Objects earlier than precursors of UC HII regions: Inflow–signpost for a common way of star formation

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Abstract. Searching for objects in the earliest phases of star formation, e.g sources at the beginning of a gravitational collapse, are essential to our understanding of massive star formation. Today a number of precursors of ultra compact HII regions (PUCHs) have been found. Embedded in dense gas and dust, these PUCHs have a high bolometric luminosity but little or no 6 cm radio continuum emission (Molinari, *et al.* 2000; Beuther, *et al.* 2002). Evidence for Collapse was found in ultra compact (UC) HII regions and 12 water maser sources (Zhang, *et al.* 1998; Wu & Evans II 2003). This paper presents the identification of massive cores with no detectable infrared and radio sources. These kinds of cores usually have strong sub-mm emission. A special case is the SCUBA core JCMT 18354-0649S which has both infall and outflow motions as indicated by the profiles of high excitation molecular lines. This core is at a stage earlier than PUCHs. Blue profiles are also found in UC HII region, which indicates that material is still infalling in this phase. Our observations suggest that infall exists in different evolutionary stages for high mass star formation, similar to the low mass cases.

Keywords. ISM: cloud – ISM: kinematics and dynamics – stars: formation

1. Introduction

Characterizing high mass young stellar objects (YSOs) in their early phases is the key to understanding massive star formation. Infall motion, if detected, would present a direct evidence to support the idea that massive stars form via a process similar to that of low mass stars. However, the nature for high mass star formation is very difficult to clarify because of the complexity of such regions and their large distance from us. Besides, their rapid evolution and ever changing conditions make it difficult to probe the processes inside the protostellar condensations amoung highly obscured surroundings. Many surveys were carried out to search for high mass YSOs in recent years (Wood & Churchwell 1989; Bronfman, *et al.* 1996; Plume, *et al.* 1997; Zinchenko, *et al.* 1997; Mueller, *et al.* 2002; Shirley, *et al.* 2003; Molinari, *et al.* 1996; Molinari, *et al.* 2002; Zhang, *et al.* 2001; Sridharan, *et al.* 2002; Beuther, *et al.* 2002). A number of precursors of ultra compact HII regions (PUCHs) were found (Molinari, *et al.* 2002; Beuther, *et al.* 2002; Churchwell 2002 and reference therein). The IRAS colors of PUCHs are similar to that of UC HII regions (Wood & Churchwell 1989) or very young stellar objects (Richards *et al.* 1987). Their IRAS flux densities are as high as $f_{60} > 100$ Jy or $f_{100} > 500$ Jy (Molinari, *et al.* 1996; Sridharan, *et al.* 2002). They are also characterized by strong mm or sub-mm emission. Their spectral energy distribution is rather flat and molecular outflow detection rate is as high as 84% to 90% (Sridharan, *et al.* 2002; Zhang, *et al.* 2001). The important
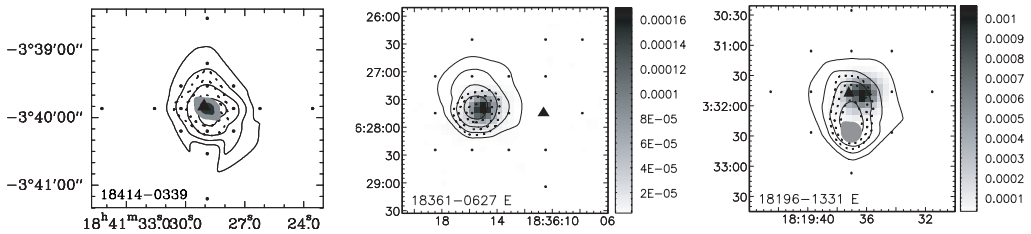
Figure 1. The left panel: Ammonia core IRAS 18414-0339 with emission peak (contours) coincidence with IRAS source (triangle). The middle pannel: Ammonia core IRAS 18361-0627 with emission peak overlapped with MSX E band image (grey scales). The right panel: Ammonia core IRAS 18196-1331 with emission peak deviated from any IRAS (triangle) and MSX E band source (grey scales). The MSX flux density is in Wm^{-2} sr^{-1} (Wu *et al.* 2005a).

indications for these objects being massive and young are the high luminosity $L_b > 10^3 L_\odot$ and the lack of 6 cm radio continuum emission.

Infall motions were detected in 12 high mass star formation regions by Wu & Evans II (2003). Inverse P-Cygni profile was found in W51 several years ago (Zhang, *et al.* 1998). Recently, $NH_3(3,3)$ line and radio continuum studies have revealed that the molecular accretion flow becomes ionized accretion flow when passing through the ionization front (Sollins *et al.* 2005).

This paper presents the preliminary results in our search for objects earlier than PUCHs and a search for inflow motions in different phases of high mass star formation.

2. A search for objects earlier than PUCHs

2.1. *Massive gas cores not associated with infrared sources*

Massive molecular cores that contain no infrared sources are potential objects for star formation at a very early phase. In an ammonia survey, with a sample similar to that of Molinari, *et al.* (1996) and Sridharan, *et al.* (2002), 5 sources with peak ammonia emission deviated from IRAS sources were detected (Wu, *et al.* 2005a). The angular distance between the amonia peak and IRAS peak are more than one telescope beam (40"). Further identification with Midcourse Space Experiment (MSX) shows that one of them is overlapped with an infrared source, and the other 4 contains 5 cores that are separated from the peak emission at MSX A and E bands. These five cores have a mass of 780 $M_\odot$ on average and the FWHM of line (1,1) is 1.80 km s^{-1}, much larger than those of low mass cores (Myers, *et al.* 1983). The detection of such cores are common in molecular line maps. In the detected sources of Zinchenko, *et al.* (1997), half are deviated from IRAS sources. In the survey of Harju, *et al.* (1993) in the Orion and Cepheus Clouds, a number of cores defined as minor cores are not associated with IRAS sources. Part of their major cores are also deviated from IRAS sources. Jijina, *et al.* (1999) listed all the ammonia cores without SIMBAD sources. We also detected several such cores with CO isotopes despite their low excitation density and depletion (Wei, *et al.* 2004). Fig. 1 presents the examples for three types of cores: cores with ammonia peak overlapped with IRAS, MSX sources or deviated from any IRAS and MSX sources. Cores deviated from infrared sources either harbor near infrared sources without 6 cm emission or are located beside an HII region.

2.2. *Sub-millimeter emission*

Sub-millimeter emission is important for studying dense cores which are too cold to be detectable at mid infrared. Here we present recent SCUBA observations of the NH_3 core
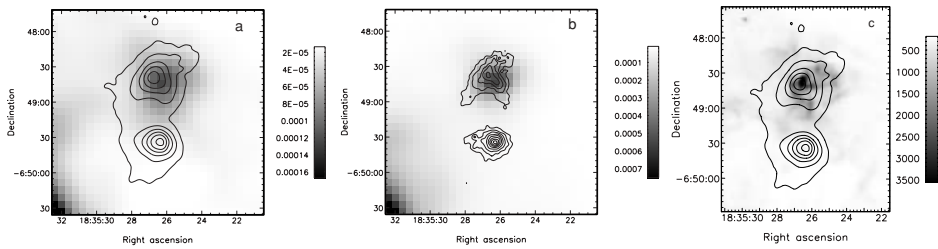
Figure 2. a) SCUBA 850 μm contours on MSX A band image ($6.8 - 10.8\mu$m). Contour levels at 850 μm are from 0.71 (10 σ) to 4.25 by 0.71 Jy/beam. b) SCUBA 450 μm contours on MSX E band image ($18.2 - 25.1\mu$m). Contour levels are from 2.9 (5σ) to 17.7 by 2.1 Jy/beam. The MSX flux density is in $Wm^{-2}sr^{-1}$. c) SCUBA 850 μm contours on IRAC 8 μm band image. The 8 μm flux density scale is in MJy sr^{-1}. Contour levels are the same as in a). (Wu *et al.* 2005b).

18354-0649 (Wu, *et al.* 2005a). This core is located near IRAS 18355-0650. But these two objects are not at the same distance because the V_{LSR} for the IRAS source and NH_3 core are 65 km s^{-1} and 95 km s^{-1} respectively (Lester, *et al.* 1985). However, the NH_3 core is associated with an HII region G25.4 NW with V_{LSR} of 95 km s^{-1}. The distance is 5.7 kpc. SCUBA detected strong continuum emission at both 850 and 450 μm (Wu, *et al.* 2005b). Fig. 2 shows the overlay of a) 850 μm contours on MSX A band; b) 450 μm contours on E band; c) 850 μm contours on IRAC 8 μm image. The diameter of the compact dust core is 10" according to the measured FWHM in the 450 mum map (after deconvolved with the 8" beam). The dust temperature is 14.4 K (if β=2) and 25.2 K (if β=1.5). This core is named as JCMT 18354-0649S.

Using $M=S_\nu D^2/k_\nu B_\nu(T_d)$ and assuming T_d=20 K, the core mass was estimated as 820 M$_\odot$ according to the 450 μm flux density. The average gas density is 1.1×10^6 cm^{-3} in the central region with a radius of 5". These parameters suggest that the core is massive and dense. They may be similar to the massive cores detected by Garay, *et al.* (2004). Zhu & Wu (2005) also identified a number of such cores from the previous mm and sub-mm surveys. The optical extinction Av of the core JCMT 18354-0649S estimated with the peak flux density at 850 μm is 630 (wu, *et al.* 2005b).

2.3. *Investigation with high density molecular tracers*

The following high excitation molecular lines were observed toward the core JMCT 18354-0649S using the JCMT in May 2004, including HCN (3-2), HCO$^+$ (3-2), H^{13}CO$^+$ (3-2), CO (3-2) and C^{17}O (2-1). Fig. 3a and 3b present the grid of HCN (3-2) and HCO$^+$ (3-2) respectively, which are 3×3 with 10" spacing. In total there were four pairs of optically thick and thin lines (Fig. 3c), all with the signature of collapse in the central region: the ratio of T_k(Blue)/T_k(Red)> 1 for both HCN (3-2) and HCO$^+$ (3-2); δv=(V_{thick}-V_{thin})/$\Delta V_{thin} < $ -0.25 (Mardones, *et al.* 1997) for all pairs. These results show that there is infall motion in this core. The radii of the infall region was estimated to be 8".

An analytic model for collapse (provided by Myers, *et al.* (1996)) was tested on JCMT 18354-0648S (Fig. 3d and 3e). This model assumes that the cloud consists of two uniform paralleled components without rotation. The resulting parameters (T_k, σ, τ_0, V_{in}) from the model fitting are much larger than the corresponding values of low mass sources, consistent with the high mass nature of the core. The kinematic mass infall rate is
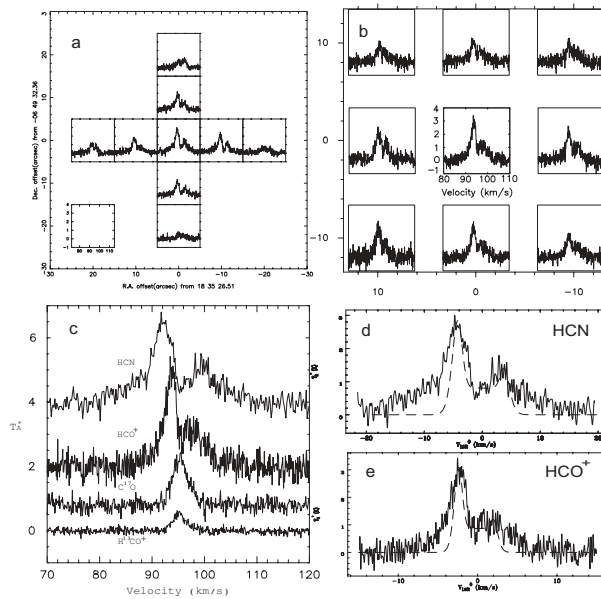
Figure 3. Spectral lines of the SCUBA core JCMT 18354−0649S. a) HCN (3−2) grid with 10"
spacing. X and Y axis are the R.A. and DEC. offset in arcsec, respectively. b) HCO$^+$ (3−2) grid
with 10" spacing. X and Y axis are the same as a). c) HCN (3−2), HCO$^+$ (3−2), C^{17}O (2−1)
and H^{13}CO$^+$ (3−2) lines at the central position. d) and e) HCN and HCO$^+$ (3−2) spectra and
model fitting (dashed line) in zero velocity frame (indicated as $V_{\rm LSR}^0$). (Wu *et al.* 2005b).
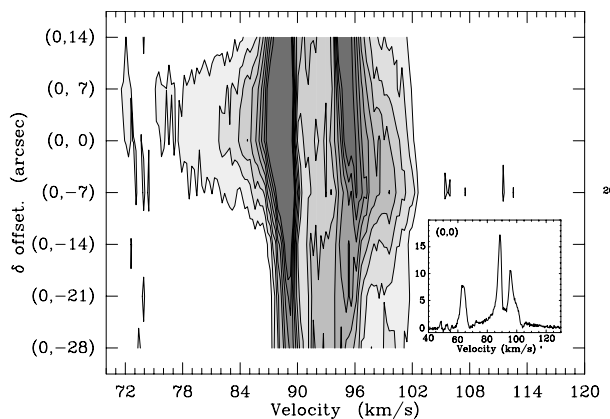

Figure 4. Position-velocity diagram of CO(3−2) spectra along $\Delta R.A. = 0$. Contour levels are
from 3σ to 27σ by 3σ ($1\sigma = 0.345$K. Spectrum at the lower-right corner is at (0,0) position
R.A.(1950)=18$^{\rm h}$35$^{\rm m}$26.5$^{\rm s}$, DEC.(1950)=−06°49$'$32$''$.

$3.4{\times}10^{-3}$ M$_\odot$/yr which is calculated according to the formula in Myers, *et al.* (1996)
dM/dt=4πR$_{in}$mnV$_{in}$. The gravitational rate is $1.4{\times}10^{-3}$ M$_\odot$/yr. The ratio of these two
values is within a factor of 2 for low mass sources (Myers *et al.* 1996), but a bit higher in
our case. CO (3-2) line was observed in a cross pattern with a grid step of 10". The total
line width reaches 38 kms^{-1}. A position-velocity diagram in Fig. 4 shows that there is
a bipolar outflow in this region. The existence of infall and outflow motions, combining
with the unusual values of the physical parameters, indicates that there is a high mass
star being formed inside the core. The fact that no MSX and near-infrared emission
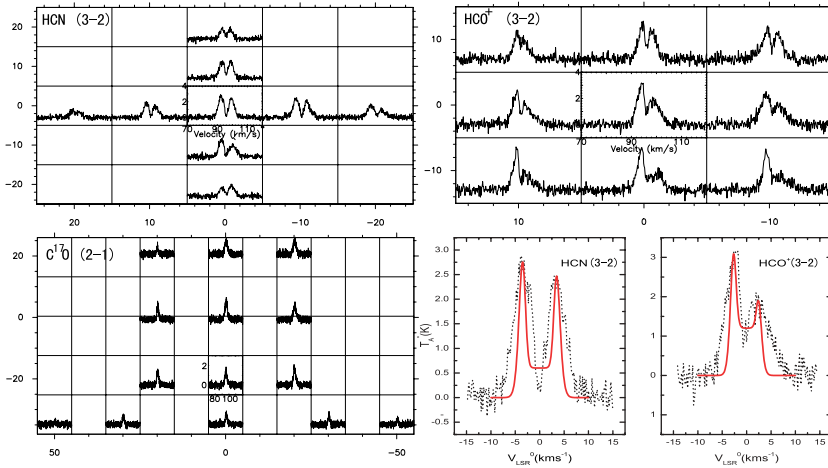
Figure 5. Spectral lines of the northern SCUBA core JCMT 18354−0649N. a) HCN (3−2) grid with 10". X and Y axis are the R.A. and DEC. offset in arcsec, respectively. b) HCO^+ (3−2) grid with 10". X and Y axis are the same as a). c) HCN (3−2), HCO^+ (3−2), $C^{17}O$ (2−1) and $H^{13}CO^+$ (3−2) lines at the central position. d) and e) HCN and HCO^+ (3−2) specatra and model fitting (dashed line) in zero velocity frame (indicated as V^0_{LSR}).

are detected is likely due to the extremely high extinction of the core. High resolution observations are necessary to provide a detailed picture and to examine the nature of this core.

3. Inflow motions in different evolutionary phases

In Fig. 2, there is a core overlapped with G25.4NW located north to JCMT 18354-0649S. G25.4NW is a well studied HII region. Infrared observations reveal that its dust temperature is 59 K (Lester, *et al.* 1985). The bolometric luminosity is $L_b = 5.6 \times 10^5$ $L_\odot$ (5.7kpc). From Fig. 2, one can see that its dust emission is more extended than that of the southern one, and of a higher T_d. Spectral line observations were also followed up at this source. Fig. 5 presents the spectra of HCN (3-2), HCO^+ (3-2) and $C^{17}O$ (2-1). There were at least two pairs of optically thick and thin lines. The ratio of $T_k(Blue)/T_k(Red)$ for HCN (3-2) and HCO^+ (3-2) are 1.2 and 1.9 respectively; and δv from HCN (3-2), HCO^+ (3-2) and $C^{17}O$ (2-1) are -0.52 and -0.48 respectively. All these satisfy the criteria for a blue profile (Mardones *et al.* 1997). Model analysis was also performed. The HCN and HCO^+ (3-2) spectra and the model fitting (solid line) in zero velocity frame (noted with V^0_{LSR})) is also shown in Fig. 5 (lower-right panel). The infall velocities derived from fitting the HCN (3-2) and HCO^+ (3-2) data are 0.03 and 0.16 kms^{-1} respectively, less than those in JCMT 18354-0649S. These results indicate that the core containing HII region G25.4NW is also collapsing. Obviously, this core is in an evolutionary stage different from that of JCMT 18354-0649S. For low mass sources, collapse features in different evolutionary phases were well known. In Table 1 we present the examples of collapse candidates in different evolutionary phases for both low and high mass sources. Although the evolutionary phases of low and high mass sources can not be compared with each other directly, the examples show that infall motions are presented in high mass star formation from a phase earlier than PUCHs to the phase of UC HII regions, just as it exists in different evolutionary stages of the low mass star forming process.

Table 1. collapse candidates in different stages of star formation

Source	Evolutionary phases		
Low mass[1,2]	Pre-protostellar	Class 0	Class I
Examples	L1544	VLA 16293, B335	L1251B, WL22
High mass	Earlier than PUCHs	PUCHs	HII
Examples	JCMT 18354-0649S	W3NE[3]?	G25.4NW

Note: 1. Shirley *et al.* 2000; 2. Andre *et al.* 2000; 3. Wei *et al.* 2004.

Acknowledgements

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