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## DISCUSSION AND CONCLUSIONS

Galactic-scale starburst-driven outflows are one of the most important evolutionary mechanisms of galaxies, and their correct interpretation has far-reaching consequences for both galaxy formation and cosmological models. Their truly multiphase nature, and the fact that they exhibit complexity on every scale, makes understanding them a difficult and time-consuming task. Furthermore, the connection between the emission or absorption lines through which we actually observe galactic winds (GWs) and the mechanisms through which they form are often unclear or ambiguous. We have seen that the hot, fast-flowing wind fluid itself is almost impossible to observe at any wavelength due to its low density and high temperature, so we are forced to observe the system at lower energies, where the wind can only be traced indirectly through its interaction with denser material.

The importance of studying winds in the local Universe where they can be easily resolved, also has ramifications for our understanding of high-redshift systems. As mentioned in Chapter 1, powerful winds are observed in many Lyman-break galaxies at  $z > 1$ , and if we are to understand their role in the evolution of the Universe (including re-ionization and IGM enrichment), then we must first know how feedback from star-formation occurs and develops locally.

In this thesis, we have presented and described the results of two intensive, multifaceted, optical observing campaigns aimed at characterising the properties of the ionized gas in the starburst galaxies M82 and NGC 1569, two of the closest galaxies with large-scale GWs. Our goals were to further our understanding of how GWs are formed and driven,

where the material is accelerated, how they interact with their surroundings, and how they evolve to be what we see at large-scales.

M82 is the most extreme example of a starburst in the local Universe. The combination of a large gas reservoir and a nuclear bar to channel this material into the centre, has resulted in the rapid build-up of a very large number of massive star clusters packed into small, dense clumps that in turn, drive a powerful, bright and well collimated superwind to distances of many kiloparsecs. In contrast, the physical conditions of the NGC 1569 GW are driven by only a handful of massive star clusters, and the outflow is instead formed of multiple supershells that have expanded into the halo along paths of least-resistance, with only a hint of a preferred outflow direction.

The work of this thesis can be divided into three main themes. In the following sections we discuss the main themes of this thesis and the most important issues connected with each, followed by how they could be addressed further in future research.

## 9.1 Main themes

This section is split into three subsections, each focussing on one of the main themes of this thesis. In discussing each, we recapitulate our main conclusions without going into too much detail, and highlight a number of key outstanding issues that deserve further thought, investigation and observation. These are listed in bullet-points at the beginning of each subsection.

### 9.1.1 Star clusters as the driving sources of galactic winds

#### Key Issues:

- **The effects of the ISM densities on cluster evolution**
- **The spatial density and number of clusters**
- **The effects of metallicity on wind strength and evolution**
- **The interaction of winds between individual star clusters**

Young, massive star clusters are interesting in their own right in many ways (as discussed in Chapter 1). However, in this thesis we have primarily been concerned with the formation and evolution of GWs, and in order to realistically model the evolution of a superwind, we must know the fundamental parameters of the discrete sources (the star clusters) that drive it as accurately as possible. For this reason, we have focussed our

work on star clusters accordingly, and interpreted their fundamental properties (mass, age, size, mass function, metallicity, and spatial relationship – *i.e.* separations, clumping) in the context of GWs.

In this thesis, we have studied two such clusters in detail, M82-A1 and NGC 1569-10, both at either end of the cluster mass-scale and in two quite disparate systems, and have derived new estimates of some of the aforementioned parameters. However, the most striking result stems from the environmental differences between the media surrounding the clusters, and manifests itself most strongly through its effect on the clusters' ionized envelopes: at  $\sim 6.4$  Myr, M82-A1 has a compact, high-density H II region, whilst NGC 1569-10, with an age of 5–7 Myr, seems to have already been able to blow away its natal gas cloud. This important finding provides clear evidence that the ambient density of the ISM must play a critical role in determining the evolution of clusters and hence the overall starburst. This result warrants a great deal more thought and investigation. How can the high gas densities in the cores of starburst clumps such as found in M82 be reconciled with the production of free-flowing cluster winds and hence a powerful superwind? Could the high interstellar densities somehow act to enhance the superwind much like a constricting pipe does to a gas flow?

### 9.1.2 Characterising the state of ionized ISM in starburst regions

#### Key Issues:

- **The consistent lower-limit to the width of the narrow component of the nebular emission lines**
- **The underlying broad component and its relation to mass-loading**
- **The energy injection zone and sonic point of the outflow**

One of the central aims of this thesis was to investigate the state of the ionized gas in starburst regions. We have used high-resolution narrow-band imaging, long-slit spectra and integral field spectra to investigate the optically emitting gas dynamics and energetics in M82 and NGC 1569. In general, we found the nebular emission-line profiles to be composed of a bright, narrow component with a fainter, very broad underlying component. We have mapped the properties of the individual components of the bright H $\alpha$  line in particular, over the central regions of both galaxies, and our study of the relationship between the components has led us to investigate the mechanisms that might result in

the observed line broadening. Most significantly, we have proposed a new model for explaining the origin of the underlying broad lines.

We find that the narrow line most likely represents the turbulent ISM gas that has been stirred-up by the effects of the starburst. Although this stirring has resulted in a characteristic minimum line-width that applies across the whole central regions of the galaxy, an additional contribution to its width must inevitably come from the inclusion of multiple unresolved kinematic components along the line-of-sight as every observation is always limited to a finite spatial- and spectral-resolution. Our detailed investigations have led us to propose that the broad line results from a much stronger turbulent velocity field created as the hot, fast-flowing winds from the surrounding star cluster(s) flow past the surface of cool, dense gas clouds embedded in the ISM. This sets up a turbulent mixing layer at the interface region, and material begins to be thermally evaporated and/or mechanically ablated from the clump, resulting in the eventual dissolution of the cloud. In this model, the broad line is being emitted by material being entrained into the wind flow, hence it should be possible to trace the inner regions of superwinds *in the optical* by using the broad component as a proximate indicator.

Our study of the origin of the broad component engenders yet more questions: can the broad component truly be modelled using a Gaussian profile? Some studies find a non-Gaussian shape for the underlying emission (*e.g.* Mendez & Esteban 1997) whilst others maintain that it can be modelled satisfactorily using a single Gaussian profile (González-Delgado *et al.* 1994; Homeier & Gallagher 1999; this work). Why is this component sometimes only seen in recombination-lines and not forbidden-lines (*e.g.* Izotov *et al.* 1996)? Since “integrated emission line profile widths can result from very different physical processes, all of which are likely to act simultaneously with different weights according to the evolutionary status or history of region” (Melnick *et al.* 1999), can we determine which broadening mechanism(s) are likely to dominate in particular environments? When do the contribution from SNRs become significant? Can we disentangle the effects of photoevaporation, thermal evaporation, turbulent mixing, and mechanical ablation in high-energy starburst systems where the situation is intrinsically more complex than in near-by Galactic systems?

The ubiquitous presence of an underlying broad component in the starburst regions studied is an intriguing result, and its accurate characterisation has been one of the most important aspects of this thesis. In NGC 1569, we have seen how the extent of the

broad-line region may be correlated with the edge of the energy injection zone and the location of the sonic point. Does the sonic point represent the location at which random turbulent gas motions begin to form an ordered, directed flow? In M82, the conditions in the wind change rapidly around the points of infection in the minor-axis radial velocity measurements, which have led to the conclusion that this location corresponds to the sonic point (McKeith *et al.* 1995; Shopbell & Bland-Hawthorn 1998; Greve 2004). However, we have yet to determine how this is related to or controlled by the conditions within the starburst. We have tentative evidence from our DensePak observations of the M82 disc that the width of the broad component gets larger near the proposed sonic point. How, then, are the gas velocities related to the line widths at this point?

### 9.1.3 Characterising the small- and large-scale wind morphologies

#### Key Issues:

- The large-scale distribution of halo material (including dust)
- Wind collimation mechanisms and their relationship to the energy injection zone
- The accurate modelling of wind outflows

A significant proportion of this thesis has been devoted to describing and classifying the optical morphology of wind outflows, and making comparisons to multi-wavelength observations. Our data have covered a large range in spatial-scales and resolutions, from 0.05 arcsec-resolution *HST* imaging, to 0.8 arcsec-resolution IFU spectroscopy of discrete  $5 \times 3.5$  arcsec regions, to overlapping  $27 \times 43$  arcsec IFU fields, to contiguous formatted-field-unit observations covering a total of  $\sim 3.5 \times 4$  arcmins, to mosaicked ground-based images covering  $\sim 8 \times 5$  arcmins. This has given us tremendous scope to investigate the phenomenon of GWs and attempt to make links between the small-scale details and the large-scale characteristics.

Through the combination of deep, ground-based imaging, and high-resolution *HST* data, we have been able to, for the first time, track large-scale structures in the M82 wind back to individual features in the inner-flow, and to individual starburst clumps and star clusters in the galaxy centre. The medium spatial-resolution WIYN/DensePak observations of the M82 disc have proved critical in connecting the long-slit *HST*/STIS measurements to the larger-scale wind morphology, by providing high spectral-resolution over a large two-dimensional area. Following on from this detailed analysis, we have

been able to both independently develop and extend previously published models of the physical state within M82's starburst clumps and the distribution of these clumps within the galaxy. Our observations support the existence of a stellar bar with an inner Lindblad resonance, which seems to have significantly affected the evolution of the inner 500 pc of the galaxy. We find the cluster M82-A1 to be associated with the bar and the unique family of  $x_2$ -orbits oriented perpendicularly to the bar major-axis.

By comparison, the GW of NGC 1569 is at a very different evolutionary stage. While M82 hosts a powerful, well-collimated, bipolar outflow exhibiting a cornucopia of structure down to the resolution limit of our observations, the NGC 1569 outflow is composed of a series of faint, discrete supershells expanding in only a roughly bi-polar distribution. Because of the low surface-brightness of the shells, they are much better identified through their dynamical signatures, so we have studied the properties of the individual supershells through a set of mosaicked WIYN/SparsePak observations. However, because of the larger disparity in spatial-resolutions between these and our Gemini/GMOS observations of the galaxy centre, similar links between the large- and small-scales to what we found for M82 have been harder to make.

A number of important unanswered questions remain: how do galactic outflows evolve from the shell/supershell stage seen in systems such as 30 Dor or NGC 1569, to the large-scale winds seen in galaxies such as M82 or NGC 253? Presumably in powerful starburst systems, this happens over a very short timescale (*e.g.* for M82). Can starburst-driven superwinds really inject material into the IGM, or does it always remain bound to the galactic system? What is the escape fraction of ionizing photons from starbursts, and does the development of superwinds affect this value? These questions have important implications for our general understanding of the evolution of the Universe, as discussed previously. Our morphological analyses have highlighted the need for a multi-wavelength approach when trying to understand the evolution of such complex systems. Clearly, the distribution of cold, neutral halo gas and dust affects the large-scale morphology of outflows, whether that material is part of a preexisting halo, has been affected by external gravitational interactions, or has been dragged out there by the wind itself, but to what extent?

The accurate and realistic modelling of GW systems is key to understanding what the light we actually observe means. We have shown that identifying and characterising the morphology of GWs is essential in order to discern which simulations best predict

the reality. Hopefully the observations presented here will motivate and encourage new models to predict the critical inner-structure of superwinds, based on the ideas first developed by Tenorio-Tagle, Silich & Muñoz-Tuñón (2003) of a correct treatment of the discrete nature of the energy sources. However, it is unlikely that a model suitable for one GW system could be easily applied to another, due to the highly idiosyncratic nature of starbursts. For example, it would be very difficult to directly apply a model that accurately reproduces the observed characteristics of the M82 outflow to that of NGC 1569 and get sensible results.

## 9.2 Technical remarks

Much of the work done in this thesis could not have been accomplished without the advantages of spatially-resolved spectroscopy. For example, our detailed study of the ionized gas in the centre of NGC 1569 would have been very difficult to do without IFS techniques. In principle, the same effect could be achieved by stepping a single slit across a region many times, but IFU observations are far more time-efficient and technically easier to carry out. Furthermore, relationships between gas properties are much easier to identify and quantify when there is both continuous spatial coverage, and simultaneous access to fully spectrally-resolved emission lines over a large wavelength range.

However, with large spectral data-sets comes the need to accurately and automatically characterise the profile shapes of the emission/absorption lines. Although we have developed a fairly robust method for line-fitting, the process is still quite time-consuming and there are several stages where errors can be introduced. The variable and irregular nature of photoionized regions means that the line profile shapes often change rapidly over short scales, and since the results are highly dependent on the accuracy of the line-fitting, visual inspection of every profile fit is still necessary. Clearly, the synergy between spectral-resolution and S/N in the accurate quantification of line profiles implies that the best results will come from good spectrographs and long integration times.

## 9.3 Future work

In this section I will discuss what I believe to be some of the most important ‘next steps’ that could be taken following the work presented in this thesis, based on the key issues

emphasised above.

### 9.3.1 Observations

To further investigate the significance and location of the sonic point in galactic wind outflows, high velocity-resolution, spatially-resolved, spectroscopic observations need to be taken of regions both up and downstream of this critical transition. As we have shown, IFS techniques are well suited for the simultaneous measurement of large areas of interstellar gas, and provide a way to easily track relationships between the subsonic and supersonic gas flows. More specifically, a medium spatial-resolution IFU such as DensePak would be ideal for mapping the proposed boundary of the broad component region in NGC 1569. This kind of data could be used to explore its relationship to the sonic point, the transition to the classic split-line profiles found in the outer-wind, and whether the seemingly mutually exclusive existence of the broad and split-line profile types is significant. Of course, any observations would have to be deep enough so that the S/N of the broad-line is not in contention at any point.

To investigate the entrainment of gas and dust into the wind, and the importance of this material in affecting the wind's evolution, long wavelength observations are essential. The *Spitzer* images shown in Chapter 4 indicate that a great deal of dust in the M82 halo, and understanding whether its presence is due to the action of the wind, by tidal stripping, or was formed *in situ*, will be important for future wind formation models. An alternative way to investigate the dust content of the wind is through polarisation imaging. These notoriously difficult observations offer the potential of both probing the distribution of dust and the influence of magnetic fields on wind evolution. The intriguing results of Scarrott, Eaton & Axon (1991) for M82 certainly deserve further investigation, particularly in light of more recent observations, and our better understanding of the M82 starburst. They found H $\alpha$  polarisation levels of 10–30 per cent throughout the wind (out to distances of 40''), forming a clear centro-symmetric pattern, and implying that H $\alpha$  emission from the wind contains a certain contribution from reflection from the central starburst. They also found the symmetry of the polarisation pattern requires that the illuminating source is less than 4 arcsecs in diameter and located very near the IR emission peak associated with the nucleus. Unfortunately, this is one of very few polarisation studies that have been made of GW systems in the local Universe.

We have been granted observing time to obtain a set of Gemini/GMOS IFU obser-

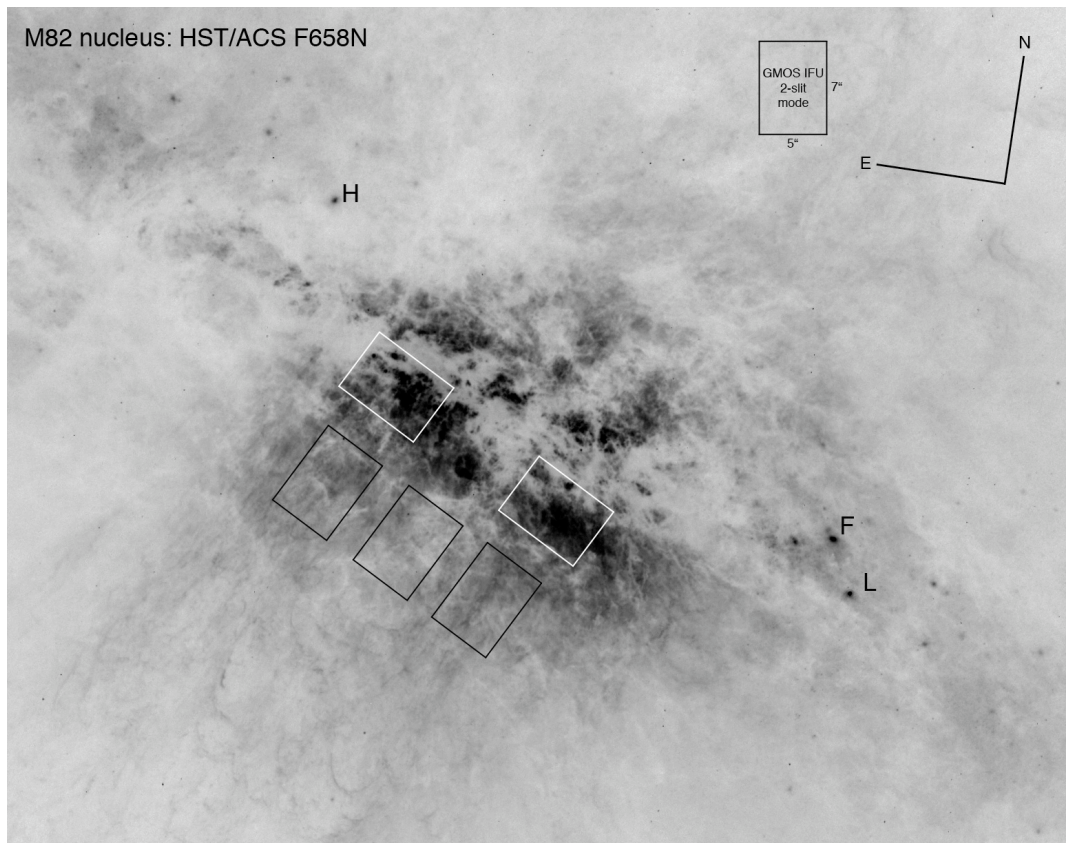


Figure 9.1: *HST*/ACS F658N image of the central region of M82 showing the positions of the five proposed Gemini/GMOS IFU pointings ( $5 \times 7$  arcsecs) for which we have recently been granted observing time.

vations of regions A and C and southern inner-wind of M82 (see Fig. 9.1). We hope to carry out a similar analysis to what we have presented here for NGC 1569, including measurements of line velocities, widths and electron densities/thermal pressures, and to look for shocks using the standard line diagnostics. These observations should significantly enhance our knowledge of the complexities of the brightest starburst clumps and inner-wind regions, particularly following our new proposed explanation for the broad-line component and our updated physical model of the M82 ISM within the starburst.

Can we isolate the direct effects of stellar/cluster winds from that of multiple unresolved kinematic components? It is unlikely that we will be able to with these GMOS data, since the core of M82 is a particularly dynamic and complex environment and it would require observations at spatial- and spectral-resolutions much higher than attainable with the GMOS instrument. However, as shown by Melnick *et al.* (1999), this can be done in near-by systems. To this end, we have recently obtained AAT/UCLES long-slit observa-

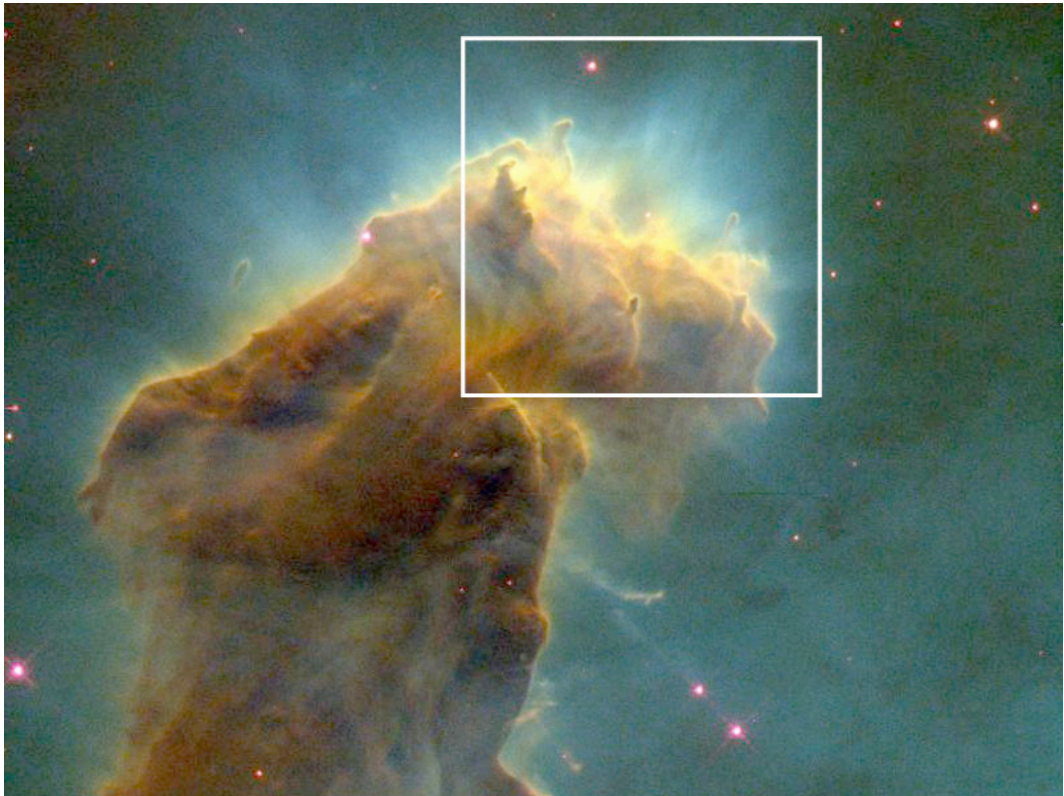


Figure 9.2: *HST*/WFPC2 colour-composite image of the head of one gas pillar in M16 (Credit: J. Hester & P. Scowen, NASA). Overlaid is the field-of-view of the  $27 \times 27$  arcsecs VLT/VIMOS IFU illustrating how modern, large-format IFUs could be used to investigate gas evaporation/ablation from the surface of dense molecular clouds. (Note: VIMOS could not actually be used to observe M16 since the instrument and object are in opposite hemispheres. This figure is to illustrate the concept only.)

tions of NGC 346, a young, intense star-forming region in the SMC, to complement a recent *HST*/ACS observing campaign of this object (Nota *et al.* 2006). We hope to characterise the ionized gas surrounding the bright, young cluster down to scales of 0.1 pc, and to fully resolve the individual line-components. These observations will be used to address the efficiency of stellar wind feedback at low metallicity, and to study the complexity of the outflowing gas from a single, resolved cluster of stars in a similar fashion to what has been done for 30 Dor or NGC 604 (Chu & Kennicutt 1994; Yang *et al.* 1996).

Can we disentangle the effects of turbulent mixing from thermal evaporation and mechanical ablation and determine which is the most important mechanism in particular situations? So far, we have discussed these mechanisms in a fairly broad sense, since we have had no unambiguous way of isolating them with our current data-sets, but

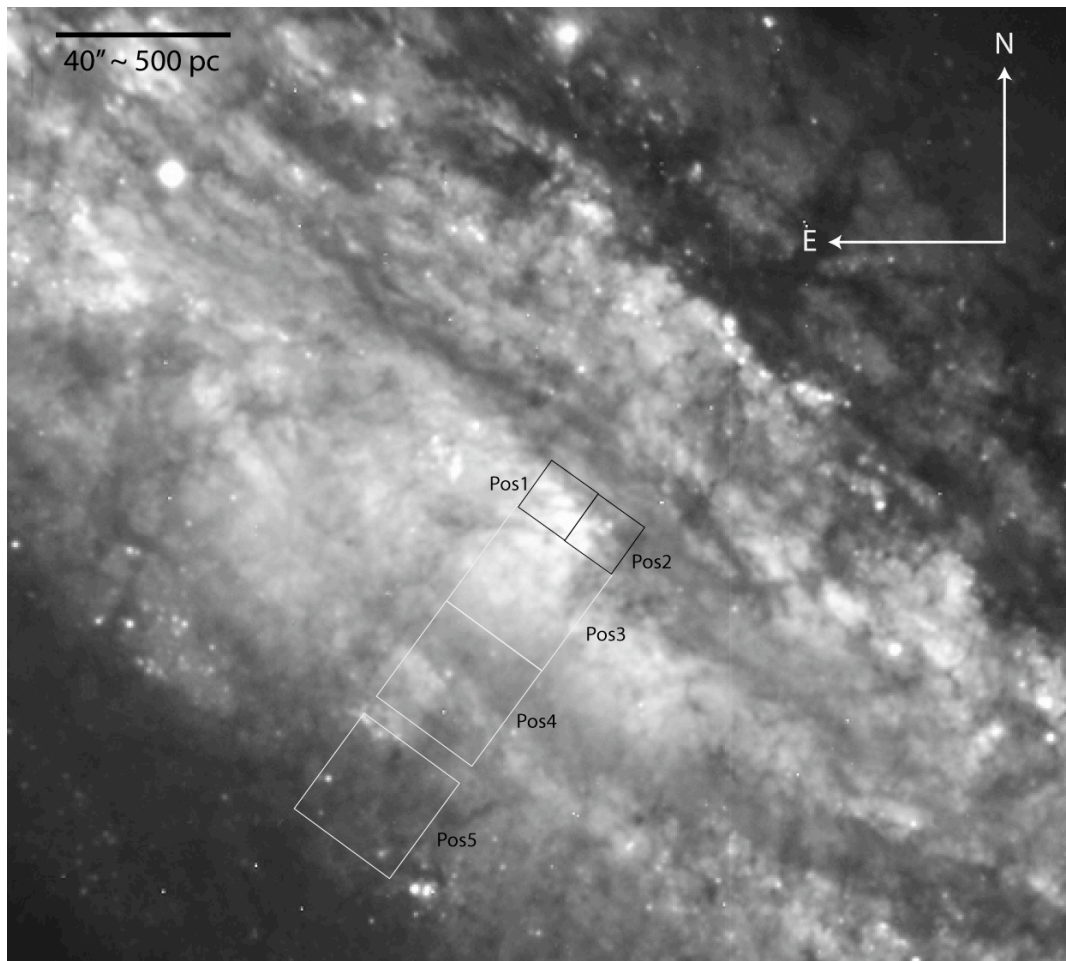


Figure 9.3: VLT/VIMOS IFU pointings overlaid on an archive mosaicked ESO 2.2 m/WFI *B*-band image of the central regions of NGC 253. The inner-most fields (Pos1 & 2) will be imaged by VIMOS in its high-spatial resolution  $0.33''/\text{fibre}$  ( $13 \times 13$  arcsec) mode, while the outer fields will be in the  $0.67''/\text{fibre}$  ( $27 \times 27$  arcsec) mode.

it would be interesting to see if their effects could be observed separately. Potentially, observations of an isolated molecular gas cloud in a near-by young star-forming region, where photo-evaporation and ablation are known to be occurring without the obfuscation of mixed, unresolved stellar sources and SNR, could yield these kind of results. Fig. 9.2 shows an example of how a large-format IFU such as VLT/VIMOS could easily capture a large section of the illuminated interface region of a molecular cloud in our own Galaxy.

In this thesis we have focussed on only two galaxies with known galactic-scale outflows, both being low-mass dwarfs. GWs are also observed in massive, metal-rich galaxies, and it is just as important to quantify their properties. To this end we will very soon be obtaining VLT/VIMOS IFU service observations (PI: M. Westmoquette) of the galactic

outflow in NGC 253, a near-by, massive, dust rich, high-inclination spiral galaxy hosting a nuclear starburst and possibly an AGN. Fig. 9.3 shows how we have made use of the multi-resolution capabilities of this instrument to propose five IFU pointings covering the nucleus (which contains known SSCs; Watson *et al.* 1996) and outflow along the minor-axis. In addition to extracting spectra of the individual star clusters over the wavelength range 6350–8600 Å from the high-resolution fields, we also hope to map the GW through the properties of the optical nebular emission lines from the point at which the wind is driven and collimated, out into the halo.

### 9.3.2 Modelling

Although it is outside the scope of this chapter to fully discuss the future of superwind modelling, it is clear that a correct treatment of the multiple discrete nature of the energy source in starbursts is important and justified. An emphasis in future models on predicting measurable quantities (line ratios, radial velocities, line widths) would be advantageous, so that they may easily be compared to the type of observations presented in this thesis. Furthermore, a realistic treatment of the ISM distribution, including an accurate account of the clumpiness, the level of molecular matter and dust, and how well the ionizing sources and ionized gas are mixed, will lead to a better estimate of the wind evolution and mass-loading factors.