8

Conclusions and outlook

A key question in astronomy is the interrelationship of mergers, starburst and AGN activity. In this thesis, I have focussed on infrared observational diagnostics of the energetic phenomena in the nuclei of ULIRGs and the insight they provide into the ultimate energy source of such objects. The main conclusions are summarized here and an outlook for future research is presented.

The mid-IR characteristics of energetic phenomena in (U)LIRG nuclei

In order to address the issues mentioned above, good infrared tracers of the different energetic processes in the nuclei have to be identified. The bulk of this research is based upon mid-infrared spectroscopy of a sample of \sim 250 normal galaxies, starburst galaxies, Seyferts, QSOs and ULIRGs. The spectra were obtained using the spectrometers SWS, PHT–S and CAM–CVF onboard ISO, at spectral resolutions of *R*=1500, 90 and 35, respectively (Chapter 2). The sample has been appended with groundbased L- and M-band spectroscopy for the nucleus of one of the nearest starburst galaxies, NGC 4945 (Chapter 4).

Ice absorption features are a common characteristic of low temperature molecular gas seen against a bright background source. The composition of the ice is strongly related to thermal and energetic processing by the background source. This is reflected in observed ice absorption spectrum. The profile of the solid CO band reveals the importance of thermal processing of the ice, while the prominence of the XCN band attests to the importance of energetic processing of the ices by energetic photons and/or particles.

Based on my sample, we found that water ice is present in most of the ULIRGs, whereas it is weak or absent in the large majority of Seyferts and starburst galaxies. The ice galaxy spectra seem to form a sequence from strongly ice and silicate absorption dominated spectra to strongly PAH emission dominated spectra. The spectral variation shows strong similarities with Galactic star forming clouds. This leads us to believe that this sequence might reflect an evolutionary sequence from strongly obscured beginnings of star formation (and AGN activity) to a less enshrouded stage of advanced star formation (and AGN activity).

The $6-12 \mu m$ spectrum of NGC 4418 is dominated by deep absorption features of water ice and methane ice, Hydrogenated Amorphous Carbon (HAC) and silicates against a fea-

tureless mid-infrared continuum. The spectrum closely resembles that of embedded massive protostars in our Galaxy. From the depth of the absorption features it is infered that the powerful central source responsible for the mid-infrared emission must be deeply enshrouded. Since this emission is warm and originates in a compact region, an AGN must be hiding in the nucleus of NGC 4418. The overall shape of the NGC 4418 6–11 μ m spectrum shows a 'false' emission peak at 7.7 μ m, which mimicks at first glance a PAH spectrum. The need for high S/N spectra is obvious to clearly distinguish between bona fide PAH spectra and absorption dominated spectra.

The 3–6 μ m nuclear spectrum of starburst/Seyfert-2 galaxy NGC 4945 shows, in addition to PAH emission, deep absorption features of water ice, CO₂ ice, OCN⁻ ice and CO ice. Tracers of AGN activity are not detected. Analogous to the processing of ices by embedded protostars in our Galaxy and assuming the AGN to be deeply buried, the processing of the ices in the center of NGC 4945 is attributed to ongoing massive star formation.

PAH emission features are generally assumed to be tracers of exposed star formation. We have investigated this assumption for a sample of Galactic regions of massive star formation on the basis of a MIR/FIR diagnostic diagram of far-infrared normalized 6.2 μ m PAH flux versus far-infrared normalized 6.2 μ m continuum flux. Within this diagram the Galactic H II regions span a sequence from embedded compact H II regions to exposed PDRs. The 6.2 μ m PAH band-to-continuum ratio is remarkably constant over this range. We have compared our extragalactic sample to these Galactic sources. This revealed that normal and starburst galaxies have a uncanny resemblance to reflection nebulae. While Seyfert-2's coincide with the starburst trend, Seyfert-1's are displaced by a factor 10 in $6.2 \,\mu$ m-continuum flux. This is in accordance with AGN unification schemes. ULIRGs show a diverse spectral appearance. Some are found with the Seyfert-1's. More, however, are either starburst-like or show signs of strong dust obscuration in the nucleus. The latter group is displaced with respect to all other galaxy types towards the position of embedded massive protostars and the deeply enshrouded nucleus of NGC 4418. One characteristic of the ULIRGs seems also to be the presence of more prominent far-infrared emission than either starburst galaxies or AGNs. We have examined the use of PAHs as quantitative tracers of star formation activity. Based on these investigations, we find that the PAH emission of normal and starburst galaxies is best represented by that of exposed PDRs associated with reflection nebulae such as the Orion Bar and NGC 2023. However, the infrared spectra of some sources — notably the architypal ULIRG Arp 220 — may be dominated by embedded massive star formation rather than exposed PDRs. NGC 4418 may be an even more extreme example of such buried star formation, where even the faintest traces of PAH are lacking.

Embedded AGN and starburst activity

The near- and mid-infrared spectrum of NGC 4945 does not provide any evidence for the existence of the powerful AGN, inferred from hard X-ray observations. The upper limits on our AGN tracers $3.94 \,\mu\text{m}$ [Si IX], $7.65 \,\mu\text{m}$ [Ne VI] and $14.3 \& 24.3 \,\mu\text{m}$ [Ne V] imply an A(V)>160 towards the NLR, assuming the NLR to be of equal strength as in the Circinus galaxy.

NGC 4418 has a very compact (r<15–40 pc) luminous ($L_{\rm IR} \sim 10^{11} L_{\odot}$) nucleus, which reveals no sign of AGN or starburst activity at mid-infrared wavelengths. The compactness of the nucleus suggests that an embedded AGN is responsible for the very high luminosity.

Arp 220 does not reveal any sign of an AGN either, not even in hard X-rays or in radio continuum emisson. The radio emission instead reveals several emission 'knots' across the two nuclei, which are interpreted as luminous radio supernovae. PAHs as tracers of exposed star formation are strongly underluminous with respect to the far-infrared luminosity. Spectral decomposition of the $6-12 \,\mu\text{m}$ ISO spectrum suggests that 40% of the $6-12 \,\mu\text{m}$ flux is associated with an NGC 4418-like absorbed continuum component and 60% with a weakly absorbed starburst component. The PAH emitting and heavily dust/ice absorbed components are tentatively associated with the diffuse emission region and the two compact nuclei respectively identified by Soifer et al. (2002) in their higher spatial resolution 10 μ m study. Both the similarity of the absorbed continuum with that of embedded Galactic protostars and results of dust modeling imply that the embedded source(s) in Arp 220 could be powered by, albeit extremely dense, starburst activity. Due to the high extinction, it is not possible with the available data to exclude that AGN(s) also contribute some or all of the observed luminosity. In this case, however, the upper limit measured for its hard X-ray emission would require Arp 220 to be the most highly obscured AGN known.

Outlook

The research presented in this thesis has opened a number of research lines that should be explored in the future. For instance, the role of embedded star formation has to be further explored. The high interstellar pressure in the central region of ULIRGs may limit the expansion of UCH II regions and the development of the normal bright signposts of star formation. Further diagnostic tools have to be developed for the study of such regions. In Chapter 4, we have demonstrated by the example of NGC 4945 that medium resolution (R=3000) M-band spectroscopy is a viable option to study the molecular environment in nearby galactic nuclei. Similar studies of other starburst nuclei are needed to determine whether the conditions probed in NGC 4945 are extreme or typical for starburst nuclei. With respect to AGNs, the energetic processing of (ices in) the molecular torus needs to be investigated.

The recent launch of the *Satellite InfraRed Telescope Facility* (SIRTF) marks the start of a decade in which infrared and submillimeter astronomy will undergo an authentic revolution. Space-based missions such as the *Herschel Space Observatory* (HSO), the *James Webb Space Telescope* (JWST), new groundbased facilities as the *Atacama Large Millimeter Array* (ALMA) and new VLT instruments like the *VLT Imager and Spectrometer for the mid-InfraRed* (VISIR) will, together with SIRTF, be the cornerstones of the future investigation of starburst and AGN activity in the Early Universe.

Particularly, the IRS spectrograph on SIRTF will provide medium-resolution (R=600) spectroscopy in the 10–37 μ m range and low-resolution (R=50) spectroscopy in the 5–40 μ m range. IRS is therefore ideally suited to measure the emission line spectra of AGN and starburst phenomena, while PAH emission bands and ice absorption features can be observed at lower resolution. As a bonus, beyond z=0.6, all important near-infrared ice absorption bands are redshifted into the IRS low-resolution range, while the main PAH emission bands can be measured in medium-resolution spectroscopy. The PACS instrument on Herschel will provide high-resolution (R=1700) spectroscopy in the 60–210 μ m range. This will give access to the main cooling lines of star forming regions and, for targets at z>1.5, also to rest-frame mid-infrared AGN tracers. The NIRSpec and MIRI spectrographs on the JWST will offer medium resolution spectroscopy in the ranges 0.6–5 μ m and 5–28 μ m, respectively.

This will allow the detection of mid-infrared star formation and AGN tracers out to redshifts of 2–3. ALMA will bring HST resolution to the field of submillimeter astronomy. This will allow the detection of galaxies out to extreme redshifts by sampling them close to the peak of their flux distributions.

These instruments offer enough sensitivity to study the energetic processes in ULIRGs and HyLIRGs in sufficient spectral detail that the contributions of (embedded) AGN and starburst activity may be traced back all the way to the youthful days of our Universe. This will allow us to determine whether all mergers go through a ULIRG/HyLIRG phase and how the role of (embedded) starburst and AGN activity changes as a function of merger phase. The observations will also allow us to study the composition of the ISM in the Early Universe and to assess the influence of extreme nuclear activity on chemical enrichment.

High spatial resolution in combination with sufficient spectral resolution will permit analysis of individual nuclear and circumnuclear components in (ultra)luminous galaxies in a large portion of the Local Universe. For instance, the nature of merger nuclei may be inferred; properties of individual (super)star clusters may be inferred; and the influence of the central X-ray sources on the chemical composition of AGN tori may be finally studied.

For ULIRG astronomy the best is still to come!



FIGURE 8.1 — The launch of SIRTF on August 25, 2003 marks the start of a decade in which infrared and sub-millimeter astronomy will undergo an authentic revolution. Photo: NASA.