Chapter 6

Future Work

The discovery of UDH II s has opened up a new field, allowing us to study the earliest stages of massive star cluster evolution for the first time as well as the influence this mode of star formation has had throughout the universe. As with any fledgling field, there is a great deal of knowledge and understanding yet to be worked out, and many questions remain. Future work will reveal the physical properties of these ultra-young massive star clusters and determine the conditions required for their formation. In addition to studying their earliest developmental stages, we will determine the properties of massive star clusters as they evolve and develop an evolutionary sequence. This work will have a direct impact on our understanding of both stellar and galactic evolution, as well as the origin of globular clusters and the physical conditions in the early universe required to create these massive clusters so prodigiously.

6.1 Expand the Sample of Known UDH II s

Because UDH II s have only recently been discovered, one of the most fundamental goals in this field is simply to expand the sample of known objects in order to better understand their properties in a statistical sense. For example, once we have obtained a large enough sample we will be able to construct an initial mass function for clusters and examine its dependence on different physical environments. This result will be absolutely crucial in understanding the physics of star formation via molecular cloud collapse.

High resolution radio telescopes, such as the Very Large Array (VLA), are ideally suited for conducting surveys of starburst galaxies at high radio frequencies (such as 5 and 20 GHz) in order to detect the characteristic optically-thick thermal spectral energy distribution of these compact sources. Because radio wavelengths do not suffer from dust extinction, we will be able to probe even the most dense and obscured star forming regions in starburst galaxies. To this end, I have already begun observing campaigns with the VLA, the Multi-Element Radio Linked Interferometer Network (MERLIN), and the Australia Telescope Compact Array (ATCA) with observations already made of eight additional Wolf-Rayet galaxies (MRK 8, MRK 33, NGC 3395, NGC 3396, IC 4662, NGC 5398, NGC 1705, and NGC 4449). In addition, I have begun a survey with ATCA (at 3 cm and 6 cm) of radio sources in the Magellanic Clouds in order to extend our knowledge of individual UCH II regions beyond the Galaxy.

6.2 Determine the Properties of the Birth Environments of Massive Star Clusters

One of my main objectives for the future is to determine the physical properties required to form massive bound clusters. We know that in the local universe, massive star clusters appear to be formed exclusively in starbursting regions of galaxies. However, we have never directly probed the environmental conditions of their formation. Similar physical conditions must have been present in the early universe in order to create the vast number of old globular clusters we see today (although metallicity is almost certainly an issue here, and studying the lowest metallicity systems available will be critical for this interpretation).

Because massive star clusters in their earliest stages are embedded in their natal molecular clouds, millimeter observations of molecular lines are particularly well suited for observing their birth environments. The highly abundant CO lines can be used to trace the molecular gas associated with UDH IIs, while higher dipole molecules, such as CS or HCN will map out the highest density gas which is expected to be directly correlated with areas of star formation. We can use molecular line diagnostics to provide information on all of the basic physical properties of the natal environments, including their temperatures, densities, and pressures.

I have already obtained two tracks with the OVRO millimeter array (with the equatorial and ultra-high resolution configurations; a track in the high configuration has not yet been observed although the time was granted) to create a high spatial resolution map of the CO(1-0) line in He 2-10, where we discovered five UDH IIs (see Chapter 4). I will also apply for time in the coming semester using the BIMA millimeter array for a project mapping the physical properties of the dense gas in the starburst galaxies known to host UDH IIs. In the more distant future, the proposed (and not quite funded to date) Atacama Large Millimeter Array (ALMA, to be built in the Atacama desert in Chile) will enable superb sub-arcsecond observations (similar to the resolution of HST) to be obtained in the millimeter regime for the first time. This instrument will be ideal for studying the physical properties of UDH IIs.

Another issue I wish to address is the relation between the morphology of warm/hot dust and the UDH IIs. UDH IIs should be embedded in knots of bright and hot dust emission. To date, only minimal mid-infrared data (such as that presented in Chapter 4) exists on UDH IIs, but this dust has not yet been observed in detail. I plan to carry out a mid-infrared imaging and spectroscopy campaign to directly measure the warm and hot dust associated with UDH IIs, allowing us to establish the nature of this relationship.

6.3 Determine the Properties of Massive Star Clusters at Different Evolutionary Stages

As massive star clusters age and begin to emerge from their birth material, their physical properties will evolve rapidly. For example, in the earliest stages of their evolution, their environment will transform from being optically thick to optically thin at radio wavelengths. As the most massive stars begin to evolve, they will dramatically affect the cluster environment via stellar winds and supernovae. After the ambient gas has been dissipated from the cluster, much of the gravitational binding energy is lost and the clusters themselves may begin to dissociate. Throughout these phases, the overall spectral energy distribution of these clusters will also metamorphose. However, since these clusters are only newly discovered, one of the large gaps in our knowledge is the nature of their spectral energy distribution and how it evolves.

There are a number of powerful techniques available in different wavelength regimes to study massive star clusters as they evolve from being completely enshrouded to being dominated by stellar light. For the youngest and most deeply enshrouded clusters, radio recombination lines provide a practical method for observing the spatial structure and physical properties of clusters. Because radio recombination lines do not suffer from the same dust obscuration as hydrogen recombination lines at shorter wavelengths (e.g., Hα, Hβ, etc.), they are naturally suited to observing the properties of the ionized gas in the youngest star forming regions. Over the past decade, the sensitivity of radio telescopes has greatly improved and radio recombination lines have been detected in a number of starburst galaxies (see Anantharamaiah et al. 2000, and references therein). Atomic lines in the mid-IR can also yield information about the properties of enshrouded clusters. Species such as [Ne II], [Ne III], [S III], [S IV], etc. can provide information about the number of ionizing photons (and therefore the number of massive stars), the temperatures, and ages of the clusters.

As UDH IIs become less enshrouded (and eventually completely transparent) to optical wavelengths, stellar light can begin to penetrate a moderate amount of extinction in the near-IR, where spectra are rich in diagnostic lines. In particular, the Paα, Brγ, He I, and [Fe III] lines are strong nebular diagnostics available in this wavelength regime. The installation of the new NICMOS cooling system (currently advertised as being available for cycle 11 with HST) will open up new possibilities for studying UDH IIs at high spatial resolution in the near-IR, particularly for diagnostic lines such as Paα which cannot be observed from the ground due to poor atmospheric transmission.

For diagnostic lines which can be observed through atmospheric windows, the new Gemini telescopes will provide superb defraction limited observations. In the near- to mid-infrared. In addition to the Gemini observations I have already obtained (Chapter 4), I have also been awarded time in the upcoming semester on Gemini South to obtain spectroscopy of the UDH IIs in He 2-10 in the thermal infrared window from 8 μm to 14 μm. These observations will allow us to measure the fine structure emission lines of [Ar III], [S IV], and [Ne II] in addition to establishing the presence or absence of the PAH features at 8.6 μm and 11.3 μm and checking for silicate absorption.

6.4 Identify an Evolutionary Sequence

It is becoming clear that we are seeing a *continuum* of sizes and luminosities for extragalactic massive star clusters in the earliest stages of their evolution. Recognition of the ubiquity of the UDH II phase of massive star formation pushes us one step closer to understanding the genesis mechanisms of all star clusters, from small associations to giant proto-globular clusters. Along with a continuum in sizes, we should also expect to find a continuous range of ages tracing an evolutionary sequence.

In addition to studying the physical conditions in UDH IIs, we can search for an *even earlier* stage of massive star birth in clusters which has not yet been identified; before stars have actually reached the main sequence and begun ionizing the surrounding ISM, they go through a “hot core” phase (see Figure 6.1). Massive star clusters should have an analogous phase, in which the regions will be defined by extremely dense and warm gas which is not associated with strong free-free emission. These sources may be observable for the first time by finding their dense molecular cores and/or associated mid- to far-infrared emission.

The Space Infrared Telescope Facility (SIRTF, the last element of NASA’s Great Observatories Program) is scheduled for launch in the summer of 2002 and will provide lower spatial resolution observations out to the far-infrared (which is a wavelength regime not observable with ground based telescopes). SIRTF observations, especially of nearby galaxies, will be a powerful tool for finding “giant hot core cluster” candidates. To this end, I will do I follow-up radio study of the galaxies in the SIRTF Legacy program SINGS (SIRTF Nearby Galaxy Survey, led by Dr. Robert Kennicutt) primarily accessing publicly available radio archive data.

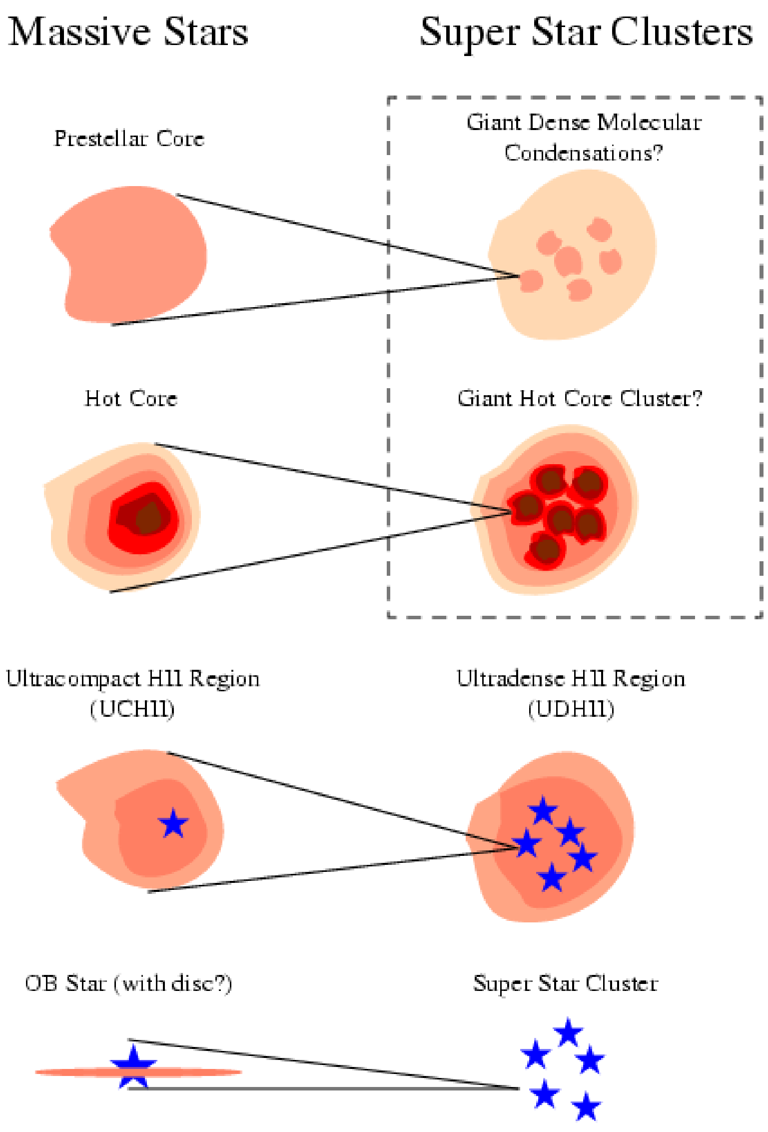

Figure 6.1: Proposed schematic illustrating the formation of massive star clusters (right) in parallel to the precepts of massive star formation (left) from Churchwell (1999). The dashed box indicates of cluster formation which have not yet been observationally identified.

6.5 Develop More Sophisticated Models

While the simple models presented in Chapters 4 and 5 are adequate for estimating mean physical properties, such as density, more sophisticated models would allow us to investigate the detailed dependence of observable quantities on varying physical conditions. More realistic models would need to include an arbitrary number of embedded stars (each with its own density profile and temperature distribution) embedded in a diffuse medium and allowed to evolve in time. Such models could predict the detailed dependence of observables such as the evolution of the spectral energy distribution of the enshrouding dust cocoon and the radio spectral index.

6.6 Summary of Future Possibilities

The origin of globular clusters has eluded researchers for many years, possibly because of the assumption that we would first need to able to observe the early universe in detail in order to find such objects. However, as we learned in Chapters 1 and 2 of this thesis, many young massive star clusters have been found with the Hubble Space Telescope in a number of systems, often in merging galaxies such as the famous Antennae. These clusters had to form *somehow*, *somewhere* in their host galaxies, and the most logical way to look for them is with the same methods used to find UCHII regions in our galaxy — radio, mm, and possibly in the far-IR. Indeed, perhaps we can even ask some of the same questions that we ask about UCH II regions. For example, is maser activity associated with UDH IIs? Do UDH IIs have the same "lifetime problem"? When stellar winds are established, how do they affect the birth environment? The first steps in understanding massive star cluster formation will be to catalog a larger sample of UDH IIs, map out their spectral energy distributions (in so far as current instrumentation will allow), and determine the physical properties of their birth environments. I look forward to providing updates on the progress of this reseach to the community in the coming years.

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