# The Earliest Stages of Star Formation: Massive Protostars and the SKA

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## Abstract

The high spatial resolution and sensitivity provided by the SKA will indubitably increase our knowledge on the processes that are taking place during the formation of high-mass stars. Free-free emission, recombination lines and molecular emission will be easily detected and mapped even in remote regions where these stars are located. This will enable us to investigate star formation in both clustered or isolated mode. In this Chapter, we describe the potential of SKA for studying the main processes of the early stages of massive star formation: cloud fragmentation, kinematics and chemistry of hot molecular cores, photo-ionized regions and photo-evaporating disks.

# 1 Introduction

Despite high mass stars ($> 8$ M$_\odot$) are more scarce than their lower-mass counterparts, they play an important role in many respects. Massive stars control the dynamics and chemical evolution of the Galaxy, and their powerful radiation heats, ionizes, photodissociates and evaporates the cloud where they are born and their surroundings ([80]). Therefore, they have a strong influence on the formation of the next generation of stars. Two decades ago, the main signposts of the early stages in the life of massive stars were the photoionized regions that these stars themselves produce in their surroundings (the so-called HII regions). Since HII regions are in expansion, the size of these ionized regions is taken as indicative of their youth, with the smaller ones (compact HII regions) being younger. More recently, the study with millimeter interferometers focussed on even earlier stages, the so-called Hot Molecular Cores (HMCs), considered as forerunners of the HII regions, and on the Infrared Dark Clouds (IRDCs), which are so dense and cold that they appear in absorption even at mid-infrared wavelengths.

The very high sensitivity and angular resolution offered by SKA will be essential to study the earliest phases of massive stars. Although ALMA is already doing many contributions on this topic through dust and molecular tracers, SKA will be the only instrument able to detect and map the ionized emission coming from high-mass protostars located at remote distances. That will provide the first surveys of HII regions associated with high-mass stars of a wide range of spectral types. Furthermore, SKA will be able to detect radio-jets driven by low luminosity objects (including intermediate- and low-mass protostars) born near massive stars. This will allow us to identify and record the number of companions in crowded regions, in order to find differences between isolated and clustered modes of star formation. But SKA will not only provide large surveys for statistical studies, but also it will permit detailed analysis of individual sources, which will be extremely useful, for example, to distinguish radio-jets from HII regions. On the other hand, SKA will allow us to test theoretical predictions by carrying out a sort of observations that currently are difficult to perform. This is the case of the weak ionized winds arising from photo-evaporating disks around massive protostars that may be detected by means of radio recombination lines (RRLs). In addition to these lines of research, SKA will gather complementary information through molecular lines at centimeter wavelengths to study the kinematics and evolution of the filamentary structures whose fragmentation originates the formation of dense cores where stars are formed. These molecular tracers will also allow us to study accretion and ejection processes (infall, outflow, accretion disks, etc) that will take place in cores in order to build up a star.

In this Chapter, we discuss several topics on the early phases of star formation with special emphasis in those aspects of massive star formation where SKA can make a decisive contribution.

# 2 Initial Conditions

It is well accepted that molecular clouds, which are the cradles of star formation, present a complex filamentary morphology. Despite filaments were identified more than 30 years ago ([71]), the omnipresence of such structures in star-forming complexes as revealed by recent Herschel observations ([2, 52, 7]) triggered again special attention on their formation mechanism and their role in the star formation process. It has been suggested that massive stars form at the intersection of massive filaments, the so-called hubs (e.g., [53, 29]), but still many questions remain open regarding this topic. How do filaments form and evolve?, how do filamentary structures fragment to form dense cores, and hence form stars? Several studies performed toward massive star-forming regions reveal supersonic non-thermal motions and suggest the formation of filaments by the convergence of flows or by filament-filament collisions (e.g. [72, 17, 39, 32]). However, other agents like large-scale turbulence and magnetic fields could also play a role in their formation (e.g. [58, 54]). In this sense, the SKA, specially in its spectroscopic mode, will play a major role in the study of the formation of large-scale filamentary structures and their subsequent fragmentation. The sensitivity reached by the SKA in line mode will be much higher than what other facilities can offer currently. By observing some key atomic/molecular lines we can obtain the physical conditions of the gas. The HI line at 21 cm as well as carbon radio recombination lines can trace the cold and warm neutral gas of the interstellar medium around filamentary structures probing the low-density material. One of the important molecules that have been extensively used to trace the dense gas material is ammonia, whose inversion transitions are at frequencies that will be accessible during the second phase of the SKA (SKA2). With this molecule, we can trace the dense filament itself where star formation takes place and derive the initial conditions of the gas that leads to the formation of massive stars (e.g. [63, 14]). Clearly, the velocity information provided by line observations is a crucial ingredient to study the initial conditions of star formation. It offers the possibility to investigate the level of turbulence at several scales, from the large-scale and low-density material to the dense filaments that subsequently fragment to form dense cores and hence stars, and to study the core-to-core velocity and the velocity dispersion. Not only the kinematics can reveal the presence of colliding flows but also observations of shock tracers such as $CH_3OH$ are expected to be present where flows converge. Therefore, it is clear that the SKA will open a new window for spectroscopic line studies that will shed light on the initial conditions of massive star formation.

# 3 Clustered vs Isolated Star Formation

It has been recognized for decades that the star formation process within filamentary clouds takes place in different modes. The most common is the "clustered" mode, where stars are formed in gravitationally bound pc-scale groups with stellar densities larger than $\sim$100 pc$^{-3}$, so that interactions between different stars may occur during their formation. On the contrary, stars can also form in a more distributed or "isolated" mode, where interactions between stars are very scarce. [12] studied the formation of stars in both modes through a numerical simulation of a turbulent molecular cloud and found that the star formation mode is determined by the local gravitational binding of the cloud and ultimately the density in the cloud, but other ingredients such as magnetic field, and radiative feedback [33], could play a role as well, and the question of what determines the mode of star formation remains open. This is in part because there is a clear lack in the literature of observational works characterizing a sample of clusters in their first evolutionary stages of formation, which should constrain both theory and simulations. Such a lack of observational works is due to the fact that protoclusters are deeply embedded in their molecular clouds, being obscured in the optical/infrared and mostly emitting at radio wavelengths. Thus, achieving the high sensitivity ($\sim$0.2 $M_\odot$) and spatial resolution ($\sim$1000 au) of optical/infrared studies at longer wavelengths (millimeter, centimeter), to properly study those protoclusters, is very challenging, given the current instrumentation capabilities, and the typical large distances of massive star-forming regions. Some approaches ([13, 60, 61]) are being conducted in the millimeter range by compiling sensitive interferometric observations with subarcsecond angular resolutions towards massive and intermediate-mass star forming regions located at distances <3 kpc. In these works, the authors find regions with high fragmentation levels and regions showing no signs of fragmentation (see Fig. 1), and suggest that the density of the cloud might play a role in determining the fragmentation level ([61]), in line with simulations of [12]. [60] explore the relation between fragmentation degree and other cloud parameters and suggest that strong magnetic fields could produce low fragmentation levels as well. The measurement of OH Zeeman splitting using the SKA (see Chapter by Girart et al. of this book) will allow to estimate the intensity of the local magnetic field and hence, its role in the fragmentation process. Since most of the known massive star forming regions are located further than 3 kpc, the more numerous intermediate-mass star forming regions have been used to test theoretical models ([60, 61]). However the results are not directly extrapolable to the most massive stars in which some effects, such as the radiative feedback, are expected to be more important. The SKA will allow, for the first time, to extend these works to a statistically significant sample of massive star forming regions and compare them with theoretical models.

Furthermore, because the aforementioned works focus on the millimeter range, it would be extremely useful to assess the richness of the protoclusters using an independent tracer of lower luminosity objects (i.e. of intermediate- and low-mass protostars) in massive star-forming regions. Low mass protostars are extremely difficult to detect in the millimeter range because their emission represent only a small fraction (<0.1%) of the total emission coming from the parental molecular cloud. Since low-mass protostars emit significantly in the centimeter range through the ionization of shocks generated by the propagation of their protostellar jets (also known as thermal radio jets), the centimeter range is an excellent window to study the number of low-mass protostars in a massive star-forming region. The highest frequency band available with the SKA1 (SKA-MID band 5: 4.6-13.8 GHz) will play a major role in the study of the continuum emission in protoclusters thanks to its excellent sensitivity and high angular resolution. Protostellar radio jets associated with low-mass young stellar objects are typically weak (e.g. [4, 5]). Figure. 3 of Chapter by Anglada et al. (this book) shows a correlation between the radio luminosity and the bolometric luminosity. Using the $L_{\rm bol}$ range of 10-100 $L_\odot$, the expected radio luminosity is $S_\nu d^2$ = 0.03-0.13 mJy kpc$^2$. Given that the aim is to detect emission arising from radio jets associated with the low-mass members of the protocluster at the typical distances of massive star-forming regions ($\sim$4 kpc), the expected flux density is then $\sim$2-8 $\mu$Jy. Then, the sensitivity required is $\sim$0.5 $\mu$Jy, which will be reached with the SKA in just one hour. Observations at different frequencies will allow us to determine the spectral index of the continuum emission in the centimeter range. By

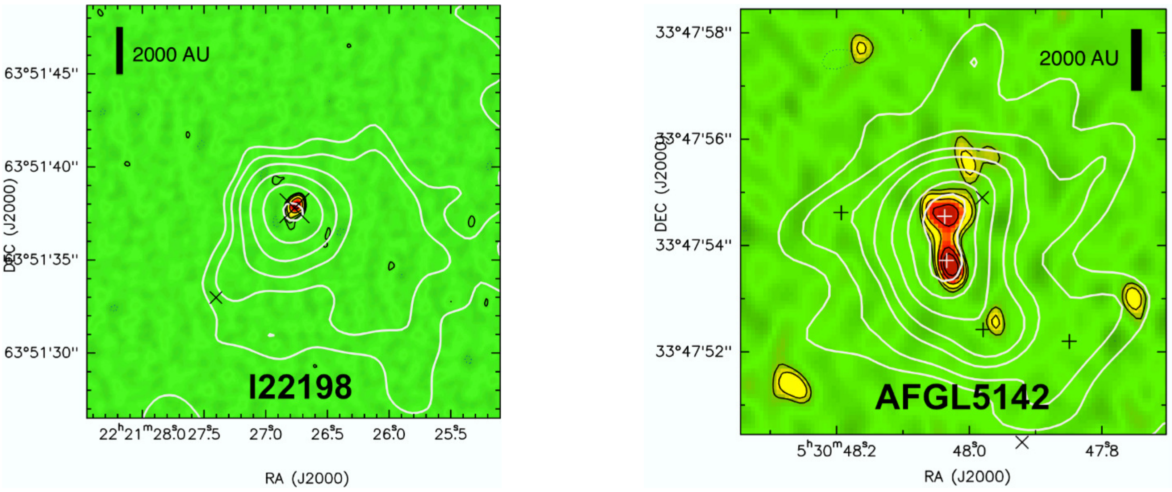


Figure 1: *Left:* IRAS 22198+6336 (I22198) star-forming region of $\sim 500\ L_{\odot}$. *Right:* AFGL5142 star-forming region of $\sim 3000\ \mathrm{L}_{\odot}$. In both panels, the color scale corresponds to the PdB 1.3 mm emission at $0\farcs4$ angular resolution ([60]) and the white contours correspond to the SMA 1.3 mm emission at $1''$-$2''$ angular resolution ([79, 67]). The plus signs indicate the sources identified by [79] in AFGL5142, and the tilted crosses correspond to mid-infrared sources. Note that for I22198 the large-scale envelope (white contours) does not split up in different subcondensations, while for the AFGL5142 case the emission splits up into around 6-7 subcondensations. The field of view corresponds to the same spatial scale for both regions (see [60]) for further details).

combining with ALMA observations in the millimeter/submillimeter range it will be possible to separate the emission coming from ionized material from the thermal dust continuum for each member of the protocluster, measure the level of clustering at centimeter wavelengths, and compare it with that found in the millimeter/submillimeter range. The SKA will open a new window to investigate the star formation process in clustered mode, by allowing to assess the number of low-mass protostars driving radio jets in distant massive star-forming regions.

# 4 Observing the Signatures of Gravitational Collapse

Although gravitational collapse should play an essential role in the star formation process, infall motions have been always elusive to a detailed study. So far, only a few observational signatures, based on the shape of molecular line profiles (1D) have been commonly used (e.g., [48]). More robust signatures, based on images that spatially resolve the infalling gas (3D) can be obtained with sensitive high angular resolution observations ([3]). These images can provide additional spatially-resolved information that allows us to further investigate the kinematics and physical parameters of the molecular core around the protostar.

Low-mass protostars provide some of the best targets to study gravitational collapse due to their proximity and often-isolated nature. Even in these objects, observations with angular resolution better than one arcsecond are required to explore the gravitational acceleration region and to separate the infalling motions from the bipolar outflow ejection. The SKA will naturally satisfy this need of high angular resolution, especially when working at the highest achievable frequencies, where sub-arcsecond observations should be routinely possible. High frequency observations are also needed to detect the lines of ammonia ($NH_3$), which lie in the vicinity of 24 GHz and represent the most reliable tracer of infalling dense gas. Ammonia seems immune to the freeze out problem that affects most other molecules, and is therefore the ideal species to determine the complex gas kinematics expected near the protostar, where infall, outflow, and rotation motions coexist in a small volume. It is therefore critical that the SKA receivers reach the high observable frequencies already planned for the full SKA design.

High mass protostars can also provide high-quality targets for the study of gravitational infall. This is illustrated by the recent VLA observations of ammonia inversion transitions that reveal, for the first time, the expected 3D signatures of protostellar infall in the very massive hot molecular core (HMC) near G31.41+0.31 ([47]; see Fig. 2). The intensity of the ammonia emission is compact and sharply increases towards the center in the blue-shifted velocity channel maps, while it shows a more flattened distribution in the red-shifted velocity channels. Additionally, the emission becomes more compact with increasing (relative) velocity for both red and blue-shifted channels (Fig. 2, central panel). A new infall signature, the "central blue spot", easily identifiable in the first-order moment maps is introduced (Fig. 2, left panel). Also, it is shown that rotation produces an additional, independent signature, making the distribution of the emission in the channel maps asymmetric with respect to the central position, but without masking the infall signatures (Fig. 2, right panel). All these imaging (3D) signatures, which are identified in G31 HMC for the first time, can be used to study other protostars, provided a high enough sensitivity and angular resolution are reached. The SKA appears as an ideal instrument to carry out a deep survey of these new 3D kinematic signatures in star-forming regions.

## 5 Hot Molecular Cores

Hot molecular cores are compact (diameters $\leq 0.1\,\mathrm{pc}$), dense ($n \geq 10^7\,\mathrm{cm}^{-3}$), hot ($T \geq 100\,\mathrm{K}$) and dark ($A_v \geq 100\,\mathrm{mag}$) molecular clumps of gas and dust in or near sites of recent massive star formation (e.g. see [43]). Nevertheless, the nature of these objects and the complex chemical and physical processes occurring in them are not fully understood. In some cases, hot cores are believed to be the formation sites of massive stars [56], more specifically the precursors of ultracompact HII regions [19]. In others, the central energizing source has not been identified and seem to be only externally heated dense cores (see, e.g., the controversial case of the Orion-KL hot core; [77]). In all cases, hot molecular cores are associated to luminous IR sources in which massive bipolar outflows, accretion disks and inflow motions are observed ([16, 59, 47]).

A common characteristic in all these objects is their extremely rich chemistry. Due

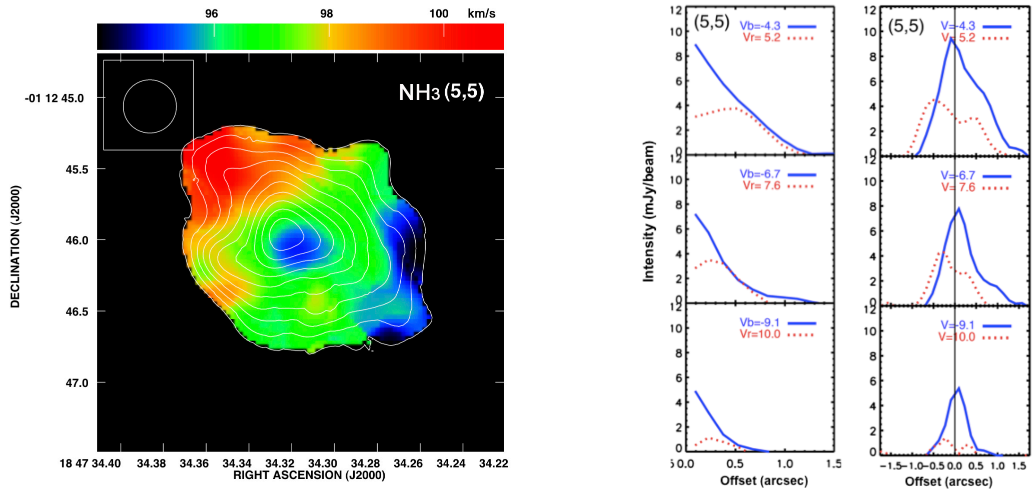


Figure 2: VLA observations of the ammonia (5,5) inversion transition in G31 HMC (from [47]). *Left:* Overlay of the integrated intensity (zero-order moment; contours) and the intensity weighted mean velocity (first-order moment; color scale) maps. The synthesized beam is shown in the upper left corner. The image shows a northeast-southwest velocity gradient and a central blue spot, indicative of infall, towards the center. *Center:* Azimuthally averaged observed intensity as a function of radius, for different pairs of blueshifted (solid blue line) and redshifted (dotted red line) channel maps. Labels indicate the channel velocity (in km $s^{-1}$) relative to the assumed systemic velocity of the cloud. *Right:* Observed intensity, averaged over half-annuli, as a function of radius. Negative offsets correspond to the NE half (redshifted first-order moment) of the source, and positive offsets correspond to the SW half.

to the phenomena associated with massive star formation, complex molecules are released from the grain mantles and subsequent gas-phase reactions give rise to high abundances of a large variety of large molecules such as $CH_3CH_2CN$ or $HCOOCH_3$ ([55, 75, 25]). However there is some controversy about the mechanism(s) that released these molecules from the grain mantles into the gas phase. Hot cores are supposed to trace the innermost parts of the condensation where the massive star is being formed. In this region, dust grains are radiatively heated by the newly formed star, increasing their temperature to $\sim$100 K and producing the evaporation of their mantles ([57]). However, the radiative heating mechanism is questioned, as some observations suggest that the complex molecules could be associated with shocks as well ([45, 18, 28, 27, 24, 77]). Recent high sensitivity and high spatial resolution millimeter interferometric observations in Orion-KL and nearby ($\sim$1 kpc) intermediate-mass star forming regions revealed that for some targets, the region where the emission of the complex molecules arises is actually the rotating disk around the young star ([59]), while in others, is associated to shocked regions along the bipolar outflow ([24, 27]). However, this kind of work is difficult to repeat for other massive star forming regions because most of them are located at a distance >3 kpc. In this sense, the SKA instrument will allow to observe the low frequency transitions of these complex molecules in large samples of massive hot cores.

Spatial distribution of molecular species such as $HCOOCH_3$, $CH_2CHCN$, $CH_3CH_2CN$, $HC_3N$, $CH_3CN$ and their vibrationally excited states have been studied in the millimeter and submillimeter domain (see, e.g., [46, 22, 20, 8]) but never at the SKA wavelength coverage due to the limited sensitivity of current instruments. The high sensitivity of SKA will provide the detection of these species, even for high energy vibrationally excited states. Frequencies of low $J$ rotational transitions in the vibrationally excited states of these complex molecules are inside the SKA coverage, most of them between 4 and 20 GHz (see, e.g., [20, 42]; JPL catalog).

At the final phase of SKA, full SKA will cover frequencies up to 24 GHz. At this point, we will have a unique opportunity for studying ammonia emission in hot cores with a high sensitivity. The Orion-KL hot core was discovered by [34], who identified it as a compact and hot source of ammonia emission, an ubiquitous molecule in hot cores. Because of its high abundance and its spectroscopic characteristics, ammonia will probably be the most valuable tool to determine the physical conditions and study the kinematics of the warm ($T_k$>100 K) gas associated with hot cores. Recent high spatial resolution observations of the ammonia inversion transitions using the upgraded VLA showed that ammonia molecules in Orion-KL have been released into the gas phase through the passage of shocks and not by stellar radiation ([27]). Thus far, this kind of study can only be done in the closest massive hot core, Orion-KL, that might not be representative of most hot cores. The full SKA will allow to observe large samples of hot cores in ammonia emission and provide the first statistically significant sample to investigate the nature of these objects and their relation with the mid/high mass star formation process.

## 6 Ultracompact (UC) HII regions

High-mass stars with high temperatures ($> 10^4$ K) emit large amounts of energetic photons ($h\nu > 13.6$ eV) that ionize the surrounding gas (mainly hydrogen), which results in the development of a region of ionized gas, known as HII region. This is one of the clear signposts and main differences of high-mass star formation with respect to low-mass star formation. In the last stages of the formation of a high-mass star, HII regions appear as gigantic structures (size $\sim$ 10–100 pc, electron density $\sim$ 10–100 cm$^{-3}$) that have already dispersed the material of the natal cloud. However, at the onset of the process, HII regions are much more compact ($<$ 0.1 pc) and have higher densities ($> 10^4$ cm$^{-3}$; [44]). This kind of objects — known as hypercompact (HC) and ultracompact (UC) HII regions — are deeply embedded in dense gas, and possibly still accreting in the form of ionized accretion flows ([41]). Their lifetimes have been measured to be longer than expected when assuming a simple model of expansion, which implies the existence of certain mechanisms that prevent the expansion and confine the HII regions [66]. Co-existing with these "young" HII regions, or even prior to their development, the first manifestation of ionized gas is the presence of outflowing ionized material in the form of collimated jets or winds (with sizes $\sim$ 100–1000 au, and velocities $\sim$ 500 km s$^{-1}$), that are likely directly related to the large-scale molecular outflows seen in many star forming regions ([6]). The study of the ionized gas is therefore, crucial to understand the accretion and feedback processes at the onset of high-mass star formation. The observations are, however, challenging due to the high sensitivities and angular resolutions that are required. HC HII regions have sizes $\sim 0.01$ pc, which at the typical distances of high-mass star forming sites ($> 3$ kpc) correspond to $< 0''.5$ [68]. It is also necessary to reach sensitivities $\sim 2$ $\mu$Jy at radio wavelengths (1–10 GHz) in order to detect the free-free emission of HII regions associated with all high-mass stars (from B3 to O4 spectral types). Finally, a high dynamic range and good image fidelity are necessary to properly map the compact and weak HC and UC HII regions that are likely to be found in the vicinity of large (1 pc), bright (1 Jy) and more evolved HII regions.

The SKA, with its high sensitivity, angular resolution, and good image fidelity, becomes the ideal instrument to study the photo-ionized gas in the first stages of high-mass stars formation by means of continuum and spectral line observations.

In the continuum, the high sensitivity that SKA offers will permit to carry out large surveys of galactic HII regions over the whole Galaxy, providing for first time a statistically significant sample of HII regions associated with high-mass stars of all spectral types (and not only detections of the more massive ones as is possible nowadays). Observations at different frequencies (from 1 to 24 GHz) will permit to construct the spectral energy distribution of ionized gas sources to help to determine the nature of the emission (optically thick/thin photoionized HII region, wind, radio jet) and the spatial structure (density gradients) of the ionized gas. We expect optically thick free-free emission (spectral indices close to +2) for deeply embedded, compact HII regions, and flatter spectral indices for thermal radio jets or winds (see Chapter by Anglada et al. in this book). High-angular resolution, multi-frequency continuum observations will resolve the structure of HC HII regions and permit to study the morphology, size, and flux dependence with frequency. These properties, together with the luminosity of the sources, will allow us to characterize the emission and structure of the sources. Given the positive spectral indices, observations in the high frequency bands of SKA (10–20 GHz) are fundamental for their study. Finally, recent works ([65], [66]) have proposed that HII regions should undergo flickering (i.e., changes in their brightness and morphology) on short periods of time due to changes in the accretion rate. SKA will easily test this scenario via multi-epoch, high-angular, and sensitive continuum observations.

Complementary to the continuum, spectral line observations of HI and recombination lines will give us information on the kinematics of the ionized and atomic gas at scales of $\sim$100 au (see Fig. 3). This high spatial resolution is required to probe the thin gas layers where the energy interchange between the parent molecular cloud and the nascent massive star occurs and eventually determine the evolution of the HII region ([69, 70]). The intensity of these lines is estimated to be only 1–10% the intensity of the continuum in the radio regime. SKA will observe hundreds of recombination lines in the different bands, that when stacked will improve the sensitivity and provide clear detections.

# 7 Disks Photoevaporation

There is increasing evidence that massive stars form by gas accretion through neutral, molecular circumstellar disks ([62, 15, 38]). These neutral massive disks are expected to suffer

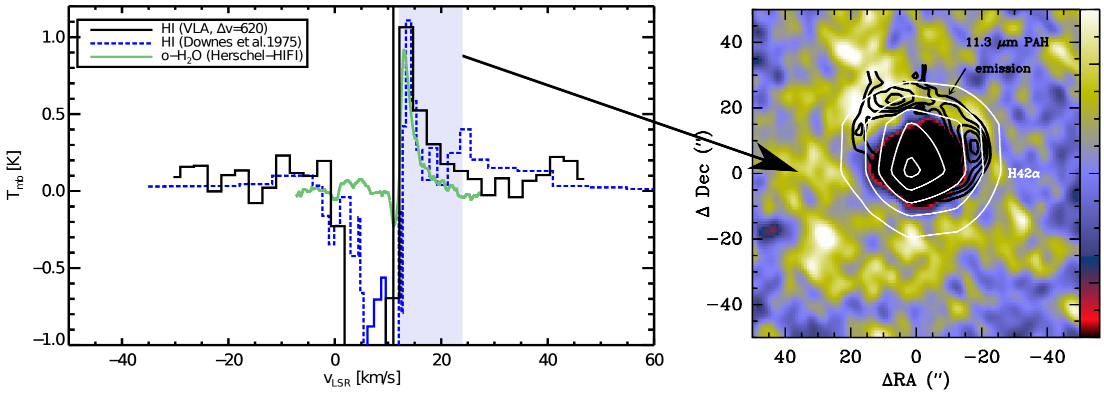


Figure 3: *Left:* Comparison of the HI spectra observed with the VLA, the single-dish observations of [21] (blue line), and the ortho-$H_2O$ ($1_{1,0} \rightarrow 1_{0,1}$) observations observed with Herschel ([64]; green line). *Right:* Image of the integrated intensity of the HI emission at red velocities (12−24 km s$^{-1}$) obtained from the HI VLA map. The HI emission arises in correspondence with the emission at 11.3 $\mu$m of polycyclic aromatic hydrocarbon (PAH) molecules ([11]; black contours) tracing the photodissociation region. The HI absorption is observed toward the UC HII region (in white contours), which is traced by the integrated intensity of the H42$\alpha$ recombination line observed at the IRAM 30m telescope (S. Treviño-Morales & A. Sánchez-Monge, private communication).

strong photo-evaporation as a consequence of the intense UV radiation field arising from the central star. Theoretical models predict that the photo-evaporation of circumstellar disks may lead to the formation of ionized disk winds at the late stages of massive star formation ([36, 30]).

The detection of ionized winds in photo-evaporating disks has been attempted mainly by performing observations of the continuum emission at centimeter wavelengths where the contribution from thermal dust emission is much smaller. Some examples are the emission line star MWC349A ([49, 74]), S140 IRS1 ([35], [51]), Cepheus A HW2 ([38]) or LkH$\alpha$ 101 ([76]). For most of these sources, the radio continuum emission from their ionized photo-evaporating component is very faint (ranging from 0.1 to 1 mJy/beam; [35, 38]), which gives an idea of how challenging the detection of these winds is with current instrumentation. The detected continuum emission follows the disk surface (as in e.g. Cepheus A HW2 or MWC349A; see Fig. 4), which supports the idea that ionized winds are produced by disk photo-evaporation. We note however that only for the exceptional case of MWC349A, which shows RRLs with non-LTE (maser) emission, we know in detail the launching radius and physical structure of the photo-evaporating ionized wind ([50, 10, 9]).

The SKA1, which will operate at wavelengths between 50 MHz and 13.8 GHz (from 6 m to 2 cm), will represent a break-through in the study of photo-evaporating disk winds in massive star forming regions thanks to its unprecedented sensitivity and high-angular resolution imaging capabilities at centimeter wavelengths. The continuum emission associated with photo-evaporating disks (of the order of 0.1-1 mJy) will be readily detected with the

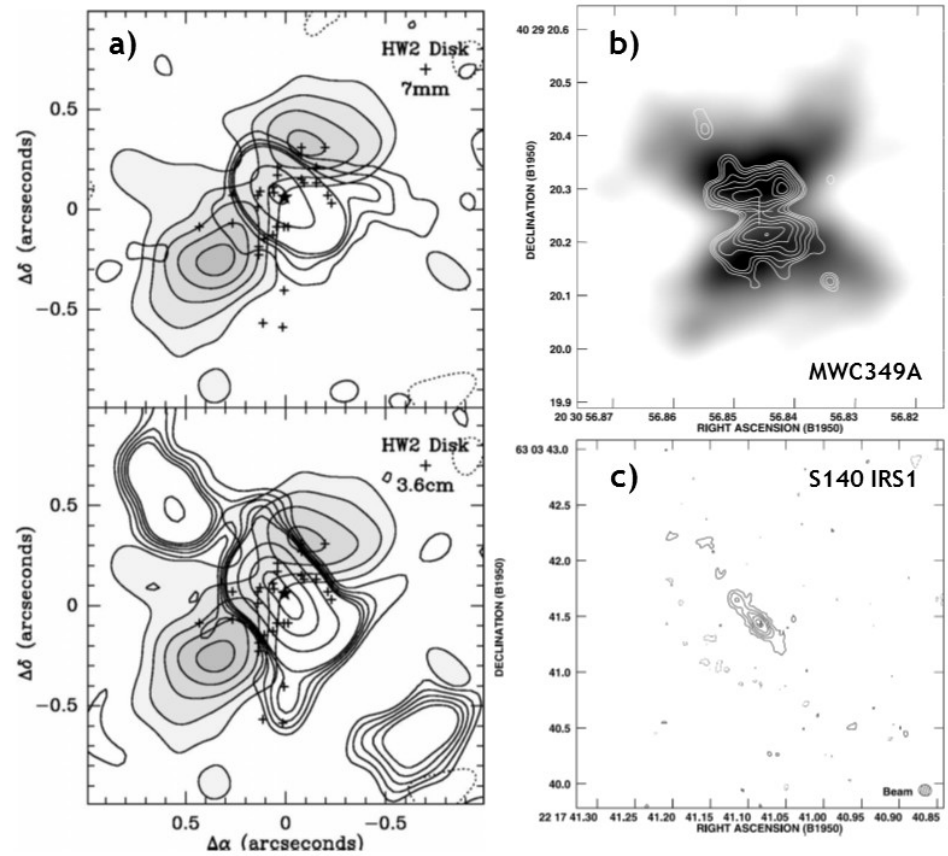


Figure 4: *(a)* Interferometric images of the Cepheus A HW2 massive star forming region (from [38]). The neutral molecular disk is detected in $SO_2$ with the VLA (gray scale and think contours). In addition to the thermal radio jet (in the direction perpendicular to the disk), the radio continuum emission at 3.6 cm and 7 mm shows an extra, fainter component that fills the surface of the disk. This component is possibly associated with the photo-evaporation of the neutral disk. *(b)* Radio continuum images obtained toward the emission line star MWC349A at 1.3 cm (in gray scale) and 7 mm (in contours; [74]). The photo-evaporating material fills the cavity left by the neutral disk (in the east-west direction). *(c)* Radio continuum emission reported by [35]) at 6 cm toward the S140 IRS1 massive protostar. The continuum emission arises from an equatorial wind produced by the disk photo-evaporation.

SKA1 in Band 5 since the expected rms is $\sim$1 $\mu$Jy hr$^{-0.5}$ for a 0.″1-beam and $\sim$ 4 $\mu$Jy hr$^{-0.5}$ for a 0.″03-beam. In addition, based on our model of MWC349A ([10, 9]), the predicted peak intensity of the H80$\alpha$ line emission at 12.6 GHz arising from the wind is 5.6 mJy for a 10 km s$^{-1}$ velocity resolution (note that the RRL linewidths are, at least, a few tens of km s$^{-1}$; [37]). This emission will be detected with the SKA in Band 5 with a signal-to-noise ratio $\geq$35 for a 0.″1-beam (rms $\sim$160 $\mu$Jy) in just 1 hour of integration time. The high signal-to-noise ratio of the RRLs detected toward MWC349A will allow to image with SKA2 the rotation and angular momentum transport of its ionized wind with extraordinary detail down to spatial scales of $\sim$ 100 au. We would like to stress that the higher the frequency of the observed RRL, the brighter the predicted intensity of these lines (their flux increases as $\nu^{1.1}$), making the Band 5 receivers of the SKA1 (from 4.6 GHz to 13.8 GHz) an essential component in the study of photo-evaporating disk winds around massive protostars.

For an object at a distance of 1 kpc with a mass loss rate a factor of 50 lower than that of MWC349A (i.e. similar to those of Cepheus A HW2 or S140 IRS1), the detection of the H80$\alpha$ RRL emission from the photo-evaporating disk would require 50 hours of integration time to achieve a signal-to-noise ratio $\geq$4 (intensity of 31 $\mu$Jy) in a 1″-beam and a velocity resolution of 30 km s$^{-1}$ (rms$\sim$7.5 $\mu$Jy). We note however that this integration time is expected to be reduced by a factor of 100 during the second phase of the SKA (SKA2). This will open the possibility not only to detect many more of these photo-evaporating disks but also to understand the physical processes involved in the formation of ionized disk winds around massive protostars.

## 8 SKA Synergy with Herschel and ALMA

Infrared surveys, in combination with complementary multiwavelength observations, have produced an extensive sample of well studied protostars, covering a wide range of luminosities, evolutionary stages and a broad range of initial environmental conditions (e.g., the Herschel Orion Protostar Survey (HOPS) in the Orion Molecular Cloud at a distance of 420 pc; [1, 26]). These observations yield protostellar Spectral Energy Distributions (SEDs) that are well-sampled over several orders of magnitude in wavelength. Combined with detailed radiative transfer modeling, these powerful data-sets have made it possible to infer physical properties (total luminosity, mass, density, temperature, mass infall rate, geometry parameters, etc.) of the dusty envelopes and disks around protostars. The excellent sensitivity, high-angular resolution and large field of view of SKA make it an ideal instrument to perform complete, deep surveys of the protostellar population in large fields. We expect that these observations will detect radio jets essentially in all the previously known sources, including very low luminosity objects, and extremely young protostars (the so-called PBRs; [73]) providing a tracer of outflow (and thereby accretion) unbiased by extinction and the capability to identify previously unknown multiple systems. It is well known that there is a dependence on outflow momentum rate and source luminosity; the next question we want to answer is whether there is a dependence on evolution. The SKA data will complement the observations at shorter wavelengths which primarily trace the evolution of the infalling envelopes, and thereby provide an important component in constructing a comprehensive audit of infall, accretion and outflow in these sources.

On the other hand, ALMA will characterize the physical conditions and chemistry of the molecular gas in hundreds of individual protostars through the rotational lines of a wealth of molecular species from CO and its isotopologues to light complex organic molecules [40]. In contrast with low mass stars, the gas in the vicinity of a massive star is ionized by the stellar UV radiation and forms a compact HII region while the young star is still accreting matter from the molecular cloud. Therefore, we need to probe the ionized, atomic and molecular gas to understand the complexity of the accretion and outflow processes in massive protostars. The SKA will provide access to different tracers of the ionized and atomic gas at comparable spatial resolution and sensitivity as provided by ALMA in molecular lines. For individual protostars, the SKA will resolve and characterize the youngest compact HII regions and their interfaces with the molecular cloud through observations of the hydrogen and carbon RRLs and of the HI 21cm line. Together with the continuum emission, these lines will also inform on the kinematics and physical conditions of the gas in the ionized jets and of the atomic gas in the innermost layers of the PDRs formed on the walls of the cavity excavated by the outflow. The high spatial resolution and sensitivity of the SKA will be enough to resolve the UV illuminated surfaces of circumstellar disks and detect the photoevaporating flows emanating from them. In conclusion, the tandem SKA and ALMA will allow to study at high spatial resolution the morphology, dynamics and chemistry of all the gas (ionized, atomic, molecular) involved in the formation and early evolution of a massive star, and surely will lead to an unprecedented advance in the comprehension of this complex process.

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