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Millimeter/submillimeter observations of massive star forming regions

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Despite their importance in shaping the interstellar medium, the formation of massive stars is not well understood, although much progress has been made the last couple of years. In this talk, I will present mm/submm surveys of massive star forming regions to investigate the initials conditions and early phases of massive star formation. The ultimate goal is to establish an evolutionary scheme for the formation of massive stars, which requires in addition the high spatial resolving power of interferometers. I will therefore give also examples of high resolution studies of selected massive star clusters in the making. I will briefly present the capabilities of the new APEX telescope and the upcoming ALMA interferometer for massive star formation research in the mm/submm and will then turn to the promising prospects of the SKA to provide answers to the understanding of massive star forming regions.

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1. Introduction

The influence of high mass stars on the interstellar medium is tremendous: during their process of formation they are sources of luminous, bipolar outflows, their strong ultraviolet and far-ultraviolet radiation fields give rise to bright HII and photon-dominated regions, and during their whole lifetime powerful stellar winds interact with the surroundings. In the course of time, this leads to the destruction of the parental cloud. Finally, their short life ends in a violent supernova explosion, injecting heavy elements into the interstellar medium and possibly triggering further star formation with the accompanying shocks. All these points together underline the importance of formation and evolution of massive stars also for the understanding of galaxies as a whole (see proceedings from the IAU 227 conference on massive star formation by Cesaroni et al. 2005 and from “Massive Star Formation: Observations confront Theory", Beuther et al. 2007).

The current picture of the process of star formation has mainly emerged from the study of regions of low mass star formation. This is understandable in view of the smaller distances to low mass star forming regions (100-200 pc, in contrast to at least 400 pc for regions with OB star formation) and the existence of a so-called isolated mode of star formation where individual stars form relatively undisturbed in individual molecular cores (Lada 1991; Shu et al. 1993). The dominant mode for massive star formation is the so-called clustered mode in which low and high mass stars form together leading to the creation of OB associations. A further complication is the above mentioned strong influence of already formed high mass stars on new generations of forming stars altering the conditions for star formation in a complicated fashion.

To progress in our understanding of massive star forming (MSF) regions, observations in the millimeter/submillimeter (mm/submm) range of of particular importance: the dust continuum emission of MSF clumps can studied while still optically thin, hence it enables direct access to the mass distribution of the objects. mm/submm dust observations are also an ideal tool to search for very cold objects, which are not detected in infrared surveys. Many rotational lines from important molecules fall in this wavelengths range (e.g. CO, HCN, HCO^+, N_2H^+, CH_3CN, HNCO, SiO, to name only a few) which allow to study the cooling of the MSF clumps, their chemistry and physical conditions. With higher rotational excitation to smaller wavelengths the critical densities of the transitions increase so that the observed lines probe deeper into the interior of the clumps, closer to where the actual star formation takes place.

There is no well-established evolutionary scheme for high mass star formation yet, in contrast to the detailed framework of classes that exists for the early evolution of low mass stars. In the 1990s, targeted surveys found many ultracompact HII regions (Wood & Churchwell 1989b), and in subsequent follow-up observations, hot molecular cores associated with them (Cesaroni et al. 1992) as early stages in the life of massive stars. More recently, so called high mass protostellar objects (HMPOs) or massive young stellar objects (MYSOs) were recognized likely to represent an even earlier stage of massive star formation (e.g. Beuther et al. 2002b,c). Very recently, cores within InfraRed Dark Clouds (IRDCs) were found to be promising candidates for even earlier stages in the formation of massive stars (see Menten et al. 2005; Wyrowski 2007, and references therein), sometimes called pre-protocluster cores.

In this contribution, only a few selected observing projects towards massive star forming regions can be described. In Sect. 2 surveys for early phases of massive star formation are presented

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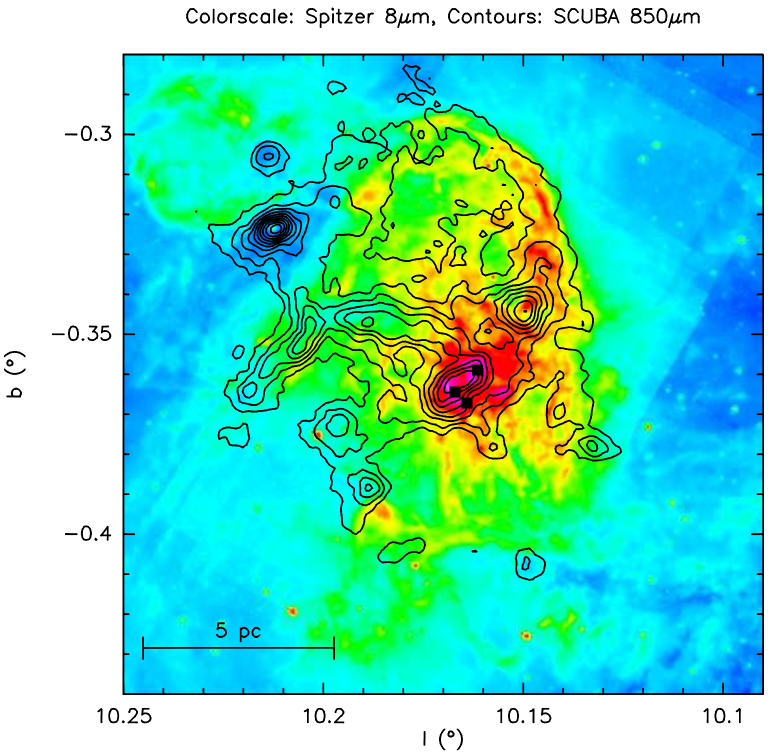

Figure 1: The giant molecular cloud associated with the ultracompact HII region complex G10.15–0.34 (HII regions marked with black squares). The colorscale shows the 8 μm mid-infrared emission from the Spitzer/GLIMPSE survey. The SCUBA dust continuum emission from (Thompson et al. 2005) is overlaid with contours.

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and Sect. 3 gives 2 examples of detailed studies of selected objects. Sect. 4 gives a brief introduction into the new submillimeter facilities on the Chajnantor plateau in Chile and Sect. 5 discusses prospects for the SKA in the field of massive star formation.

2. Surveys for the early phases of massive stars

In the past, most young massive star forming regions were found by their association with compact HII regions, maser emission and infrared sources with characteristic colors from e.g. the IRAS point source catalog (e.g. Wood & Churchwell 1989a; Molinari et al. 1996; Walsh et al. 1998; Sridharan et al. 2002).

Further progress to find even earlier stages was brought by the availability of sensitive bolometer arrays to probe the cold dust content of potential massive star forming regions, which are not yet associated with HII regions and bright infrared sources. Examples are the recent surveys conducted with the SIMBA 1.2mm bolometer array (Nyman et al. 2001) at the SEST telescope (Faúndez et al. 2004; Hill et al. 2005; Beltrán et al. 2006).

A large sample of ultracompact HII regions was observed by Thompson et al. (2006) with the SCUBA bolometer array. They found many regions with evidence for secondary dust emission peaks and went back to 37 of these fields to obtain large 13”^{2} dust continuum maps (Thompson et al. 2005), which resulted in the detection of many new massive clumps. Their masses are sufficient for cluster formation, but they have luminosities still below those of O and B stars, which indicate a very early stage of cluster formation. Pillai et al. (2007) carried out molecular line follow-up observations of infrared quiet sources in the fields. From Effelsberg 100m telescope ammonia observations, they found typical temperatures of the clumps between 10 and 20 K. Millimeter line follow-ups with the IRAM 30m telescope revealed high deuteration of ammonia and depletion of the gas, hence indicators for a cold stage of the clumps before or very to close the formation of stars. An example is given in Fig. 2 which shows Spitzer/GLIMPSE mid-infrared emission as colorscale with contours from the SCUBA dust continuum emission overlaid. The ultracompact HII regions in the field are marked by squares. Many parsec-scale dense clumps can be seen, a fraction of them not associated with 8 μm emission, hence without signs of heating sources.

Another opportunity to probe early stages of star formation is provided by so-called Infrared dark clouds, cold and dense molecular clouds seen in silhouette against the bright diffuse mid-infrared (MIR) emission of the Galactic plane. They were discovered during mid-infrared imaging surveys with the Infrared Space Observatory (ISO, Perault et al. 1996) and the Midcourse Space Experiment (MSX, Egan et al. 1998). Recently IRDCs from the sample of Carey et al. (1998) were studied by Pillai et al. (2006) in ammonia: they find a trend of increasing temperature from cold IRDCs with high ammonia column density over high mass protostellar objects to the hot core/UC HII regions – very suggestive of an evolutionary trend. Also, based on their recent MAMBO study of IRDCs, Rathborne et al. (2006) conclude that IRDCs are the cold precursors to star clusters. This is supported by growing evidence for ongoing massive star formation in IRDCs (Ormel et al. 2005, Pillai et al. 2006).

The most systematic observational approach to probe all stages of massive star forming regions are Galactic plane surveys. Infrared surveys such as MSX and the new Spitzer Space Observatory GLIMPSE survey (Benjamin et al. 2003) are biased towards stages where sources of luminosity have already formed within the clumps. The above mentioned IRDCs will only give incomplete statistics since whether clouds show up as IRDCs depends strongly on the MIR background and the evolutionary state and geometry of the parental giant molecular cloud. Therefore surveys in the mm/submm range are needed. The first Galaxy-wide continuum survey at submillimeter wavelength is ATLASGAL conducted with the 850μm LABOCA bolometer camera at the APEX telescope. It has finished its first coverage of the inner Galactic plane (Schuller et al., in prep.) and reveals thousands of sources, many of them only detected at mm/submm wavelengths.

3. Detailed studies of selected regions

The evolutionary sequence of massive star forming regions can be studied either by surveys of a large sample of young massive star forming regions selected to cover a wide range in evolutionary phases or by studying in detail template regions which harbor several of these phases simultaneously. Two examples of instructive detailed studies are given in the following two sections.

3.1 APEX and ATCA observations of the southern hot core G327.3-0.6 and its environs

An example of such a region is the giant molecular cloud associated with the bright southern hot core G327.3–0.6 which has the potential of becoming a southern hemisphere hot core template for upcoming observatories like ALMA and was therefore studied with APEX (Wyrowski et al.

2006) and ATCA (Wyrowski et al. 2007). On a 0.03 pc scale these observations show a compact and bright single hot core in the G327.3–0.6 region with a mass of 500 $M_\odot$ and a luminosity of $0.5-1.5\times10^5$ $L_\odot$. Additionally a fragmented clump is seen in N_2H^+. The N_2H^+ emission avoids the hot core itself. The hyperfine structure of the (1-0) lines is partly resolved in the observations and therefore the optical depth and the excitation temperature and, in turn, the N_2H^+ column density of the cores can be determined. These parameters can be used together with Non-LTE molecular radiative transfer modeling (RADEX, van der Tak et al. 2007) of the higher excited lines observed with APEX to constrain the density of the cores. To reproduce the strong emission of the higher-J N_2H^+ lines, densities of at least 5×10^6 cm^{-3} are needed. Together with the observed sizes this points to masses of order few hundred $M_\odot$, hence similar to the hot molecular core. The observed line widths of N_2H^+ can be used to estimate the virial masses of the cold cores, which are only several 10 solar masses, hence these cores are likely gravitationally unstable and therefore represent a promising and rare example for massive pre/protocluster cores. Together with cm continuum observations, the data reveal several stages of massive star formation associated with the one parsec clump, with the youngest stages likely hiding in the cold N_2H^+ cores analyzed with a multilevel study of the APEX and ATCA observations.

3.2 IRAS 05358+3543

IRAS 05358+3543 is one of the closest in the sample of IRAS color selected massive star forming regions by Sridharan et al. (2002) at a distance of 1.8 kpc.. The Beuther et al. (2002b) single dish dust continuum study resolved the sources already into several clumps which were found to be associated with several collimated outflows (Beuther et al. 2002a). Subsequently, Beuther et al. (2007) and Leurini et al. (2007) conducted more detailed mm/submm continuum and line studies with the PdB and SMA interferometers, pushing the angular resolution at the limits of what currently can be accomplished in the mm/submm range. The high angular resolution revealed as substructure in the inner 0.1 pc a massive protocluster with at least four cold and hot cores (Figure 2(a)). The core from which the most collimated massive molecular outflow originates is associated with a methanol maser, a hypercompact HII region and a mid-infrared source. With the highest resolution images, it splits up into a double-source with a projected separation of 1700 AU. One of them, likely the main powerhouse of the region, is a hot molecular core with a temperature of 220 K (Figure 2(b)) and shows evidence for a massive circumstellar disk. In a projected distance of only about 0.1 pc, the least active of the millimeter sources, could be a starless massive core, which is cold ($T<20$ K) and massive, but no molecular emission peaks on it.

4. APEX and ALMA

Given their importance for the field of massive star formation, the new mm/submm facilities on the Chilean Chajnantor plateau, APEX and ALMA are briefly described.

APEX, the Atacama Pathfinder EXperiment Güsten et al. (2006a,b), is a new submillimeter facility in the southern hemisphere. It's dish has a diameter of 12 m and it is a modified copy of the American ALMA prototype antenna. It is located at 5100 m in northern Chile on the Chajnantor Plateau , the future ALMA site. With its surface accuracy of 17 μm and the outstanding atmospheric conditions of the high site, observations in all atmospheric windows up to 200 μm are

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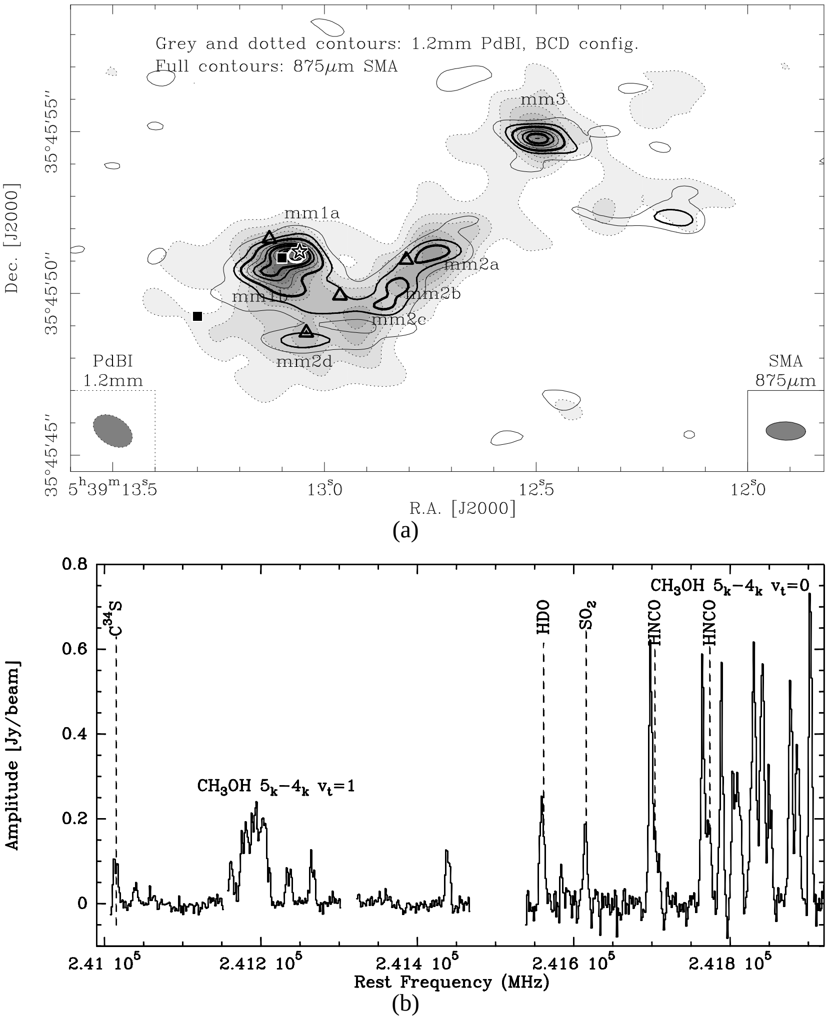

(a)

(b)

Figure 2: a) (Sub)mm continuum images toward IRAS 05358+3543 at 1.2 mm (PdBI) and at 875 μm (SMA) taken from Beuther et al. (2007). In grey-scale with dotted contours the 1.2 mm data (BCD configuration) is shown and in full contours with increasing thickness the 875 μm data. The star, triangles and squares mark the positions of Class II CH_3OH and H_2O masers and mid-infrared sources. b) Molecular spectrum of mm1 taken from Leurini et al. (2007).

possible. It is a collaborative effort of the Max-Planck-Institut für Radioastronomie (MPIfR), the Onsala Space Observatory (OSO) and the European Southern Observatory (ESO) who share the observing time (45% MPIfR, 24% ESO, and 21% OSO) in proportion to their investments, with 10% allocated to the Chilean host nation. All atmospheric windows accessible from ground will be covered by receivers in the course of the operation of the telescope. Results from the first heterodyne observing campaigns were published in a Astronomy and Astrophysics special issue in 2006. A powerful 300 pixels 850 μm bolometer camera, LABOCA, was commissioned in mid-2007 and is delivering now first results. APEX will be a pathfinder for other submillimeter wavelength missions, most of all for the Atacama Large Millimeter Array (ALMA) with is in construction on the Chajnantor Plateau and will consists of at least 50 submm telescopes (for details see the contribution by Tony Beasley, this volume).

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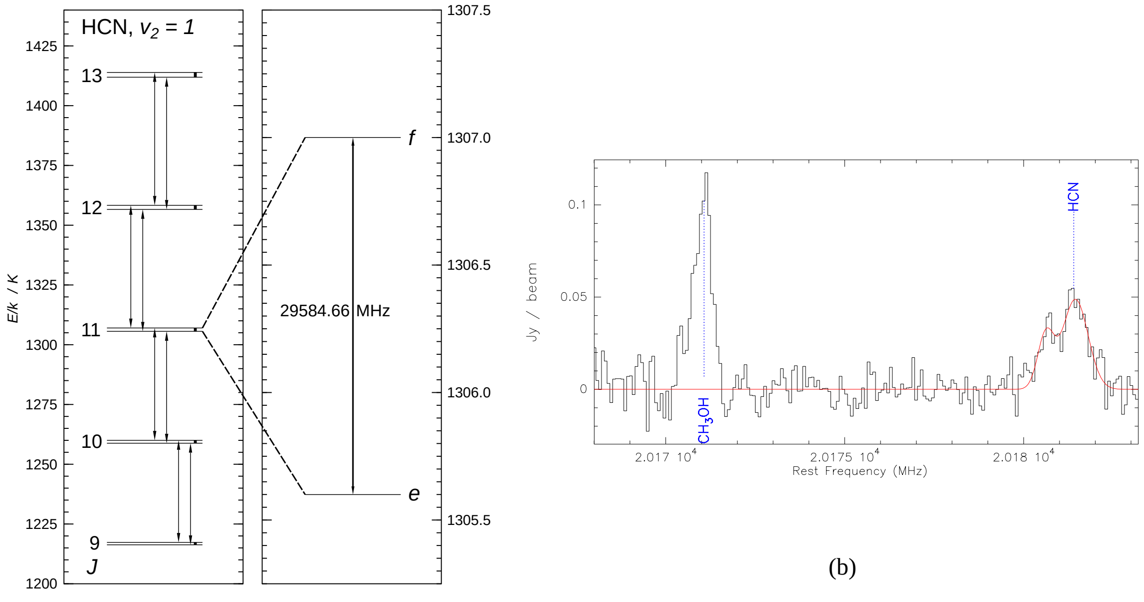

(a)

(b)

Figure 3: a): HCN energy level diagram illustration the direct *l*-type transitions (Thorwirth et al. 2003). b) HCN direct *l*-type spectrum towards SgrB2 (Thorwirth 2001).

5. Prospects for the SKA

Despite the current high impact of mm/submm observations on the field of massive star formation, there are a couple of shortcomings: e.g. in the submillimeter, towards the innermost, high column density parts of massive star forming cores, the dust might get optically thick, so that line emission from the inner parts is not accessible. Even if lines can still be detected, in many hot molecular cores the line density in the spectra gets very high so that the detection of weaker lines from highly excited states or optically thin isotopologues is limited by confusion. Here the SKA will have an impact: at cm wavelengths the line blending problem will be greatly reduced. And even optically thin, high excitation lines are observable. An example are direct ℓ-type transitions: Coriolis forces lead to an interaction of bending vibration and rotation and to a small split in the energy levels called ℓ-type doubling (Figure 3(a)). Direct ℓ-type transitions were observed for the first time by Thorwirth et al. (2003) from the HCN molecule (Figure 3(b)). They trace highly excited rotational and vibrational excited states about 1400 K above ground. The first extragalactic observations of these lines towards the starburst galaxy Arp220 were presented on a poster by Momjian et al. (this conference). Rotational transitions having $J = 11 \ldots 13$ would otherwise only be observable in the THz range and therefore, these lines might be a unique tool to investigate highly excited gas at centimeter wavelengths in a variety of astrophysical environments. To longer wavelengths, even direct ℓ-type transitions from HCCCN should be observable.

But there are also many other important applications in the centimeter wavelengths range: Ammonia as a interstellar thermometer was already mentioned several times. With the high sensitivity of the SKA, also non-metastable transitions could be establish as a tool to probe very high volume densities. $^{15}NH_3$ would help to constrain column densities in cases where the main isotopologue

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becomes already optically thick (Wyrowski & Walmsley 1996). Even in cold cores ammonia is still observable in the core centers where many other molecules are already frozen out onto the grains (Tafalla et al. 2002). With high angular resolution, the SKA will be able to study the kinematics, temperature gradients and mass function of such objects in detail (e.g. Wang et al. 2008).

In the study of recombination lines the SKA can make many contributions: carbon recombination lines are a powerful probe of the dense gas content of photon dominated regions (Wyrowski et al. 1997). The high sensitivity of the SKA will allow many studies of hydrogen recombination lines in external galaxies to derive star formation rates without obscuration by dust (e.g. Anantharamaiah et al. 2000).

Furthermore, the astrochemistry of complex large and heavy organic molecules can be studied with the SKA with a much higher sensitivity than what currently is being done with the Green Bank telescope (e.g. Snyder et al. 2006). It's sensitivity will even be sufficient to detect at centimeter wavelengths the dust emission from protoplanetary disks where the emission is optically thin. The centimeter range will be especially important to probe emission from large dust grains where the dust opacity index is low. Finally, non-thermal continuum emission from young stellar objects (e.g. Wilner et al. 1999) should be mentioned as a possible field of research as well as high sensitivity maser searches.

6. Conclusions and outlook

With a growing number of mm/submm dust emission surveys, used in combination with IR surveys of the Galactic plane, this is a very prolific time for the identification of the initial stages of massive star forming regions. The surveys reveal many new object and constrain the properties of massive cold clumps. mm/submm interferometer are now powerful enough to distinguish different stages of star formation within the clumps. For a proper analysis, the multi-wavelengths information from centimeter to MIR wavelengths are crucial. For the SKA, its high frequency part will be key for high mass star formation studies.

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