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From Clouds to Protostellar Cores

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Abstract. Understanding the evolution of cores into protostellar envelopes is important in the star formation study. The initial condition of star formation such as density structure, kinematics, chemical composition, and magnetic field of dense cores can be derived from high resolution molecular line and continuum images at millimeter/submillimeter wavelengths. Besides, most low-mass stars are formed in clusters although the study of protoclusters is still rudimentary because of lack of observations with sufficiently high resolution to resolve individual cores/envelopes. High resolution observations with the coming SMA and ALMA will be crucial to testing and improving theoretical models of low-mass star formation.

1. Introduction

Star formation is one of the most fundamental processes in astronomy. A molecular cloud complex is a site of star formation and a dense core is natal to form stars. With recent progresses of astronomical instrumentation, a lot of data of dense cores with or without stars have been accumulated in the last decade providing more concrete understanding of the star formation process. Although theoretical models reasonably reproduce observational properties of dense cores, details in the star forming process and key parameters are still not well clarified. This is partly because our understanding is mainly based on relatively isolated dense cores such as Bok globules or ones in the Taurus molecular cloud and because current observations do not well resolve the structure on core/envelope/disk scale simultaneously. This contribution attempts to provide a critical review of current understanding of star formation in terms of observations of dense cores. Only low-mass star formation is treated and in particular the phase from pre-stellar to protostellar cores will receive special attention.

The outline of this review is as follows. In §2, the observational data are presented by stressing high resolution. Importance of calibration is also emphasized to obtain reliable results. Summary and future prospects will be briefly mentioned in §3.

The topics in this review is too wide to be covered in depth and thus relevant topics, density structure, infall motion, chemical properties, turbulence, magnetic field, disk formation, and cluster kinematics are reviewed in more details by other contributers in this volume (Ward-Thompson, Ohashi, Aikawa, Matthews, Vázquez-Semadeni, Hogerheijde, and Di Francesco). More compre-

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hensive reviews of low-mass star formation can be found in the textbook by Hartmann (1998) and in the review by Evans (1999).

2. Observations of starless and protostellar cores

Star formation is not a very efficient process and only a small fraction of molecular cloud material appears to turn into dense cores or stars. Although magnetic fields or turbulent motions are likely against gravitational collapse, it is not clear how these physics comply with the low efficiency of star formation. Young stars are not randomly distributed in a cloud but rather more or less clustered even in the Taurus Molecular Cloud where a distributed star formation occurs. The mechanism to form such clusters and its evolution is not well understood. Different kinds of theoretical models to form a star have been proposed. To test these models, it is crucial to determine the initial conditions of star formation through careful analysis of observational data with sufficient spatial resolution.

2.1. Density Structure

The column density structure of a cloud core can be estimated by observations. The column density profile then is converted into a density structure, which is very crucial to test theories under certain assumptions. There are two methods often used; infrared absorption and (sub)mm emission maps.

Infrared imaging is a powerful technique to estimate the extinction of a core, corresponding to column density of a core, at a very high resolution (Alves et al. 2001; Bacmann et al. 2000). One of the best example is the Bok Globule B68 whose density structure agrees very well with that of a Bonnor-Ebert sphere (Alves et al. 2001). The infrared maps are, however, heavily undersampled with usually only a few data points near the center.

Molecular line and continuum observations in radio can obtain column density structure of a dense core at various stages (Saito et al. 1999; Evans 1999; Ward-Thompson et al. 1999). The flux density of the optically thin continuum emission at an impact parameter, b, can be written by

$$I_\nu(b) = 2\kappa_\nu \int_b^{r_0} B_\nu(T_d(r))\rho(r)\frac{r}{\sqrt{r^2 - b^2}}dr. \tag{1}$$

Here, r_0 is the outer radius, and κ_ν is dust opacity (e.g. Evans 1999). Thus, the observed intensity is the convolution of the above equation with the beam pattern of a single dish antenna or with the synthesized beam of an interferometer.

Wide field multi element bolometers such as SCUBA are intensively used to investigate the structure of both starless and stellar cores. Several starless cores including well studied L1544, show a flat density feature in the center (Ward-Thompson et al. 1999). The isolated class 0 star B335, on the other hand, has a power-law density profile with an index of -1.8 (Shirley et al. 2002). These studies, so far, do not conclude what theoretical model best explains the observed properties.

A measured density profile is coupled with several things; temperature profile, dust opacity, and beam pattern. In order to obtain reliable results, these things should be carefully examined. 1-d radiative transfer models self-consistently calculate the temperature structure of these cores. It is now accepted that the central part of a starless dense core has a lower temperature of about 7 K than the outer part of a core with 10-15 K, which is firstly pointed out by Masunaga and Inutsuka (1998) and later confirmed by ISO observations (Ward-Thompson et al. 2002). Dust opacity may not be constant throughout a cloud due to grain growth (e.g. Bianchi et al. 2003; Kandori et al. 2003). This will be investigated more carefully in the near future. Shirley et al. (2002) stressed that the telescope beam profile should be measured and applied to derive the density structure since it affects results considerably. Further, the emission from a disk and the presence of an outflow cavity make the analysis more complicated.

Interferometric data also have become important to distinguish theoretical models since it can disentangle emission from envelope gas and a disk thanks to its high angular resolution. One of the earliest studies was done for B335 by Harvey et al. (2003). They analyzed the data in the visibility domain not in the map domain without suffering non-linear deconvolution processes of interferometer imaging (Fig. 1). They showed that a simple power law model best fit to the data rather than a Bonnor-Ebert sphere or the inside-out collapse models. The key thing here is the amplitude calibration of interferometric visibilities. The future array such as ALMA indeed aims at the amplitude calibration with a 1 % accuracy at mm bands.

In many cases, however, dense cores show asymmetric shape. One of the example is B335 itself as shown in Fig. 1. The integrated intensity map $C^{18}O$ with the Nobeyama 45m telescope shows elongated along the north-south direction (Saito et al. 1999; see also Harvey et al. 2001). For the B335 case, the east-west molecular outflow likely produces a cavity in the core making its shape elongated perpendicular to the outflow. Several studies revealed that the typical axial ratio of dense cores are 1.5 - 2.0 (e.g. Myers et al. 1991). Combined with radiative transfer calculation, future high resolution data and multidimensional modeling are promising to obtain a more reliable density structure of dense cores.

2.2. Kinematics

The initial condition of a protostellar core ultimately determines the fate of stars in the core (e.g. Matsumoto and Hanawa 2003). Many theoretical models indeed predict kinematical behaviors of a core/envelope system at the starless and protostellar phase. Thus, the key parameters of kinematics of a dense core such as infalling velocity, mass accretion rate, and specific angular momentum, are crucial to test collapsing models.

Initiated by Zhou (1992) and Zhou et al. (1993), searches for evidence of collapse have been extensively conducted with mainly single dish telescopes (Mardones et al. 1997; Gregersen et al. 1997; Lee et al. 1999). In mm spectral lines they observe an "infall profile" – an asymmetric self-absorbed line profile with a brighter blue-shifted peak. Observations with single dish telescopes are open to alternative explanations. Another approach is to image the disk infall motions using interferometers (Hayashi et al. 1993, Momose et al. 1998, Saito et al. 2001). Among these studies, Ohashi et al. (2001) observed one of the early

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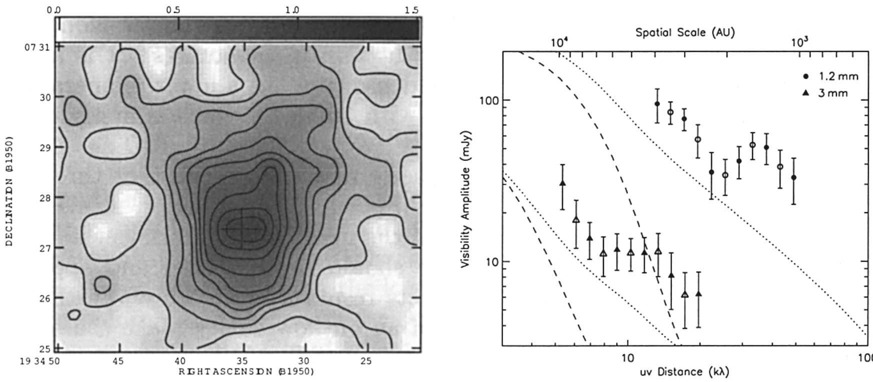

Figure 1. Left: Total integrated intensity map of $C^{18}O$ (J=1-0) emission toward B335 taken by the Nobeyama 45 m telescope. A cross represents the stellar position determined from the 2.6mm continuum peak by Hirano et al. (1992). Modified from Saito et al. (1999). Right: Binned visibility amplitudes vs. (u, v) distance at 3.0 (triangles) and 1.2 mm (circles) for the PdBI observations of B335 with theoretical curves for the Bonnor-Ebert sphere with $\xi_{max} > 12.5$ (dashed lines) and the inside-out collapse model with R_{inf}=0.03 pc (dotted lines). Neither of these models can successfully match the data. The spatial scale on the top is defined as 250 pc (λ/D) where D is the baseline length (Harvey et al. 2003).

type molecules CCS and found that the outer part of the starless core L1544 is contracting with slow rotation.

One notable result was obtained in the study of a class 0 protostar NGC 1333 IRAS 4; inverse P-Cygni profile, the strongest evidence of infall so far, toward the protostar (Di-Francesco et al. 2001). High resolution with high sensitivity interferometric data enable them to conduct this study. Choi (2002) demonstrates the powerful capability of the interferometer at submillimeter wavelengths to study infall and proposes ultimately to constrain collapsing models.

Rotation and angular momentum transfer is closely related to the formation of a disk or binary stars. Goodman et al. (1993) showed that rotation is not a main driving force against collapse although rotation structure of very few starless cores have been spatially resolved. Later Ohashi et al. (1997) showed that the specific angular momentum becomes roughly constant below 0.03 pc scale. No significant differential rotation of a dense core, which is expected to occur in a collapsing core with initial rigid rotation, was observed until the high resolution study by Belloche et al. (2002). They conducted observations of IRAM 04191, a class 0 star in Taurus, in different molecules and found that differential rotation is more prominent in robust molecular line maps. Future interferometer and single dish data are promising to provide a spatially resolved rotation structure of dense cores at various stages.

2.3. Chemistry

The chemical composition of cloud cores is closely coupled with the physical condition. In a cold dense core, depletion of molecules onto dust grains bringing a drastic change of molecular abundances in the gas phase. Grain surface chemistry, not quantitatively well understood, plays an important role in dense cores. Several chemical network models have been proposed and some common features can be retrieved from these models (Bergin & Langer 1997; Aikawa et al. 2001; Lee et al. 2003). 1) Early type molecules such as carbon chain molecules are heavily depleted in a relatively short time of $\sim 10^5$ yr. 2) CO and HCO^+ molecules also eventually deplete in the central cold part of a dense core. 3) Late type molecules such as NH_3 or N_2H^+ are robust although recent observations reported that even N_2H^+ is depleted in the starless core B68 (Bergin et al. 2003). Caselli et al. (2003) detected H_2D^+ line emission toward the starless core L1544 and suggest that H_2D^+ may be an excellent tracer to study such cold region. Notably, Tafalla et al. (2001) demonstrated that depletion and excitation condition can solve a long standing puzzle that CS cores shows larger velocity widths and larger spatial distribution than NH_3 cores.

Once ignition of a central star occurs, it heats surrounding material causing a drastic change of chemical composition. Frozen CO in grains comes back to gas phase and even molecules having high dissociation temperature also evaporate from grains (Jørgensen et al. 2002). Shock chemistry accompanied by jets or molecular outflows are not negligible in this stage. Despite of some studies (e.g. Hogerheijde et al. 1999), the study of chemistry at the protostellar phase is still a work in progress.

Ionization fraction, $x(e)$ is a key parameter for chemical reaction and also coupling with magnetic field. Several attempts have been conducted by observing a combination of CO, HCO^+, DCO^+, and N_2H^+, and found that $x(e)$ is around 10^{-8} at low-mass dense cores (Williams et al. 1998). Reliable measurements of $x(e)$ require careful treatment of molecular depletion and physical condition of a dense core (Caselli et al. 2002). Further, fractional abundance of deutrated molecules significantly decreases at a high temperature region such as nearby protostars making the analysis more complicated.

Chemical composition in a cloud was found to be not well mixed as shown in Fig. 2 (Takakuwa et al. 2003). Their maps show early type molecule CH_3OH and relatively late type molecule $H^{13}CO^+$ appear to avoid each other on smaller than 0.1 pc scale and moreover very compact features on 0.01 pc scale are discerned in the interferometer maps. Future molecular line maps with high angular resolution will reveal various faces of molecular cloud cores that we have not yet known.

2.4. Magnetic field

Understanding magnetic fields is important toward understanding molecular cloud cores. In particular, it is crucial if the magnetic field is strong enough against gravity, i.e. collapse, at the pre-stellar phase. Related questions are if there is any correlation between the field direction and the shape of a core, and how the field configuration near the center changes with evolution. The latter question is interesting because the infalling material coupled with the magnetic field drags, and pinches the field or a core may decouple from the magnetic field

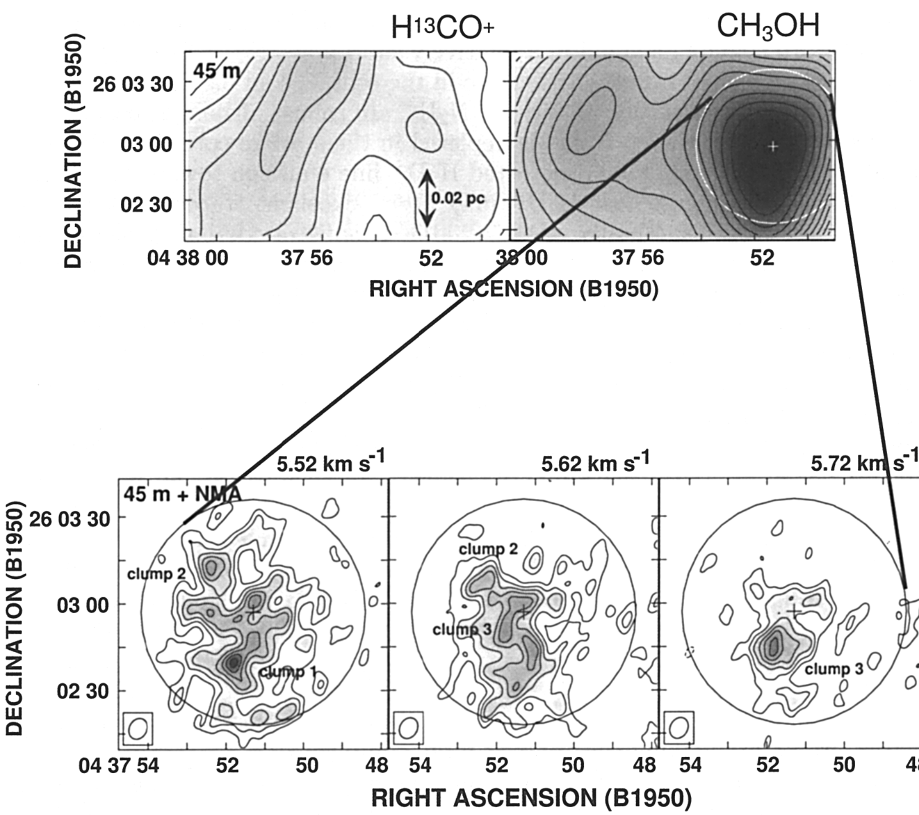

Figure 2. Top: Single-dish velocity channel maps in the $H^{13}CO^{+}$ (J=1-0) line (left) and the CH_3OH ($J_K = 2_0$ - 1_0 A^{+}) line toward the CH_3OH core 6 region in the TMC1-C cloud taken at a grid spacing of 17". Bottom: Velocity channel maps of combined the 45m telescope data with the NMA data in the CH_3OH ($J_K = 2_0$ - 1_0 A^{+}) line. Modified from Takakuwa et al. (2003)

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at some point. Despite its importance, it is extremely difficult to obtain both the field direction and field strength in the three dimension.

The line of sight field strength can be obtained by the OH or CN Zeeman observations (e.g. Bourke et al. 2001). The typical field strength in this method is about several tens of μG. The OH Zeeman observations do not appear to trace the very dense part of a core where a star forms (Crutcher et al. 2003).

The field geometry can be obtained by polarization maps of either dust continuum emission or molecular line emission. Polarization capability of the SCUBA with high sensitivity data enables us to make polarization maps of starless or protostellar cores at modest spatial resolution (Ward-Thompson et al. 2000; Matthews & Wilson 2003; Wolf et al. 2003; Crutcher et al. 2003). Most cores show more or less alignment of the magnetic field although the field direction is not necessarily perpendicular to the minor axis of a dense core (Ward-Thompson et al. 2000). From study of the magnetic field of protostellar cores in Bok Globules, Wolf et al. (2003) further suggest that orientation of the magnetic field relative to the outflow direction is not constant but changes during the evolution of the outflow/disk. The degree of polarization decreases toward the center of dense cores (Matthews & Wilson 2002; Wolf et al. 2003). There are several explanations, but not conclusive requiring high resolution data.

The magnetic field strength in the plane of sky is estimated from dispersion of the polarization position angle, namely the Chandrasekhar-Fermi method. The field strength estimated in this method is typically about 100 μG larger than that from OH Zeeman method. A likely explanation for the difference is that the OH Zeeman observations did not sample a dense part of a core, i.e. $n(H_2) > 10^4$ cm^{-3} (Crutcher et al. 2003). From observations of starless cores L183, L1544, and L43, Crutcher et al. (2003) suggest that these cores are magnetically supercritical and that magnetic support cannot prevent collapse.

Interferometric polarization maps of high mass star forming regions currently become available with the BIMA. Molecular line polarization direction is predicted to be either parallel or perpendicular to the magnetic field. Figure 3 clearly shows that CO polarization is parallel to the that of the magnetic field as traced by dust emission, agreeing with the prediction. The SMA or the ALMA will have capability of polarization measurements and are promising to resolve the magnetic field geometry of a low-mass star forming core on scales of an envelope/disk system.

2.5. Cluster Formation and IMF

Most stars in our galaxy appear to be formed in clusters (Lada & Lada 2003) and therefore understanding star formation in clusters is crucial. Study of dense cores/condensations in a cluster region needs high spatial resolution data.

Testi & Sargent (1998) first conducted large scale interferometric mosaicing observations toward the Serpens cloud with the OVRO and identified numerous dust condensations in the region. Interestingly, those condensations have a mass spectral index of -2.1 which is similar to that of field stars but different from that of molecular clouds previously obtained. The following study using the 30m telescope obtained similar results in the ρ Ophiuchi molecular cloud where cluster formation partially occurs (Motte & André 1998).

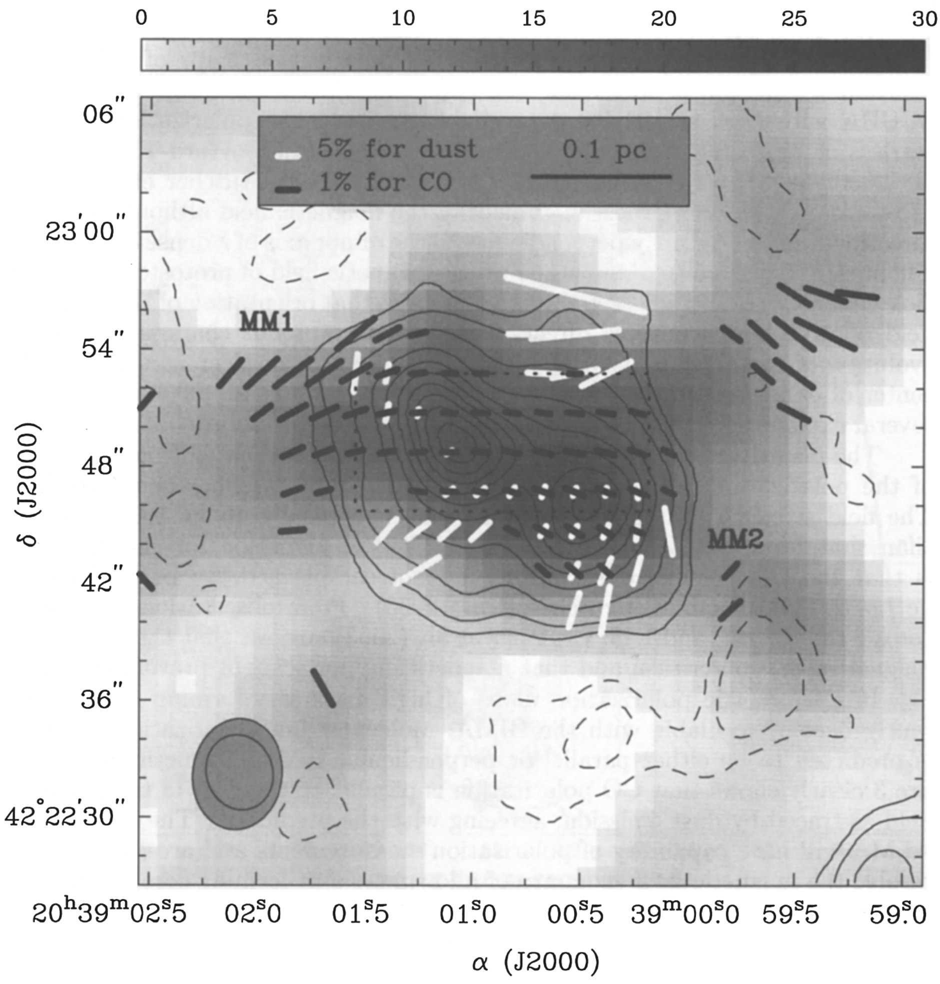

Figure 3. Polarization map of DR21(OH) taken with the BIMA array (Lai et al. 2003). The contours show the Stokes I of the dust continuum and the grey scale shows the Stokes I of the CO(2-1) emission. The white and black line segments represent the dust and CO polarization vectors with a scale of 5 % and 1 % per arcsecond length, respectively. Note that the dust polarization vectors are perpendicular to the magnetic field vectors.

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Recently large scale molecular line maps also enable us to identify large number of dense cores nearby star forming regions. Umemoto et al. (2003) carried out $H^{13}CO^+$ observations covering the ρ Ophiuchi molecular cloud (Figure 4). Several tens of starless dense cores are identified. The $H^{13}CO^+$ emission distribution is very similar to the dust continuum map obtained by the SCUBA suggesting $H^{13}CO^+$ is a good tracer of dense cores in this cloud. In addition, the mass spectrum index is obtained to be -2.5. Surprisingly this index is very similar to that by Onishi et al. (2002) in the Taurus molecular cloud where the mode of star formation is different. Many cluster forming regions are far compared to these clouds and therefore higher angular resolution data are necessary to conclude if the index of -2.5 is universal.

High resolution study toward the ρ Oph A region with the NMA shed a new light on the cluster formation as shown in Fig. 5 (Kamazaki et al. 2001). Their interferometric map clearly shows very small condensations with a size of 0.01 pc and a mass of 0.1 $M_\odot$ order. Those condensations are roughly virialized and its dynamical time scale is similar to the free fall time. This may suggest that in such a crowded region, coalescence of small cores may play a role to form stars.

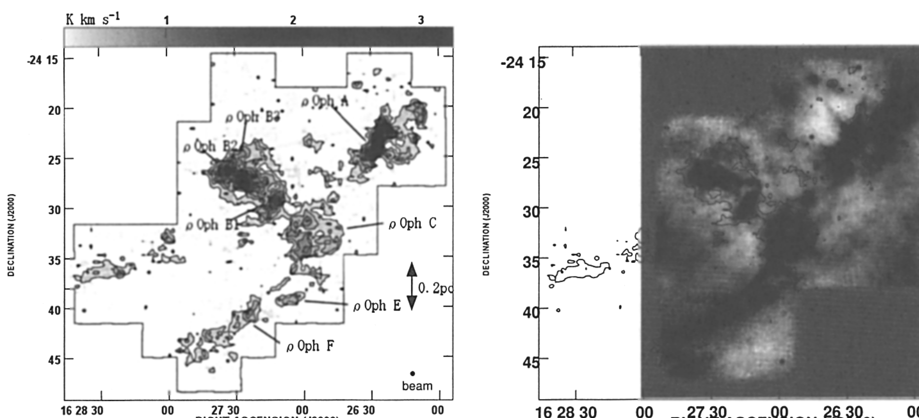

Figure 4. Left: the $H^{13}CO^+$ (J = 1–0) integrated intensity map in the ρ Ophiuchi main cloud (Umemoto et al. 2003). The area observed in $H^{13}CO^+$ is indicated by a thin line. The spatial resolution of the observations is shown in the bottom right-hand corner. Right: the 850 μm dust continuum map of the ρ Ophiuchi main cloud reproduced from Johnstone et al. (2000). The thin line contour indicates the outline of the map of $H^{13}CO^+$ in left panel.

3. Summary and Future Work

The present article briefly covers the topics of dense cores from starless to protostellar stages. In the last decade, large scale single dish surveys followed by interferometric data of a few examples lead the study. In the near future, however, a large survey or mosaicing maps with (sub)mm interferometers become

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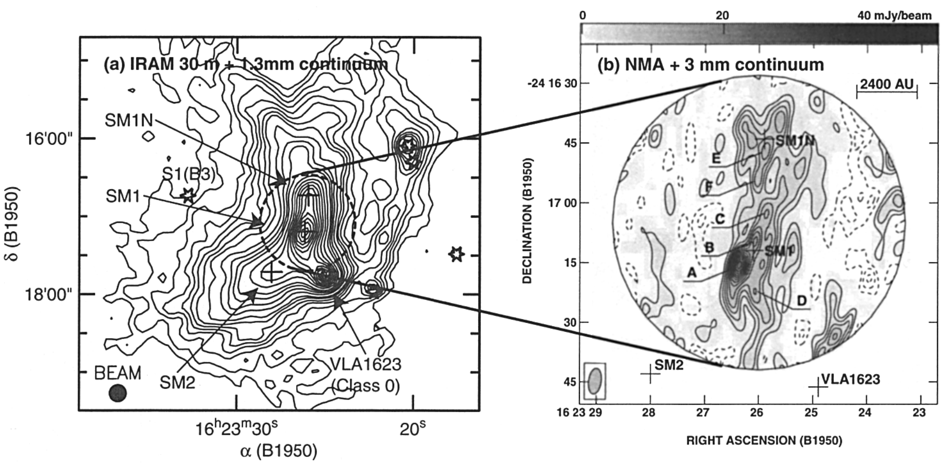

Figure 5. Left: 1.3mm continuum map of ρ Oph A region with the IRAM 30m telescope by Motte & André (1998). A dashed circle indicates the field of 3mm continuum map taken by Kamazaki et al. 2001 (Fig.1b). Crosses represent submillimeter continuum sources, SM1, SM1N, SM2 and VLA1623. Star marks are protostars and pre-main sequence stars. Right: 3 mm continuum map with the NMA by Kamazaki et al. (2001). Crosses are same submillimeter sources in the left map. The labels (A-F) indicate the small condensations identified by Kamazaki et al. (2001).

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available particularly thanks to the SMA and the ALMA. Then the density structure, chemical properties, magnetic field, and kinematics will be revealed at disk, envelope and core scales. In addition, understanding of cluster formation will be dramatically improved by high resolution data because single dish data cannot resolve each condensation in a cluster. Multiwavelength studies from the (sub)mm through the infrared will be increasingly important and will stimulate further advances in theoretical studies.

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