\odot}\mathrm{yr}^{-1}$ (for the whole galaxy), while in a starburst galaxy this rate can be $10-100 M_{\odot}\mathrm{yr}^{-1}$ for a normal starburst galaxy, up to $10^2-10^3 M_{\odot}\mathrm{yr}^{-1}$ in the more extreme (merging) galaxies, like Ultraluminous Infrared Galaxies (ULIRGs, see section below). One thing they have in common is that the burst can only be sustained for a limited period of time, typically 10^7-10^8 years, until the gas supply for star formation is exhausted.

Starbursts are commonly associated with galaxy interactions and can occur in locations spread over the whole galaxy, but often the burst is confined to a region of a few$\times$100 pc near the galaxy nucleus. In most cases collisions of clouds are the scene of enhanced star formation, with the collisions occurring either in perturbed disks or between clouds originally belonging to different galaxies. In some cases the interacting galaxies are far apart and the disks are rather undisturbed, so that internal effects of tidal stress must be responsible. One example of how galaxy interaction can induce star formation without signs of direct merging is in the presence of a bar: the companion induces the formation of a bar, which in some cases can last much longer than the encounter itself. This can help substantial amounts of gas from the outer parts to loose angular momentum and reach the nuclear region, possibly leading to a nuclear starburst. Another example is a companion that can perturb the disk potential causing the gas to collapse. This is supported by the fact that the regions in spiral galaxies where star formation is observed coincide with regions in which gas is unstable by the Toomre (dynamical) criterion (Toomre 1964).

A starburst can be recognised by several characteristics. Starbursts have spectra similar to those of HII-regions, with strong recombination lines, e.g. the Balmer, Paschen and Brackett series. They can be luminous in the blue and ultraviolet (UV), because of the contribution from massive young stars, but also, and even more, in the infrared, because of the dusty environment in star forming regions, with the dust absorbing the UV radiation and re-radiating it at longer wavelengths. There may be strong radio continuum emission as well, in the form of thermal radiation from HII-regions or non-thermal synchrotron radiation from supernova remnants.

The absorption of radiation by dust is a serious problem when observing starburst galaxies. The solution is to move to infrared wavelengths, the near-infrared (1.0-2.5 μm), where extinction is less but stellar light is still observed, or at longer wavelengths in the mid- and far-infrared, where it is possible to look further into the dust.

1.2 Ultraluminous Infrared Galaxies (ULIRGs)

Ultraluminous infrared galaxies (ULIRGs) share the definition that they are very luminous and emit the bulk of their energy in the infrared, with $L_{\mathrm{IR}} \geq 10^{12} L_{\odot}$, but they have much more in common. This luminosity criterion selects merging galaxies or merger remnants with large amounts of molecular gas, while the infrared luminosity is predominantly powered by star formation rates as high as $10^2 - 10^3\, M_\odot \mathrm{yr}^{-1}$, although a central AGN may also contribute to the nuclear power.

ULIRGs can be divided into two groups by their infrared colours, often expressed by the ratio of flux in the $25\,\mu$m and the $60\,\mu$m bands: "cool" ULIRGs have a typical ratio $f_{25}/f_{60} \leq 0.10$, whereas "warm" ULIRGs have $f_{25}/f_{60} > 0.2$. The warm ULIRGs have more compact and brighter nuclei compared to cool ULIRGs.

It has been proposed that cool ULIRGs are dust-obscured precursors of Quasi Stellar Objects (QSOs) (e.g. Sanders et al. 1988). On this evolutionary path, the AGN disperses the dust and gas, shifting the bulk of energy toward shorter wavelengths (the cool ULIRG gradually becomes a warm ULIRG), AGN feedback terminates star formation, and the ULIRG eventually becomes an optically bright QSO. This is also a conceptually simple explanation for the relation that has been found between stellar mass and black hole mass of spheroid systems like bulges of galaxies and ellipticals. This mechanism is explained in the next section.

ULIRGs and the AGN-starburst connection

It has been discovered that in spheroidal systems, the mass of the central black hole and the stellar velocity dispersion (or black hole mass and stellar mass) are related, suggesting a relation between starburst and AGN, the AGN-starburst connection (Magorrian et al. 1998, Ferrarese & Merritt 2000, Gebhardt et al. 2000). This relation should be established at the time of their formation. ULIRGs have high star formation rates, $10^2 - 10^3\, M_\odot \mathrm{yr}^{-1}$, and often host an AGN as well, and since we assume them to be ellipticals in formation, we may consider this process to be similar to that of the formation of old ellipticals in earlier times. Several studies have addressed this topic, indicating that local ULIRGs evolve into intermediate mass ellipticals rather than giant ellipticals (e.g., Genzel et al. 2001, Tacconi et al. 2002). Direct influence of the black hole on star formation would be the key to establishing the relation between the black hole mass and the stellar mass. The black hole grows by consuming its environment and stellar content grows by vigorous star formation. At some point the black hole becomes so massive that its feedback expels the gas, causing star formation to stop. But the dispersal of the gas also stops the growth of the black hole. The stellar mass is then given by the integral of star formation over time during the ULIRG phase, the black hole mass by the integral of accretion rate over time.

In the beginning of the merging process, the gas components flow towards the centre of the system very efficiently because the gas can dissipate mechanical energy, while the stellar components merge much slower by dynamical friction, the stars do not collide themselves. It has been shown that in ULIRGs the gas rotates regularly in a disk or a ring, showing a rotation that flattens at about 0.5 kpc or smaller (e.g., Downes & Solomon 1998). Such a molecular disk is initially stable against star formation, but as surface density continues to build up, it will get unstable and start to form stars. Because of the local conditions, the critical density that needs to be reached for unstability is very high and when star formation starts, this will be in a burst at a very high rate. This process, too, can destroy the disk and disperse the gas, and the AGN that was previously hidden, becomes visible. This theory is described by Elmegreen (1994).

ULIRGs and the fundamental plane

Elliptical galaxies are a class of objects with surface brightness that can be well described by the surface brightness and a characteristic radius. The De Vaucouleurs' $r^{1/4}$ law fits this profile very well: $I(r) = I_0 \exp(-r/r_0)^{1/4}$. It is common to use the effective radius $R_{\rm eff}$, the radius that contains half of the total light, and the surface brightness at this radius, $I_{\rm eff}$. Together with the central stellar velocity dispersion, σ_0, these parameters are closely related and the elliptical galaxies lie on the empirically found fundamental plane (FP). The physical explanation for this relation is that these elliptical galaxies are self-gravitating systems with roughly constant mass-to-light ratios.

If ULIRGs indeed evolve into elliptical galaxies, they should also show the characteristic scaling relations of elliptical galaxies and lie on the fundamental plane, or they should lie close with plausible evolution towards the FP. However, the location of a galaxy with respect to the FP depends on its mass to light ratio (M/L), and an important evolving young stellar population will have a different M/L than a quiescent elliptical galaxy.

1.3 This thesis

The aim of this work is to study starbursts and the dynamical processes involved, both from gas and stellar components. For this purpose, we selected a galaxy with a nuclear starburst, M83, that is nearby (D=4.5 Mpc), in order to be able to study processes in detail. This is described in **Chapter 2**. We observed the central region of 330×330 pc, which includes the optical peak, and a starburst that is displaced from the nucleus, as well as several young star clusters. Star formation is traced by Brγ, the molecular gas by H_2 (2.12 μm), and [FeII] emission features indicate shocks from supernova remnants, which are spread over the whole observed region, all stages of (massive) star formation can thus be localised. The stellar population code Starburst99 is used to determine ages of the young star clusters. All this plus the gas and stellar velocity fields contribute to our understanding of this galaxy, but also show that these regions can have complex structures while starburst triggering mechanisms are not always easily understood.

The next goal was to place this in a wider context and we observed a sample of 6 ULIRGs to test if we can find signs of ULIRG evolution as described above. In **Chapter 3** we first describe the nearby (the nearest, z=0.018 or D=78 Mpc) cool ULIRG Arp 220. In this ULIRG-merger both nuclei of the progenitor galaxies are still recognisable and the spatial resolution is relatively high, compared to more distant ULIRGs. Various studies have investigated the origin of the infrared luminosity, provisionally indicating that the starburst is the (major) power source. We show that the two nuclei can still be recognised as dynamically independent entities, while most of the gas is already rotating in a single disk. We derive dynamical masses both from stellar dynamics and from gas dynamics and derive the near-IR mass-to-light ratio, which is used to roughly constrain the age of the starburst.

The other 5 ULIRGs of the sample, though local, are more distant with redshifts ~0.04-0.12. They were selected to have a range in infrared colours (thus presumably stages of merging or evolution). All are classified as merger end-products with only one peak observed in the (near-)infrared. However, we keep in mind what the nuclear region of a ULIRG can look like when observed with higher spatial resolution, as in the case of Arp 220. In Chapters 4 and 5, the rest of the ULIRG sample is described.

In **Chapter 4**, we focus on the stellar kinematics of the ULIRGs in the sample. Dynamical masses are calculated according to a model that approximates these objects as spherical bodies, a method that has been used in several studies before. The near-infrared (K-band) mass-to-light ratios are determined and are used to constrain the age of the starburst, as in the case of Arp 220.

In **Chapter 5**, we used the velocity fields of Paα and/or H_2 for determination of the gas rotation curves. These curves were modelled with a spheroid (bulge) and a disk component. We used this model to derive the dynamical mass from gas kinematics, and compared these (and the mass-to-light ratios) to those from stellar dynamics. We argue which mass determination is the most reliable and finally, we placed the ULIRGs in (a projection of) the fundamental plane to find their location with respect to the elliptical galaxies that they are supposed to evolve into.

All observations were done with SINFONI, the Spectrograph for integral field observations in the Near-Infrared which is mounted on UT4 of the VLT on mount Paranal, Chile. All ULIRGs were observed with use of the laser guide star (LGS) facility for adaptive optics (AO), in order to achieve the best possible spatial resolution.

1.4 Conclusions and outlook

M83 From the analysis of the nuclear region of M83, we conclude that there is a separation between a compact and a diffuse component with large percentages in the diffuse emission in most lines. From our data in the central 330x330 pc, the diffuse component of [FeII] is 74%, the diffuse component of Brγ is 30% and the diffuse component of H_2 is 75%. The optical peak does not correspond to the dynamical centre. The gas dynamics show a rotating ring of gas, while the stellar dynamics show a different rotation pattern of regular rotation.

ULIRGs For the sample of 6 ULIRGs we compared the gas and stellar dynamics. The derived velocity fields are of excellent quality, and with the integral field spectroscopy it is possible to define the kinematic major axis with great confidence, which is which is a big improvement compared to older slit data studies. Even when our results are comparable to these literature data, these data give better accuracy. We conclude from our ULIRG analysis that

- the stellar dynamics is generally the better tracer of the mass than the gas dynamics, because the gas can still have disturbed morphology from the merger event. However, if the gas shows regular rotation and if an independent measurement of the gas mass is available (e.g. from mm CO observations), the gas kinematics can be used to derive the total mass which then agrees with the mass from stellar dynamics with high accuracy.

- there is no clear connection between the infrared colour (f_{25}/f_{60}) and K-band mass-to-light ratio (M/L_K); we explain this by concluding that we are observing the age of the most recent staburst in stead of age of the system.
- the ULIRGs are offset from the fundamental plane by M/L_K, and passive evolution (the increase of M/L) will put the ULIRGs on the FP on the location of intermediate mass ellipticals, and not giants.

Outlook This study is far from completed. For most targets, our data provide a wealth of information, which has not been used fully. Several spectral lines in the ULIRG spectra, e.g. from H_2, are left out of this study but could contain interesting information about the circumstances in these objects. More effort should be put in investigating the proposed sequence from cool to warm ULIRGs, which has still not been proved. The power of integral field spectroscopy (with adaptive optics) is essential for this purpose. The next thing that would be interesting to study in this sense is the ratio of gas mass to stellar mass, $M_{\rm gas}/M_{\rm stars}$. While the gas mass and stellar mass *an sich* highly depend on the properties of the merger progenitors, $M_{\rm gas}/M_{\rm stars}$ should decrease in an evolutionary sequence because the gas is consumed and the stellar mass is being built up. It would be worthwile to work this out for a sufficiently large sample in the near future.

References

Downes, D. & Solomon, P. M. 1998, ApJ, 507, 615
Elmegreen, B. 1994, in Violent Star Formation from 30 Dor to QSOs, ed. T. G.
Ferrarese, L. & Merritt, D. 2000, ApJ, 539, L9
Gebhardt, K., Bender, R., Bower, G., et al. 2000, ApJ, 539, L13
Genzel, R., Tacconi, L. J., Rigopoulou, D., Lutz, D., & Tecza, M. 2001, ApJ, 563, 527
Magorrian, J., Tremaine, S., Richstone, D., et al. 1998, AJ, 115, 2285
Sanders, D. B., Soifer, B. T., Elias, J. H., et al. 1988, ApJ, 325, 74
Tacconi, L. J., Genzel, R., Lutz, D., et al. 2002, ApJ, 580, 73
Toomre, A. 1964, ApJ, 139, 1217