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INFLOWS IN MASSIVE STAR FORMATION REGIONS

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ABSTRACT

How high-mass stars form is currently unclear. Calculations suggest that the radiation pressure of a forming star can halt spherical infall, preventing further growth when it reaches 10 $M_\odot$. Two major theoretical models on the further growth of stellar mass have been proposed. One model suggests the merging of less massive stellar objects, and the other is through accretion, but with the help of a disk. Inflow motions are key evidence for how forming stars gain further mass to build up massive stars. Recent developments in technology have boosted the search for inflow motion. A number of high-mass collapse candidates were obtained with single dish observations, and mostly showed blue profiles. Infalling signatures seem to be more common in regions which have developed radiation pressure than in younger cores, which is the opposite of the theoretical prediction and is also very different from observations of low mass star formation. Interferometer studies so far confirm this tendency with more obvious blue profiles or inverse P Cygni profiles. Results seem to favor the accretion model. However, the evolution of the infall motion in massive star forming cores needs to be further explored. Direct evidence for monolithic or competitive collapse processes is still lacking. ALMA will enable us to probe more detail of the gravitional processes.

Key words: stars: formation—stars: pre-main sequence—ISM: kinematics and dynamics

1. INTRODUCTION

Gravitational collapse is an essential process for star formation. However, when the forming stellar object reaches 10 M⊙, the strong radiation pressure can prevent material from falling onto the star. (Wolfire & Cassinelli, 1987). A new model proposing that more massive stars can be formed through coalescence of less massive stellar objects has been suggested (Bonnell et al. 1998). The accretion model was also improved (Yorke & Sonnhalter, 2002; Jijina & Adams, 1996). Observational evidence of inward motions of material in massive star formation regions are critical to test these models. Nevertheless, it is more difficult to observe infalling material in massive star formation regions than in low mass ones because of their complex environment, large distance and quick evolution. The interactions between the environments of massive young stellar objects and their feedback bring additional difficulties for the identification of gas infall motion. The development of millimeter and sub-millimeter instruments has made such probing feasible. In recent decades a number of searches for evidence of gravitional infall in high mass star formation regions were carried out with single dishes, but typically sources were also examined with interferometers. These have greatly deepened our understanding of massive star formation. Since some basic questions still remain, however, and more observations are needed in the future.

2. SURVEYS OF INFLOW MOTIONS IN MASSIVE STAR FORMATION REGIONS

Ten years after the blue profile was detected in the low mass core of B335 (Zhou et al., 1993) it was found in a spectroscopic survey toward 28 massive star formating cores associated with H_2O masers (Wu & Evans 2003). With CSO and IRAM, HCN (3-2), CS (5-4), (3-2), (2-1), and $H^{13}CN$ (3-2) were used to probe optically thick and thin lines and blue profiles were obtained in 12 cores and red profiles in 6 cores. Soon 77 candidates high mass protostellar objects (HMPOs) were searched with IRAM and JCMT (Fuller et al. 2005). They identified 22 promising infall candidates. Meanwhile toward 12 UC Hii regions, Wyrowski et al (2006) detected 9 blue profiles with CO (4-3) and ^{13}CO (8-7) lines with APEX. Using MOPRA, Purcell et al. (2006) observed 83 CH_3OH maser-selected regions with lines of CH_3OH (5-4), (6-5), and HCO^+ and $H^{13}CO^+$ (1-0) transitions. They detected 12 blue profiles. Klaassen & Wilson (2007) observed 23 UC Hii regions with outflows using

Table 1
Blue excesses of inflow surveys

Sources	Evolutionary phases			Ref.^{a}
High mass	Earlier than PUC HII	PUC HII	UC HII	
examples		Core JCMT	G 34.26	1,2
E (HCO+(1-0))	?	17%	58%	3
		15%	70% (CO 4-3)	4,5
HCO+(3-2)	-0.04			,6
Low mass	Class -I	Class 0	Class I	
examples	L1544	B335	L1251B	7,8
E HCN (3-2)	30%	31%	31%	8

Ref.: 1, Liu et al., 2011a; 2. Liu et al., 2013; 3. Wu et al., 2007; 4. Fuller et al., 2005; 5. Wyrowski et al., 2006; 6. Velusamy et al., 2008; 7. Mardones et al., 1997 ; 8. Evans (2003)

Table 2
A comparison between single dish and interferometer results

Source	Phase	Single dish	High resolution	Ref.^{a}
JCMT 18354	PUC HII	Blue	Blue	1.2
W3-SE	PUC HII	Blue	Blue	3,4
G9.62-0.19F	Younger PUC HII	Blue or Red?	Red	5.6
Orion KL/Hot	core Younger PUC HII	—	Blue	7
G8.68	PUC HII	Blue-outer; Red-iner?	–	8
G19.61-0.23	UC HII	Blue or Red?	Inverse P Cygni	3,9
G9.62+0.19E	UC HII	Blue or Red?	Blue	5,6
NGC7438 IRS1	UC HII	Blue	Inverse P CYgni	3, 10
G10.6-0.4	UC HII	Blue	Inverse P Cygni	11,12
G34.26-0.15	UC HII	Inverse P Cygni	Inverse P Cygni	3, 13
Orion KL/Source I	Radio source	—	Inverse P Cygni	7
G45.12+0.13	UC HII	Inverse P Cygni	Inverse P Cygni	14, 15
			No inverse PCygni	16

Ref. 1. Wu et al., 2005; 2. Liu et al., 2011; 3. Wu et al., 2007; 4. Zhu et al., 2010; 5. Hofner et al., 2001; 6. Liu et al., 2011; 7. Wu et al., 2014; 8. Ren et al., 2012; 9. Wu et al., 2009; 10. Zhu et al., 2013; 11. Wu & Evans, 2003; 12. Liu et al., 2013a; 13. Liu et al., 2013b

JCMT. They used tracers of HCO$^+$ (4-3), H^{13}CO$^+$ (4-3), CO (2-1) and found 9 sources having infall motion. Towards very early Orion cores are likely precursors of protostars, Velusamy et al.(2008) detected 27 cores with HCO$^+$ and H^{13}CO$^+$ (3-2) with CSO. They found a dichotomy in the dynamical status: 9 sources had blue profiles and 10 red profiles. These surveys found a number of inflow candidates and showed inflow motions are common in massive star formation regions.

To further examine characteristics of inflow motions in massive star formation regions, a mapping survey of HCO$^+$(1-0), CS(3-2), N$_2$H$^+$(1-0), and C^{18}O(1-0) was made with IRAM (Wu et al. 2007). Rotation could be excluded from the spatial distribution of the asymmetric line profiles. In addition, the peak positions of blue profiles and associated molecular outflows can be identified. To see differences in inflow motion at different evolution statuses, this survey includes two group of sources. Group I contains 33 UC HII precursors (PUC HII or HMPOS) and Group II consists of 12 UC HII regions. Using HCO$^+$(1-0), nine and seven blue profiles were obtained in Group I and Group II respectively. However there are 4 red profiles in Group I but no red profiles in Group II. The asymmetric lines detected result in a blue excess E= is 0.17 and 0.58 for the two groups respectively, where E= (N$_B$-N$_R$/N$_T$), and N$_B$, N$_R$ and N$_T$ are the number of sources with blue profiles, red profiles and the survey sample (Mardones et al. 1997). Results show the UC HII regions have higher blue excesses than their precursors. Meanwhile the results of the survey show that blue profiles are usually peaked at the core center and some of the sources have high velocity outflows. Figure 1 presents the HCO$^+$ (1-0) mapping grid, comparing optical thin and thick lines as well as P-V diagrams of two sources, one a PUC HII and the other associated with an UC HII region.

We compare the blue excess of the two groups of sources in this survey with those of previous surveys. Table 1 gives the blue excess (E) of cores at different evolution statuses. We can see the following situations:

(1) For the same HMPOS, with the same tracer (HCO$^+$ (1-0)), the value of E for two surveys are about the same, $\sim$ 16%;

(2) Using different tracers of HCO$^+$(1-0) and CO(4-3), E>50% was obtained for UC HII regions;

(3) For the youngest massive cores (see Table 1), the

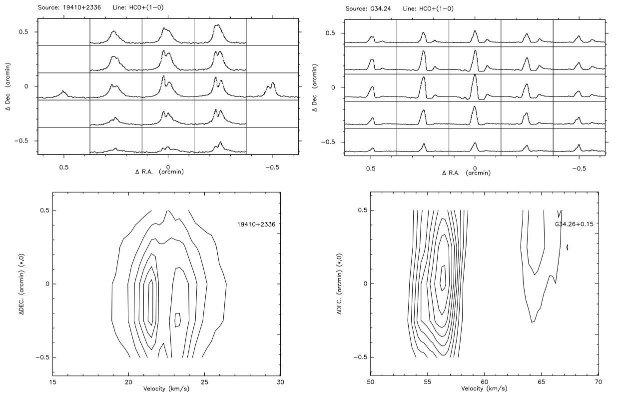

Figure 1. Left: UC Hii precursor 19410+2336; Right: UC Hii region G34.26+0.15. (See Table 1 of Wu et al., 2007. The figures are not published yet.)

E value is negative.

We also compare the E value of massive star formation regions with their low mass counterparts. From Table 1, one can see that there is no tendency for E to vary with time for the low mass cores. However the tendency for the E value of the late phase to be larger than that of the early phase for massive star formation cores is evident. This contradicts the theoretical result since the radiation pressure of UC Hii regions should be larger than that of earlier phases. Possible explanations for the difference may involve thermalization of the flow regions, influence of outflows or turbulence and gas reserves (Wu et al. 2007), and needs to be further explored.

3. PROBING INFLOWS WITH HIGH ANGULAR RESOLUTION OBSERVATIONS

To examine inflow motions in the inner regions of massive cores and test the results of single dish observations, higher angular resolution observations are needed. In particular, interferometery is a powerful probe of the deep layers of cores. In recent years excellent examples such as W51N, NGC 7538 and Sgr B2 have been obtained (Zapata et al. 2008; Qin et al. 2008; Qiu et al. 2011). Some other massive core collapse candidates from single dish observations were observed with various interferometers. Below we make a brief comparison of the line signatures of cores observed with single dishes and interferometers. Table 2 gives the source name, evolutionary phase, adn signatures detected with different resolution observations. The results are as follows:

(1) Generally no obvious conflict was found between the results of single dish and interferometeric observations in these cores, but more strong signatures of gravitational collapse were detected with interferometers. Core JCMT18354-0649S was mapped with HCN, HCO^+, $H^{13}CO^+$ (3-2) and $C^{17}O$ (2-1) at JCMT (Wu et al. 2005). The blue profile was shown in multiple pairs of optical thick and thin lines. Two layer model fitting gave an infall velocity of 0.25 km/s. The SMA observations of molecular lines including CH_3OH (5_{23}-4_{13}) and HCN (3-2) also showed a blue profile which is more prominent than the one obtained by JCMT (Liu et al. 2011a). The infall velocity is 1.3 kms^{-1} from the same model fitting. The inflow signature of W3-SE obtained with IRAM was confirmed by the Combined Array for Research in Millimeter-wave Astronomy (CARMA) (Zhu et al. 2010). For NGC7538, the blue profile was observed with single dish, while the inverse profile was obtained with SMA (Zhu et al. 2013: Qiu et al. 2011).

(2) Profiles were distinguished in the inner regions of the cores. For example, high excitation density molecular lines of $CH_3CN(12_4$-$11_4)$ and $CH_3OH(8_{-1,8}$-$7_{0,7})$ detected with the Atacama Large Millimeter/Submillimeter Array (ALMA) in Orion KL region show a collapse signature for the first time; an inverse P Cygni profile for Source I and a blue profile for the hot core (Wu, Liu & Qin 2014). In G9.62-0.19, there are compact cores C, D, E, F and I within a region with a diameter $< 5''$ (Testi et al. 2000). Core E is a young massive star surrounded by a small UC Hii region (Hofner 1996), and core F is a very young young stellar object (Linz et al. 2005). Hofner et al. (2001) observed G9.62-0.19 with HCO^+ (1-0), SO (43-32) and SiO (5-4) lines using IRAM. The HCO^+ (1-0) line shows both blue and red shifted absorption at a spatial resolution of $27''$. SMA observations revealed that the blue asymmetric profile comes from Core E and the red one from Core F (Liu et al. 2011b). The profile differences of the two cores, Source I and the hot core in Orion KL, and core E and core F in G9.62-0.19 are consistent with the results of single dish surveys, $E_{Late} > E_{Early}$.

(3) Infall velocity differences for different sizes of inflow regions were found. For example, in G19.62-0.23, the red shifted gas absorption region of the CN (N=3-2) line is smaller than that of ^{13}CO (3-2), while the infall velocity obtained from CN (3-2) line is larger than that from ^{13}CO (3-2), which is consistent with an inside out collapse model (Shu, Adams & Lizano. 1987). G34. 26+0.15 is the only source for which an inverse P Cygni profile was detected in the IRAM survey (Wu et al. 2007). SMA detected six cores in this region. Multiple CN (N=2-1) lines of each core show an inverse P Cygni profile (Liu et al. 2013a). The largest infall velocity corresponds to the smallest absorption area. The tendency of the velocity to change with the inflow region size is consistant with the inside-out model as well.

(4) Fragmentation was detected. In G10.6-0.4, there are seven sub-millimeter cores. All cores show red shifted absorption gas (Liu et al. 2013b), four of which are associated with infrared point sources. The center core has largest mass and largest infall velocity. The difference between the kinematic and Bondi-Hoyle mass accretion rates is within a factor of 2. These results are consistent with competitive accretion (Bonnel et al. 2001). However, the core structure and mass spectrum need to be further examined.

(5) SMA observations of G8.68-0.37 did not show infall motion signatures. However, the lines of CO (1-0) and (2-1) observed with PMO and CSO show prominent blue profiles. The HCN(3-2) lines observed with JCMT show a red profile although the S/N ratio is low. This

source contains an EGO (Ren et al. 2012). Similar situations may be found in some other EGOs. A survey toward 72 EGO by PMO (Chen at al. 2010) found 29 sources having blue profiles, and 19 have red profiles, giving an E of 0.14. In another HCN (3-2) survey of EGOs wiht JCMT (Wu, Liu, Reipurth, on going), the number blue asymmetric and red asymmetric profiles are 8 and 14 respectively, giving an E of -0.24. In cores such as G8.68-0.37, there are inflow motions outside and expansion in the interior, which needs more observations for study. In source G45.12+0.13, NH_3 (4,4) and (5,5) lines detected with the 100 m telescope at Effelsberg show inverse P Cygni profiles (Cesaroni, Walmsley & Churchwell, 1992). VLA observations of NH_3 (2,2) and (4,4) lines with beam size $2''.9\times2''.7$ also showed such profiles (Hofner, Peterson, & Cesaroni, 1999). However, high spatial resolution observations of $5''$ failed to identify inverse P Cygni profile in this region (Wilner et al., 1996). Such a complex situation in the inner region of a source needs to be explored further as well.

4. SUMMARY AND PROSPECT

Searches for evidence of gravitational collapse of massive star formating cores as progressed greatly. During the last decade, after blue profiles were found in low mass cores, searches toward various phases of massive dense cores were frequently made. Results suggest that inflow motions are common in massive star formation regions as well.

A number of the candidates were observed with high angular resolution and strong evidence of inverse P Cygni profiles was found. Velocity changes at different sizes of inflow regions were detected. Multiple cores and their inflow motions were also obtained. These results suggest that high mass stars may form via an accretion model.

There may be fundamental difference between collapse in the two kinds of star formation processes. Surveys in massive cores at different evolutional statuses show that there is evolution of the blue excess. Profiles of core pairs which consist of a young massive core and a UC HII region are consistent with $E_{Late} > E_{Early}$. Inflow motion appears to occur at outer side while expansion or outflow occurs inside of some massive cores, which has not been seen in low mass cores so far. The structure, mass distribution and inflow processes of massive dense cores need more probing. ALMA has better sensitivity and resolution, which will enable us to detect fragmentation or mass secretion, and determine their mass spectra. Future studies will provides us with a better picture of gravitational collapse in massive star formation regions.

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