Star Formation, Massive Stars, and Super Star Clusters in Nearby Galaxies

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1. INTRODUCTION

1.1. The Importance of Studying Extragalactic Star Formation

Star formation is a critical process – arguably one of the most fundamental physical processes (next to gravitational collapse) in determining the appearance and properties of the visible universe. The formation of massive stars is particularly important because they have a major effect on the energetics of galaxies: massive stars are responsible for the ionization of the interstellar medium, their stellar winds and supernovae are main sources of mechanical energy, their ultraviolet radiation powers thermal-infrared (IR) luminosities through the heating of dust, they are a main driver of chemical evolution via supernova explosions at the end of their lives, and they may be the sources of gamma ray bursts.

Nevertheless, despite the significant role of massive stars throughout the universe, their birth is not well understood and we are only beginning to piece together a scenario for the youngest stages of massive star evolution. There has been some progress understanding the early stages of massive star formation in the Milky Way, but the current knowledge about the early stages of massive star evolution in other environments is mediocre at best.

The reasons for this dearth of information about extremely young massive stars in other galaxies are predominantly threefold: (1) the earliest stages of stellar evolution are deeply enshrouded and inaccessible at optical and near-infrared wavelengths; (2) compared to other types of radio sources (e.g. AGN, SNe, SNR), individual stars are relatively faint and require exceptionally sensitive observations; and (3) high spatial resolutions are necessary to disentangle the individual massive stars from their surrounding environment and background contamination.

The study of star formation in environments outside of our own Milky Way is critical for advancing our understanding of stellar and galactic evolution. The Square Kilometer Array (SKA) will clearly enable investigations of star formation in the Milky Way with an unprecedented level of detail. However, without similar investigations in other galaxies, it is difficult to place Galactic work in a larger context. The SKA will revolutionize the field of star formation by enabling detailed studies that have never been possible outside of the Milky Way.

The ability to observe star formation taking place in a range of conditions will enable us to better interpolate and extrapolate details of the star formation process throughout the universe. For example, we do not know how the properties of star formation depend on various environmental parameters, including metallicity, pressure, turbulence, stellar densities, triggering scenarios (including bars, bubbles, and galactic interactions), or how star formation might differ in nuclear regions or in "burst" and quiescent modes. Investigations of all of these issues will be possible with the sensitivity and resolution of the SKA.

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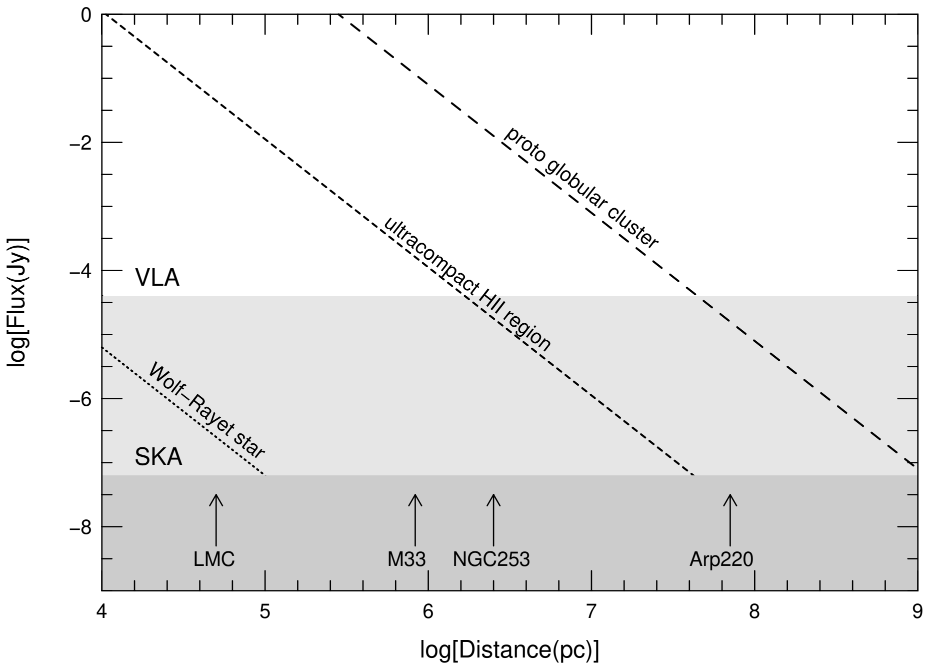

Figure 1. A schematic comparing the 5σ sensitivities for the Very Large Array and Square Kilometer Array for an 8 hour integration at 6 cm ($\sim 40\mu$Jy and 0.07μJy, respectively). The flux densities of "typical" WR-stars, UCHIIs, and natal globular clusters are indicated.

2. THE NATURE OF STAR FORMATION ON A SMALL SCALE

Because of their extremely short lifetimes, massive stars trace the most recent episodes of star formation in a galaxy, and therefore allow a detailed probe of recent star formation history. In particular, ultracompact HII regions indicate the *current* ($\lesssim$ 1 Myr) star formation and Wolf-Rayet (WR) stars trace the recent star formation ($\sim 3-6$ Myr). However, because of the (relatively) low radio luminosity of these individual stars, at the present time radio studies are largely limited to the Milky Way. The SKA will enable detailed investigations of extragalactic UCHII regions and WR-stars for the first time.

Massive stars evolve through several phases that can be studied in the radio, shedding light on the physics and time-dependence of star formation in galaxies. Dense prestellar cores begin their gravitational collapse on poorly known timescales, forming hot molecular cores with $\sim 10^5$ year lifetimes. Once accretion has slowed sufficiently (possibly stopped), a hypercompact HII region forms, which in turn (probably) evolves into ultracompact HII region, providing the first opportunities to study the protostar as it joins the main sequence (Figure 2). There is probably a very compact HII region in the hot core phase, but existing radio telescopes have had insufficient

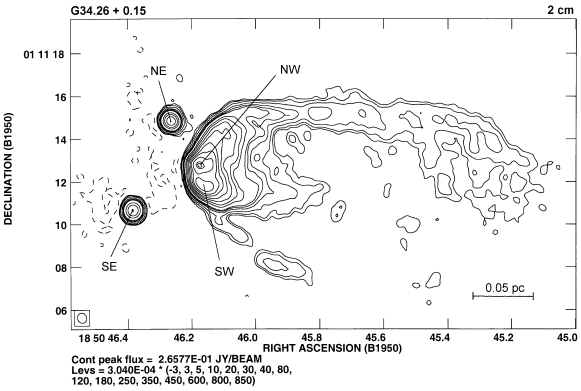

Figure 2. Radio contours of the massive protostellar object G34.26+0.15 showing a cometary ultracompact HII region and two hypercompact sources to the NE and SE. Radio recombination line spectra show that the compact source NE has a broad line width, while the compact source SE has a narrow line width [26]. These may correspond to different evolutionary states.

sensitivity to detect it. Detection by the Square Kilometer Array would be an extremely important development in understanding the earliest, heavily accreting phase of massive protostellar development.

Studying ultracompact HII regions aids our understanding of massive star formation on the timescales of their first $\sim 10^5$ years. After the ultracompact HII region stage of massive stars, their main sequence lifetimes can be observed as conventional HII regions for the next several Myr. Following the process further involves tracing the shortest-lived massive stars, Wolf-Rayet (WR) stars with lifetimes of a few $\times 10^6$ years. Because of their luminosities, WR stars can have a major impact on the optical and ultraviolet spectra of galaxies, and their spectral features are commonly used as diagnostics. As described in section 2.2 below, radio observations can be important for understanding the nature and lifetimes of WR-stars and for the interpretation of starburst galaxy spectra.

2.1. Extragalactic Ultracompact HII Regions

In the Milky Way, extremely young massive star forming regions have been resolved into individual ultracompact HII (UCHII) regions [29]. During this stage of massive star evolution, the ionizing star is still deeply embedded in its natal cocoon, but it has probably ceased accreting material. Thus the UCHII region phase represents the first opportunity to observe fully formed massive stars and their impact on the surrounding interstellar medium.

As their name suggests, UCHII regions are small; they have diameters of < 0.1 pc. However, they do not remain small for very long. The HII region will evolve from a compact embedded state to that of a large optically visible nebula on timescales of less than 1 Myr. UCHII regions are also extremely dense with electron densities typically well in excess of 10^4 cm^{-3}, which imply correspondingly high pressures of $P/k_B > 10^7$ cm^{-3} K [7]. With such high pressures, UCHII regions must either dissipate on rapid timescales or be confined by a source of external pressure. Indeed, it has been estimated that the lifetimes of UCHII regions are roughly a hundred times longer than they would be in the absence of significant confining pressure [30].

Although the UCHII region phase is a key stage for studying massive star evolution, these objects are inherently difficult to observe due to their embedded nature, small sizes, and short lifetimes. Because UCHII regions are shrouded by many magnitudes of visual extinction, they typically cannot be observed at wavelengths shorter than $\sim 1-2\mu$m. Due to their sizes of < 0.1 pc, extremely high spatial resolution is required in order to observe them. Finally, their lifetimes of < 1 Myr make these objects relatively rare, requiring large data sets in order to compile adequate statistical samples.

The SKA will have the sensitivity to detect individual UCHII regions out to the distance nearly 50 Mpc, and the spatial resolution to unambiguously disentangle UCHII regions from their surrounding environment out to the distance of ~ 1 Mpc (see Figure 1). While a handful of pilot studies have attempted to identify UCHII regions in the most nearby galaxies (e.g. the Magellanic Clouds [14]), the interpretation of these data is severely limited by the lack of spatial resolution. The capabilities of the SKA will enable detailed studies of extragalactic UCHII regions for the first time.

Studies of ultracompact HII regions are mature in our Galaxy, but nearly unexplored other galaxies, making fundamental discoveries by the SKA almost inevitable. The spatial distribution, morphology, and population statistics of embedded massive stars are fundamental properties of massive star formation that the SKA will be able to investigate. While observations of UCHII regions in the Milky Way provide an important case study, observations of massive star formation in other galaxies are essential for understanding the process of massive star formation in general.

One outstanding issue that the SKA will be able to address is the exact location of massive star formation relative to other protostars, density enhancements in the molecular gas, shock fronts, and various other features of the interstellar medium. While massive stars may typically have proper motions of $\sim$ a few to several km s^{-1} (e.g. the Orion Trapezium members [9]), a significant number of "runaway" massive stars exhibit high velocities of up to 200 km s^{-1} [13]. By the time a massive star has become optically visible, it may have moved away from its birth location by many parsecs. Indeed, during the lifetime of a massive star it may travel as far as $50 - 100$ pc from its original location.

Compared to galactic scales, the distance of a few to $\sim$ 100 pc is relatively small, but it is enough to impact our understanding of where massive stars form in a cluster (or if they were formed in a cluster at all), and erase any signature of sequential triggering. By observing massive stars immediately after they are formed, it will be possible to determine exactly what fraction of massive stars (if any) are formed in isolation. Moreover, observations with the SKA will enable investigations of the nature of mass segregation in clusters – whether it is due to competitive accretion during the formation stage, or if it is only due to dynamical evolution of the stellar population. Both of the issues of clustering and competitive accretion are critical to understanding massive star formation. The clustering properties of massive stars are integral to understanding the nature of the stellar initial mass function and also the possible role of coalescence and encounters in massive star formation. Likewise, determining the extent to which competitive accretion may affect the mass of stars in a cluster has important implications for the stellar initial mass function; competitive accretion of gas in a proto-clusters leads to a large dynamic range in the stellar mass function regardless of the initial masses of the molecular cores [8].

For the most nearby galaxies, roughly out to the distance of M33, it will also be possible to assess the relationship between the size of compact and ultracompact HII regions and their spectral energy distributions. This type of analysis will be invaluable for studying the early stages of massive star evolution and how the ionizing star interacts with its environment. For example, as the UCHII region evolves and begins to expand and emerge from its birth material, its spectral energy distribution over decades in wavelength will transform. The exact nature of this transformation will depend on the physical state of the surrounding interstellar medium. For example, as UCHII regions begin to evolve and expand, their environment will transform from being optically thick to optically thin at radio wavelengths. As the HII is expanding, the ionizing flux from the embedded massive star is also dissociating the surrounding dust and molecular material while its winds are also helping to clear away its natal material. Throughout this process, the star will become less obscured at optical wavelengths while the radio and thermal infrared emission become fainter and eventually undetectable.

In addition to simply determining the sizes of UCHII regions, the SKA will also provide a tool for investigating the leakiness and clumpiness of UCHII regions. The vast majority of UCHII regions are not ionization bounded (e.g. [19,18], and references therein), but rather are associated with extended envelopes of emission. This emission can include components up to $\sim$ 20 pc in size, the structure of which will be clearly resolvable with the SKA (see Figure 3). Along with

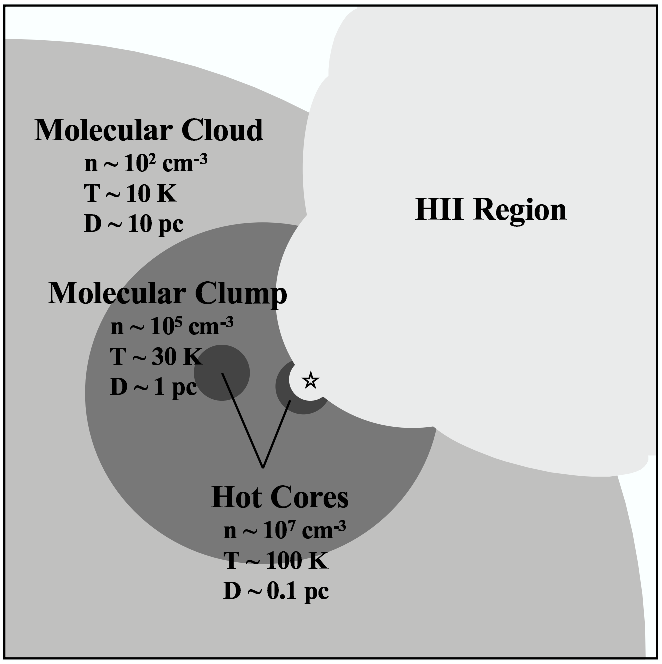

Figure 3. A cartoon of the Kim & Koo (2001) model for the extended halos of emission associated with UCHII regions. The Square Kilometer Array will be able to examine this scenario in a variety of nearby galaxies and environments.

high spatial resolution, good uv-coverage is necessary to address the ubiquity and nature of the extended emission around UCHII regions. By observing a large sample of these objects in a variety of galaxies, the SKA will also make it possible to ascertain whether the extended emission depends on environmental parameters and evolutionary state.

The SKA will also enable a detailed census of the population of ultracompact HII regions in a large number of galaxies. A comprehensive census will enable progress on a variety of issues. For example, the timescales which massive stars spend in the UCHII region phase is rather poorly constrained by the sample of such objects in the Milky Way. It must be stressed that no other diagnostics are available to ascertain the ages of UCHII regions, and we are forced to rely on estimates from statistics and dynamics. By determining the fraction of massive stars that are still embedded in their birth material in a large number of galaxies, it will be possible to statistically determine the lifetime of the UCHII region phase with much greater accuracy. Moreover, by determining the population of massive stars that are hidden from view at optical and ultraviolet wavelengths, it will also be possible to estimate the local and total contribution of massive stars to the energetics of the interstellar medium in a galaxy.

The luminosity function of ultracompact HII regions can also provide strong constraints on two fundamental parameters in star formation – the stellar and cluster initial mass functions. The HII region luminosity function is dependent on both the mass function of the stellar cluster that powers each region and on the distribution of mass fluctuations from which the different clusters were formed. Studies of the extragalactic HII region luminosity function have been performed in the optical and shed light on a variety of issues, such as whether the mass functions are different in and out of spiral arms (e.g. [16,21]). These studies have not been able to probe the youngest stages of cluster formation (compact and ultracompact HII regions), in which photon leakage and evolution are least likely to be a concern. Previous studies have also not been able to probe the luminosity function down to the small-numbers regime, involving single or small clusters of stars. The SKA will allow detailed study of HII luminosity functions over the full number and mass range of exciting stars, for hundreds of diverse galaxies.

2.2. Extragalactic Wolf-Rayet Stars

Wolf-Rayet (WR) stars are the descendants of the most massive stars [2,20] and exhibit powerful stellar winds with mass-loss rates on the order of $10^{-5} - 10^{-4} M_{\odot}$ yr^{-1} and terminal wind velocities of $\sim 10^3$ km s^{-1}. Because massive stars have inherently short lifetimes, the WR stage of stellar evolution happens very quickly after the onset of a starbirth event; approximately 3-6 Myr after a burst of star formation, the massive stars will evolve into WR stars. Because the WR phase has such a short duration, WR stars can provide a powerful diagnostic for tracing how star formation progresses with time.

WR stars are visible in the radio via their strong and dense stellar winds that produce thermal free-free emission (e.g. [25]). One of the most fundamental parameters that characterizes WR stars is their mass loss rate; the rate at which WR stars lose their mass in their winds can significantly affect their subsequent evolution and their impact on the ISM [1]. The most reliable determinations of their mass loss rates have come from radio measurements at centimeter wavelengths because this method requires the fewest assumptions about temperature and density structure in the wind. The mass loss rate can be derived from radio observations using only three quantities [31,23] – the distance to the star D, the terminal velocity of the wind v_{∞}, and the radio flux density S_{ν}:

$$S_{\nu} \propto \left(\frac{\dot{M}}{v_{\infty}}\right)^{4/3} \frac{\nu^{0.6}}{D^2} \qquad (1)$$

Once mass loss rates have been determined from radio measurements, the velocity, temperature, and ionization structure of the wind can be better constrained using methods available at optical and ultraviolet wavelengths. Moreover, because the timescales for WR star evolution are contingent on their mass loss rates, the predicted number of massive stars as a function of age in starburst events is dependent on knowing these rates accurately. This in turn affects the interpretation of stellar synthesis models throughout the universe.

Although understanding the nature of mass loss rates from evolved massive stars has an impact on a range of astrophysical topics (including the interstellar medium, stellar evolution, and starburst galaxies throughout the universe), there is not a clear understanding of how the mass loss rates of WR stars depend on environmental properties. For example, because radiatively driven winds are dependent on metal line absorption to transfer the photon momentum, the properties of the wind must depend on metallicity. However, the dependence on metallicity has not been well constrained by observations; because the free-free emission scales as $\nu^{0.6}$, stellar winds are relatively faint at radio wavelengths, and this has prohibited radio observations of this sort in an extragalactic context. Furthermore, massive stars are typically formed in clusters and embedded in HII regions, necessitating high spatial resolution in order to overcome the issues of crowding and contamination. The SKA will enable radio observations of WR stars outside of the Milky Way for the first time (Figure 1), roughly out to a distance of $\sim$ 100 kpc. This capability will make radio observations of WR stars in the Magellanic Clouds possible, and thereby vastly expand the range in environmental conditions in which mass loss rates from these stars can be studied.

3. THE BIRTH OF SUPER STAR CLUSTERS

The formation of super star clusters (SSCs) represents one of the most extreme mode of star formation in the local universe. With masses of $\sim 10^4 - 10^6 M_{\odot}$ and radii of only a few parsecs, SSCs are the most massive and dense stellar clusters, and it is believed that extreme pressures are required to form them [11]. The properties of many SSCs are consistent with their being the progenitors of globular clusters, although questions about their evolution and survival remain [12]. Because of the large number of massive stars densely packed into SSCs, these clusters can have a violently disruptive effect on the host galaxy – blowing bubbles, expelling gas, enriching the interstellar and intergalactic medium, and triggering further star formation. The impact of massive star clusters was probably even more important in the earlier universe when galaxy mergers and starbursts were common, and the formation of globular clusters was ubiquitous. Despite the importance of massive star clusters throughout the universe, the physical conditions required for their formation are poorly understood.

While SSCs have been extensively studied at optical wavelengths since the launch of the *Hubble Space Telescope*, very little is known about their formation because the early stages of their evolution are deeply enshrouded by dust. Deep high-resolution radio observations are required to advance this area of research. The current radio studies of these objects only extend out to distances of $\sim 10 - 20$ Mpc, where the sensitivity and resolution of the Very Large Array become inadequate. In contrast, the SKA will have the ability to detect natal super star clusters to redshifts of nearly $z \approx 0.1$, vastly increasing the sample of of starbursts and range of environments in which we can study the formation of super star clusters. Furthermore, for the most nearby galaxies, the SKA will resolve the physical structure of natal clusters with an unprecedented level of detail.

3.1. Using Radio Continuum Observations to Identify Natal Super Star Clusters

High resolution continuum observations between $\sim 5 - 20$ GHz are a powerful way to identify natal SSCs via their "inverted" spectral index ($\alpha > 0$, where $S_\nu \propto \nu^\alpha$, see Figure 4); this kind of spectral energy distribution results from optically thick free-free emission, similar to the spectral energy distributions of UCHIIs observed in the Milky Way. The specific spectral morphology of an HII region at radio frequencies is due to a combination of size and density structure, and these two factors can be determined given the turnover frequency and thermal radio luminosity (as determined from observations at high frequency where the emission is optically thin) of a cluster. In the case of clusters in nearby galaxies ($\lesssim$ 100 Mpc), the radii of the dense HII regions can be independently measured using the high spatial resolution of the SKA.

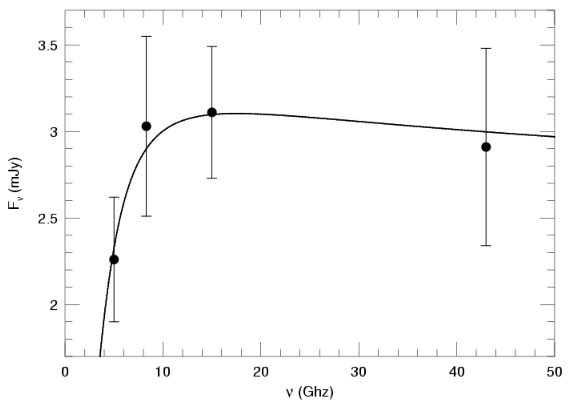

Figure 4. The radio flux densities (as measured using the Very Large Array of the most luminous natal super star cluster in the starburst galaxy Henize 2-10 ($D \approx 10$ Mpc), along with the best fit model HII region [15]. Observations similar to these can be used to estimate the radii and electron densities of embedded HII regions, as well as the mass of the natal ionizing cluster and pressure in the ionized gas.

A variety of other physical properties of the star forming regions can also be inferred from these measurements. The temperatures and densities can be used to infer the pressures of the HII regions. Combined with estimated cluster masses, pressures can be used to test theories of cluster formation. The optically-thin thermal flux density can be used to infer a total ionizing luminosity, and the ionizing luminosity can be translated into an embedded stellar mass by assuming a stellar initial mass function. These measurements can also be used to determine the total extinction in these star forming regions by comparing the ionized flux density as determined from radio observations with observations of recombination lines in the near- and mid-IR (such as Brγ, Paα, and Pfα). If the youngest clusters are the most embedded, the extinction measure can be used to crudely place the clusters on an evolutionary sequence.

3.2. Using Radio Recombination Lines

Observations of radio recombinations lines (RRLs) can be used to constrain a range of physical properties of the ionized gas, including electron density, temperature, gas mass, spatial structure, and kinematics. The major benefit of using RRLs to estimate physical properties is that they do not suffer from the extinction that plagues optical recombination lines (e.g. the Balmer series); therefore RRLs can provide a powerful way to probe star forming regions.

RRLs have been detected in ~ 20 nearby galaxies to date ([22], and references therein) from gas with extremely high emission measures in the nuclear regions of starburst galaxies as far away as Arp 220 [4]. However, even for the H92α line (8.1 GHz), which is located in the most sensitive observing band for the Very Large Array, these kind of observations are both difficult and expensive; typical H92α observations of nearby galaxies have relatively poor velocity resolution ($\sim 100-200$ km s^{-1}), spatial resolutions of only $\gtrsim 1''$ ($\gtrsim$ 350 pc at the distance of Arp 200), and required fairly long integrations ($\gtrsim 6-12$ hours) to reach an rms noise in each channel of $\gtrsim 50-100\mu$Jy. The sensitivity, spatial resolution, and spectral resolution of the SKA will allow the kinematic imaging of ionized gas in a range of extragalactic star forming environments that are far beyond the capabilities of the current radio facilities.

The SKA may also enable observations of radio recombination lines from elements other than hydrogen associated with star forming regions outside of the Milky Way. In particular, carbon recombination lines that are associated photo-dissociation regions (PDRs) will be useful for probing the physical environments immediately surrounding natal SSCs amid large and variable amounts of dust. Because carbon is the most abundant element with an ionization potential lower than that of hydrogen (11.3 eV), it produces RRLs in the PDRs surrounding young massive stars. As with hydrogen lines, the carbon lines can be used to constrain the physical properties of the region, including density and temperature [24]. However, the integrated intensity of carbon RRLs are typically only a few percent of that of hydrogen [5], requiring very sensitive observations.

3.3. Using Masers

Given the tremendous number and density of young massive stars in natal super star clusters, it is logical to ask whether we should expect to see other typical signposts of massive star formation associated with these objects. For example, molecular masers are common in the vicinity of newly formed massive stars, and H_2O masers in particular are signposts of massive star formation [7]. Approximately 70% of UCHIIs in the Milky Way are associated with H_2O masers [6], which suggests that the conditions required for these masers are fairly persistent over the lifetimes of UCHIIs. Therefore, at a given time, a large fraction of the massive stars in a natal SSCs should be associated with water masers. Because masers are typically confined to small and dense clumps, they can probe the kinematics of star forming regions on very small scales, providing information on both organized and turbulent motions such as accretion and outflow.

Recent observations with large single-dish radio antennae (e.g. Effelsberg and the Byrd Green Bank Telescope) have shown that prominent star forming regions in nearby galaxies can be associated with H_2O "kilomasers". Compared to "megamasers" observed in active galaxies, the masers associated with extragalactic star formation are relatively weak. Water kilomasers have thus far been detected outside of nuclear regions toward five galaxies (see [28], and references therein). The most distant galaxy found to contain such extra-nuclear water masers to date is NGC 2146 (14.5 Mpc, [28]).

Systematic and detailed studies of extragalactic extra-nuclear masers associated with star formation cannot be done without a new sensitive and high resolution radio observatory such as SKA. The SKA will enable us to address whether H_2O maser emission is common in starburst galaxies at the kilomaser level and below. With the spatial resolution of the SKA, it will also be possible to pinpoint the location of the maser emission, and assess the specific environments in which this type of emission found.

4. DETERMINING STAR FORMATION RATES

Accurate measurement of the overall star formation rates in galaxies is important for a broad range of astrophysical studies (see also van der Hulst et al. in this volume). The star formation rate (SFR) has direct implications for addressing the relationship between star formation and galactic evolution, mechanical energy input into the interstellar medium, and metal enrichment, just to name a few issues. A variety of techniques at different wavelengths have been used to estimate star formation rates including those that use the Balmer emission lines to measure the ionized gas, the ultraviolet continuum to observe the hot young stars, observations of infrared and sub-millimeter flux to estimate to bolometric luminosity, and observations of the non-thermal radio continuum to determine the synchrotron flux density due to recent supernovae ([3], and references therein). However, these methods have been plagued by uncertain corrections that need to be applied in different physical scenarios. Ultraviolet and optical measurements are sensitive to dust obscuration; infrared and sub-millimeter observations are difficult to obtain due to the Earth's atmosphere and the resulting estimates depend on the dust content and properties; non-thermal radio techniques (typically done at 20 cm) can only indirectly measured the SFR via cosmic ray acceleration from supernovae.

In order to estimate star formation rates most effectively, a technique must measure a quantity associated with young stars in a direct and well-defined way with as few assumptions as possible. To date, radio studies of the SFR in galaxies have largely relied on measuring the non-thermal flux density, which is not directly related to star formation. The non-thermal synchrotron flux density of a galaxy depends critically on the magnetic field strength of a galaxy and the cosmic ray production rate. In particular, the synchrotron emission from low-luminosity galaxies is often suppressed [32]. In principle, the thermal free-free emission from a galaxy is an ideal tracer of the SFR because it directly reflects the young massive star content. However, in practice it is difficult to isolate the thermal free-free component (which has a spectral index of $\alpha = -0.1$, where $S_\nu \propto \nu^\alpha$) from the non-thermal synchrotron component (which typically has a steep spectral index of $\alpha \sim -0.8$):

$$S_\nu = S_{syn}\nu^\alpha + S_{therm}\nu^{-0.1} \quad (2)$$

At wavelengths longer than approximately a few cm, free-free emission is typically fainter than the synchrotron flux density, and accurate measurements of a galaxy's radio flux density over more a large range in radio wavelengths are required in order to disentangle the two flux density components. In particular, sensitive observations at ~ 1 cm are necessary to disentangle the thermal flux density from the synchrotron emission. However, at high frequencies where the thermal component begins to dominate the radio flux density, most normal galaxies are inherently faint [10].

Once the thermal flux density is disentangled, it can be converted into an ionizing luminosity because it directly reflects the amount of ionized hydrogen. Following [10],

$$\begin{aligned} Q_{Lyc} &\geq 7.9 \times 10^{53}\ \mathrm{s}^{-1}\Big(\frac{T_e}{10^4\ \mathrm{K}}\Big)^{-0.45}\Big(\frac{\nu}{\mathrm{GHz}}\Big)^{0.1} \\ &\quad \times\Big(\frac{S_{therm}D^2}{10^{27}\ \mathrm{erg\ s^{-1}\ Hz^{-1}}}\Big), \end{aligned} \quad (3)$$

where D is the distance to the galaxy. The inequality reflects the possibility that a fraction of the ionizing photons could be absorbed by dust. This ionizing luminosity can be converted to a star formation rate following [17],

$$SFR(M_\odot \mathrm{year}^{-1}) = 1.08 \times 10^{-53}\ Q_{Lyc}(\mathrm{s}^{-1}). \quad (4)$$

Using these equations as guides, the SKA will easily be able to measure star formation rates at a redshift of $z \sim 1$ as low as $\approx 1 M_{\odot}\mathrm{year}^{-1}$, as well as provide an independent constraint on the star formations rates in Lyman break galaxies at $z \sim 3$ estimated to be tens to hundreds of $M_{\odot}\mathrm{year}^{-1}$ [27].

5. THE SQUARE KILOMETER ARRAY IN COMBINATION WITH OTHER OBSERVATORIES

Because star formation activity is primarily observable at wavelengths longer than the near-IR, the host of facilities that are becoming available now and over the next decade at thermal-IR and millimeter wavelengths are complementary to the Square Kilometer Array. While, the Atacama Large Millimeter Array, *Spitzer*, *Stratospheric Observatory for Infrared Astronomy*, and *James Webb Space Telescope* will probe the dust cocoons and molecular properties of the medium surrounding natal stars and clusters, only the Square Kilometer Array will be able to observe their HII regions with sufficient angular resolution. Therefore, the combined observations from the infrared to the radio will provide powerful and independent diagnostics of extragalactic star forming regions.

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