Studies for High-mass Star Formation with Millimeter and Centimeter Emissions

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Abstract Studies of high-mass star formation are less advanced than those of low-mass stars, though they started earlier. Many unexpected discoveries from centimeter(cm)-millimeter(mm) emission observations have been made on the characteristics of high-mass forming regions. Ultra compact (UC) HII regions have been examined adequately. With the advancement of the understanding of low-mass star formation and the development of detection technology, remarkable progress has been obtained in the examination of dynamic processes and the searches for early evolutionary phases.

1 Introduction

Studies of star formation is advancing rapidly since radio emission was employed widely in astronomy and since the mm emission lines were found in the 60 s of the past century. But such advancement is mainly on low-mass star formation (van der Tak et al. 2000). Abundant objects with various observation characteristics such as Bok globules, T Tauris, Fu Oris and a large number of infrared sources with different SED classes have been observed. Meanwhile a single evolution route was established and a clear picture of low-mass star formation has been obtained(Shu et al. 1985). For high-mass star formation our knowledge is less though studies actually began earlier than those of low-mass ones mainly because of the relatively small population of high-mass stars, long distances and high complexity of their regions and the rapidity of their evolutionary processes. As radio and mm technologies are developing, attention is dedicated to high-mass star formation and new progress is being made.

2 Early discoveries and high-mass star formation regions

Four decades ago, interstellar molecules were found by the means of radio emission. Then, star formation studies began a new era and developed rapidly. Many discoveries with cm-mm emission lines were unexpected and many concerned with high-mass star formation. We present some examples in Table 1. The first column presents the name of object or phenomenon discovered for the first time; Column 2 and 3 list the year and the authors; Column 4 lists the lines. The last column presents the regions.

One can see from Table 1 that these discoveries were made with cm-mm emission, including continuum and lines, thermal and non-thermal, all in massive star formation regions. These phenomena indicate that the corresponding regions are dense and rather cold. For example, in the NH_3 emission regions, the kinetic temperature is 23K and the column density is $2\times10^{16}\,cm^{-2}$(Cheung et al. 1968). CO maps of these regions are large and complex (Habing & Israel 1979 and the reference there). Massive stars are formed in clusters. More distant than low-mass star forming regions. For example, Orion where there are high-mass stars being formed is about 500 pc, while low-mass star formation regions T Tauri are 140 pc. Most of the high-mass star formation regions are farther away from us than Orion. The distribution of different mass molecular outflows also shows the distance difference between high-mass and low-mass young stellar objects (Wei & Wu in this proceeding).

Table1. Examples of early discoveries

Object or phenomenon discovered	year	Authors	Emission	Regions
molecule OH the first radio molecule found in ISM	1963	Weinreb et al.	1665/67MHz 18cm absorption	Cas A
Ammonia molecule NH_3 The first polyatomic molecule found in ISM	1968	Cheung et al.	23.69GHz 1.3 cm emission lines	Galactic center
H_2CO The first organic molecule found in ISM	1969	Synder et al.	4829.7MHz 6cm lines	radio sources
OH maser The first molecule maser found	1965	Weaver et al.	1665MHz non-thermal emission 18cm lines	W_3(OH)
CO The most abundant molecule(except H_2)	1970	Wilson et al.	115GHz 2.6 mm lines	Orion
CO molecular outflows	1976	Zuckerman & Palmer 1975 Kwan & Scoville 1976 Zuckerman et al. 1976	115GHz 2.6 mm lines	Orion

3 UCHII regions and high-mass YSO evolutionary time

A discovery was made also from studies in centimeter emission. Ryle and Downes (1967) obtained the E. M. = 5×10^7 cm^{-6}pc in DR21, a 6cm emission source. Mezger et al. (1967) also got E. M. =10^8 cm^{-6}pc in W49A. These require ionization of one or more O type stars (Habing & Israel 1979). A new class of Galactic source HII regions were also found with infrared emission. Actually, the newly formed stars are bright. The surrounding dust absorbs UV or optical emission and re-emits at longer wavelengths. The SED of UCHII regions is shown in Fig.1 (Churchwell 1999).

UCHII regions usually have electron densities of 10^5 cm^{-3}, E. M. of 10^8 cm^{-6}pc, life time of 10^5 yrs, and sizes of 10^{16} cm. Their SED was explained with various models (Churchwell 1999). For the morphologies of UCHII regions, Wood and Churchwell (1989) divided them into cometary(20%), core-haro (16%), shell-like(4%), irregular or multiply peaked (17%), spherical or unresolved (43%). UCHII regions also received much theoretical attention (Churchwell, 1999). Fig.2 is the in-falling

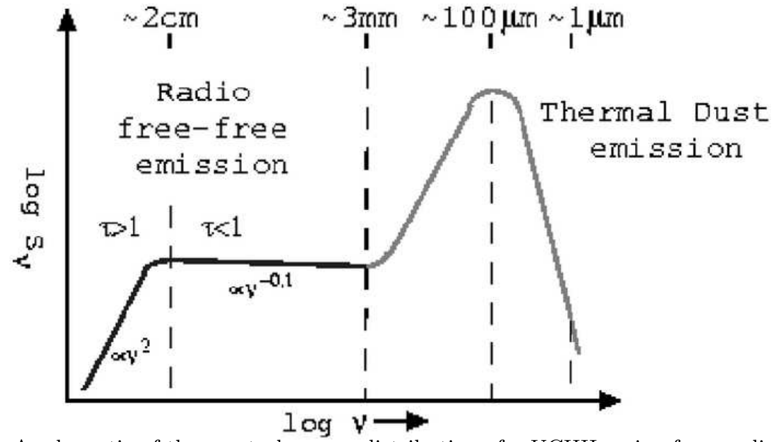

Fig. 1 A schematic of the spectral energy distribution of a UCHII region from radio to the near infrared. (Churchwell,E., 1999)

model, explaining the observation characteristics, whose density and pressure increase at the I-front of the HII region (Churchwell 1999 and the reference there).

UCHII regions were thought as a sign post of high-mass star forming processes. But the stars inside are already on the main sequence while still surrounded by the materials of the parent cloud. The Young-Stellar-Object (YSO)-shell system means that the in-fall materials of the cloud are really slower than the K-H contract. The vicinity of the star was destroyed by ionization, which makes it difficult to catch the star's early evolutionary characteristics.

4 A Current Bloom

Efforts were made to resolve the forming regions to see whether high-mass stars have the same formation procedures as low-mass stars. A number of typical and relatively isolated sources were found, which are good examples with different evolutionary characteristics. IRAS 23385+6053 was identified as a massive class 0 object (Molinari et al. 1998a). A bipolar outflow was also found in this source (Yang & Wu, 2000). In W51, G192.16-3.82 and IRAS 20126+4104, in-fall and/or disc were detected (Zhang et al. 1998; Shepherd & Kurtz 1999; Cesaroni et al. 1997). Recently, IRAS 00117+6412 and IRAS 02461+6147 were found as isolated sources (Shi et al. & Zhao et al. in this proceeding). Particularly, high velocity molecular outflows are found frequently near massive YSOs. In a sample of 39 sources Zhang et al. (2001) measured 35 outflows. Among 26 high-mass star formation regions, Beuther et al.(2002a) found 21 bipolar outflows. More than 350 molecular outflows have been found till June of 2002(Wu et al. 2002a), about $\sim$100 of them are associated with infrared source with the bolometric luminosity greater than 10^3 L$\odot$. They may be high-mass YSOs. Considering the smaller population of high-mass stars, the detection rate of outflows in high-mass star formation regions is similar to that in low-mass ones. These should be evidence that high-mass star formation also proceeds through accreting rather than coalescing. Wang (2002) recently suggested a route of massive star formation.

Searching for early evolutionary phase is another focus in the current studies of massive star formation. Hot cores are observed. They are dense, $\sim 10^6\,cm^{-3}$ and hot, with temperature of $\sim$100-200 K (van der Tak et al. 2000; Cesaroni et al. 1992). They are close to HII regions, but do not overlap with HII regions. Fig.3 is the contours of CH_3OH J=12-11 integrated intensity superpost on the 3.6 cm continuum images (Wilner et al. 2001 and the reference there). The hot core lifetime is most likely to be shorter than, but comparable to that of the UCHII regions. CH_3OH J=12-11 and dust images show that hot cores may be produced by young stellar sources precursors to O-type stars (Wilner et al. 2001).

Recently Molinari et al. (1996, 1998b, 2002) and Zhang et al. (2001) have investigated 163 IRAS sources. Their samples exclude known HII regions and with flux density at 60 μm $\geq$100Jy. The IRAS colors are:

$$0.61 \leq [60-25] \leq 1.74$$

$$0.087 \leq [100-60] \leq 0.52$$

They divided the sources into a high group and a low group with [25-12]>0.57 or <0.57 respectively. They have examined the two group sources with cm−mm−submm emissions. Fig.4 shows their observation chart. The left column lists the sources and results for the high group. The right column lists similar facts for the low group. The middle column lists the items of results. In conclusion they obtained 11 sources which are without free-free emission and detected with mm continuum emission (one of the 12 sources was detected at 3.6 cm later). Their dust temperature ranges from 24 K to 45 K, and their luminosity is $\sim 10^4 L_\odot$. The outflow detection rate is 90% (Zhang et al. 2001); the exponent of the dust emission vs frequency power-law of these sources indicates that these sources may be younger than those with radio continuum. These sources may be precursors of UCHII regions.

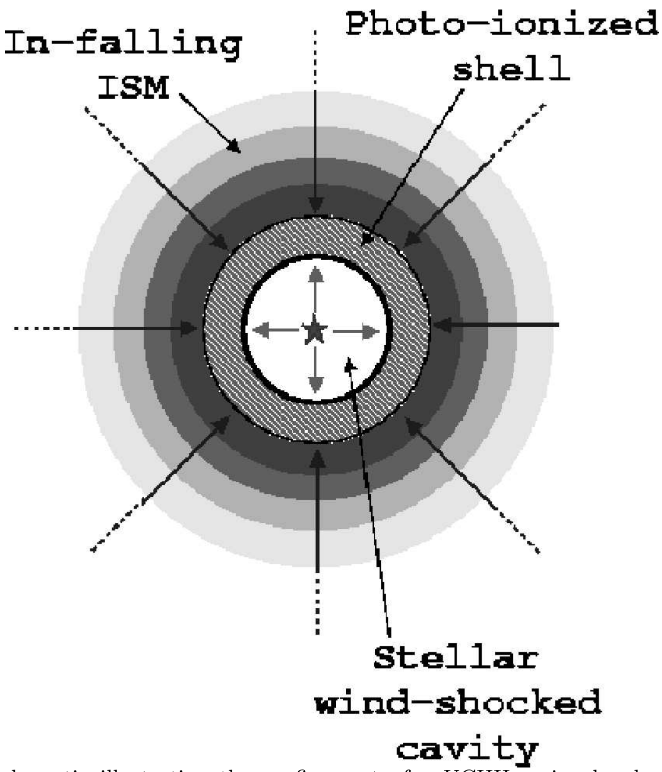

Fig. 2 A schematic illustrating the confinement of a UCHII region by dense, ambient, molecular gas which provides the thermal pressure required for confinement. (Churchwell,E., 1999)

Sridharan et al. (2002) and Buther et al. (2002b) have investigated another group with 69 IRAS sources. The samples satisfy the criteria of UCHII regions and have CS J=2-1 emission. The samples are also without known HII regions and bright with flux density of f_{100} >500Jy and f_{60} >90 Jy. They observed continuum and spectral lines at millimeter and radio wavelengths, including 3.6 cm, 1.2 mm, CO J=2-1, NH_3, H_2O and CH_3OH maser emissions. They found most of the sources are prior to UCHII regions. Rotation temperature from NH_3 (1, 1) (2, 2) is ~20 K. The dust temperature is ~40 K. The analysis of radial intensity profiles indicates that the inner regions are more quiescent. The outflow detection rate is 81% (Burther et al. 2002a) and the detected H_2O and CH_3OH masers are 29 and 26 respectively. Those sources are similar to those of Molinari et al. (2000). Plume et al. (1997, 1992), Zinchenko et al. (1998) and Wu et al. (2001) also studied massive YSOs or massive dense cores. Samples of all these surveys are bright and without an upper limit of flux density of IRAS sources.

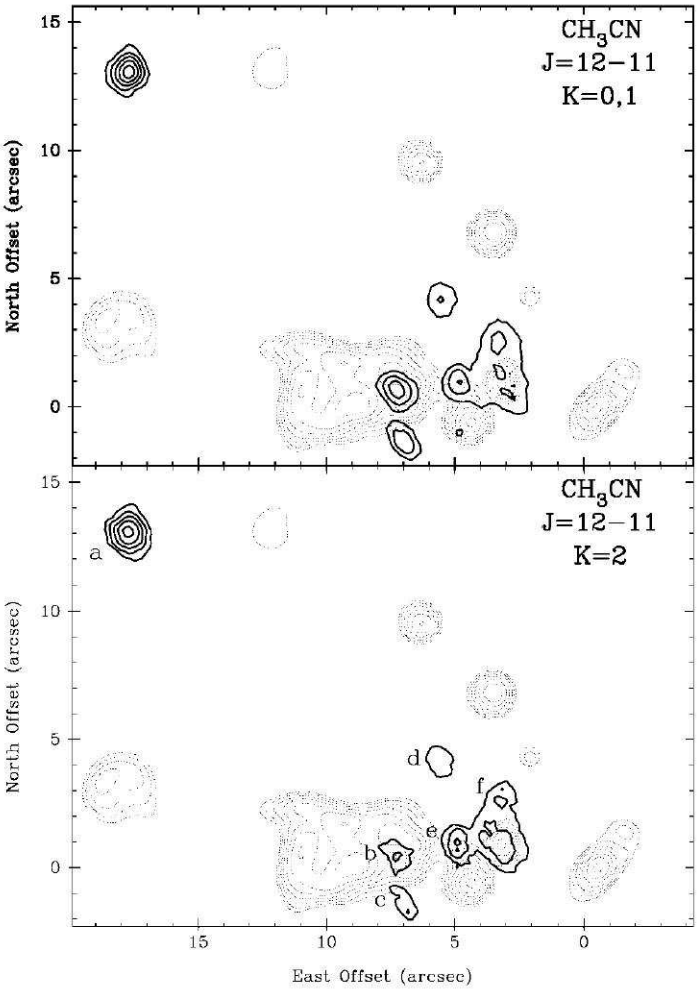

Fig. 3 Images of CH_3CN J=12-11 integrated intensity superposed on the 3.6 cm continuum image. (Wilner et al. 2001 & the reference there.)

Then a question is arising: how to find a much earlier evolutionary phase of the high-mass stars, which means earlier than the precursors of UCHII regions as mentioned above?

We recently have surveyed 22 IRAS sources with ^{13}CO and $C^{18}O$ $J = 1 - 0$ lines (Wu et al. 2002b). The sources are red, with [25−12] >0.7 and [60−12] >1.4. They are not known HII regions and not associated with low-mass sources. An upper limit of IRAS flux density was set: f_{100} <500Jy. All the sources were detected with the pair line emissions. The column densities of $C^{18}O$ are $\geq 10^{15}$ cm^{-2}. The excitement of $C^{18}O$ is $\sim 13K$. We examined the sources with MSX data. The middle infrared emission of these sources are very weak. The MSX and IRAS energy distributions show that the emission peak of these sources falls in far infrared or longer wavelength. All these facts show that these sources are cold, dense and young. We judge whether they are massive or not from

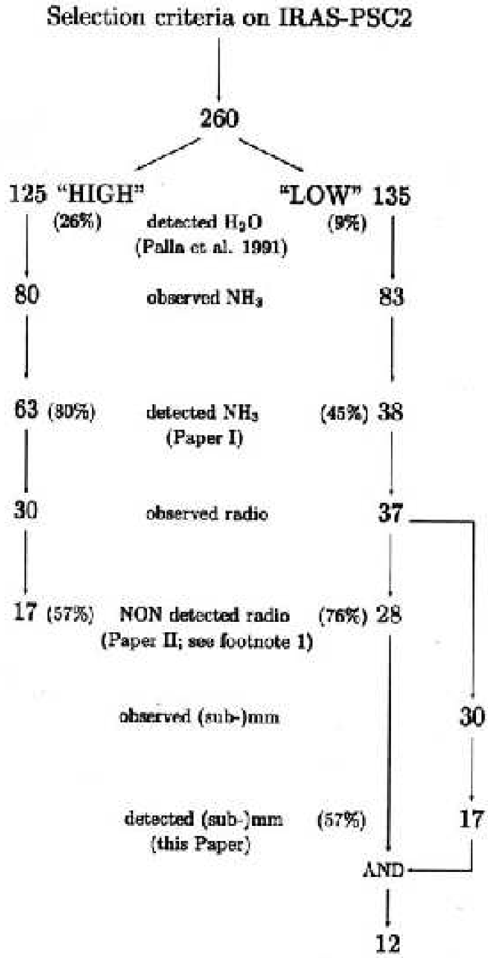

Fig. 4 Flow-chart for the selection of the sample of intermediate-to-high mass candidate protostellar objects. (Molinari, S. et al. 2000)

line widths and bolometric luminosity. According to Myers et al. (1983) and Wu et al. (2001), the widths of ^{13}CO lines are $\sim$1.3 km/s and $\sim$3.0 km/s for low-mass dense cores and massive dense cores respectively. For our sources there are 11 with with ^{13}CO line width $\geq$3.0 km/s. According to Beichman et al. (1986) the bolometric luminosity of low-mass sources are usually $<50L_\odot$. Among the 11 sources with the line widts $\geq$3.0 km/s, there are 7 with bolometric luminosity $>50L_\odot$, which may be high-mass or intermediate-mass YSOs. Of course, mapping with some dense molecular probes, mm and sub-mm continuum emission observations will be helpful for further identification of these sources.

Recently, Yang et al. (2002) surveyed 1331 cold IRAS sources with CO J=1-0 line, which may contain very young stellar objects. Li & Goldsmith (2000) have detected molecular clumps with temperature inside lower than that of outside, showing these regions to be at very early evolution phase.

5 A Bright Future

Recently, unresolved problems of high-mass star formation draw much attention, such as initial conditions, formation of ISM fragmentations, formation of clusters, formation dynamic process, driving mechanics of outflows, as well as roles and evolution of discs. These make the studies of high-mass star formation a real hot topic in the astrophysical frontier. With the availability of new and fine equipments such as SMA, SIRTF, Herschel and ALMA, the mysteries of high-mass star formation are going to be revealed. With the domestic cm-mm equipments and international opening equipments we have much to explore in this field.

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References

Barrett A.H., Meeks M.L., Weinreb S.,AJ, 1964, 69: 134
Beichman, C. A., Myers, P. C., Emerson, J. P. et al. ApJ, 1986, 307, 337
Beuther, H., Schilke, P., & Menten, K.M., ApJ, 2002b, 566: 945
Beuther H., Schilke P., Sridharan T.K., et al. A&A, 2002a, 383, 892
Cesaroni R., Felli M., Walmsley C.M., et al., A&A, 1997, 325: 725
Cesaroni R., Walmsley C.M., Churchwell E., A&A, 1992, 256: 618
Cheung A.C., Rank D.M., Townes C.H., et al., PhRvL, 1968, 21, 1701
Cheung A.C., Cudaback D.D., Rank D.M., et al., BAAS, 1969, 15: 236
Churchwell E., Massive Star Formation, in The Origin of Stars and Planetary Systems. Eds. C.J. Lada & N.D.Kylafis, Kluwer Academic Publishers, 1999, 515
Li D., Goldsmith P.F., A&AS, 2000, 197, 1801
Habing H.J., Israel F.P., ARA&A, 1979, 17, 345
Kwan J., Scoville N., ApJ, 1976, 210: L39
Mezger P.G., Schraml J., Terzian Y., ApJ, 1967, 150, 807
Molinari S., Brand J., Cesaroni R., et al, A&A, 1996, 308: 573
Molinari S., Brand J., Cesaroni R., et al., A&A, 1998b, 336, 339
Molinari S., Brand J., Cesaroni R., et al, A&A, 2000: 355, 617
Molinari S., Testi, L., Brand, J. et al. ApJ, 1998a, 505, L39
Myers P.C., Linke R.A., Benson P.J., ApJ, 1983, 264: 517
Plume R., Jaffe D.T., Evans N.J.II, ApJS, 1992, 78: 505
Plume R., Jaffe D.T., Evans N.J.II, et al., ApJ, 1997, 476: 730
Ryle M., Downs D., ApJ, 1967, 148: L17
Shepherd D.S., Kurtz S.E., ApJ, 1999, 523: 690
Shu F.H., Adams F.C., Lizano S., ARA&A, 1987, 25: 23
Snyder L.E., Buhl D., Zuckerman B., et al., PhRvL, 1969, 22: 679
Sridharan T.K., Beuther H., Schilke P., et al., ApJ, 2002, 566: 931
van der Tak F.F.S., van Dishoeck E.F., Evans N.J.II, et al. ApJ, 2000, 537, 283
Wang J., in Massive star formation, proceedings of BAC Workshop, Nanjing, 2002, in preparation
Weaver H., Williams, D. R. W., Dieter, N. H. et al., Nature, 1965, 208, 29
Weinreb, S., Barrett, A. M., Meeks, M. L. et al., 1963, Nature, 200, 829
Wilner D.J., De Pree C.G., Welch W.J., et al., ApJ, 2001, 550: L81
Wilson R.W., Jefferts K.B., Penzias R.W., ApJ, 1970, 161: L43
Wood D.O.S., Churchwell E., ApJS, 1989, 69: 831
Wu Y., Wei Y., Shi Y., et al., 2002a, in preparation
Wu Y., Wang J., Wu J., 2002b, Submitted to Chin. Phy. L.
Wu Y., Wu J., Wang J., A&A, 2001, 380: 665
Yang J., Jiang, Z., Wang M. et al., ApJS, 2002, 141: 157
Yang, C., Wu, Y., ACTA ASTROPHYSICA SINICA, 2000, 20, 141
Zhang Q., Ho P.T.P., Ohashi N., ApJ, 1998, 494: 636
Zhang Q., Hunter T.R., Brand J., et al., ApJ, 2001, 552: L167
Zinchenko I., Pirogov L., Toriseva M., A&AS, 1998, 133: 337
Zuckerman B., Palmer P., ApJ, 1975, 199: L35
Zuckerman B., Kuiper T.B.H., Rodriguez Kuiper E.N., ApJ, 1976, 209, L137