

A Survey of Molecular Outflows toward the Orion A Clouds
with the Nobeyama 45-m Telescope

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March 2020

Abstract

During the early phase of star formation, molecular outflows are ubiquitous phenomena both in the low- and high-mass star forming regions. Outflows are high-speed and collimated molecular gas flows of several to tens of km s^{-1} released in bipolar directions from a protostar. They inject substantial energy into the parent molecular cloud and may play an important role in star formation process. Outflows also make the chemical evolution of molecular clouds, specifically, the shocks in outflows dissociate molecules to ions and mix the grains. However, research on elucidating detailed mechanism that drives the outflows and quantitative evaluation of the influence of outflows onto the surroundings environment is insufficient. The main purposes of this thesis are to investigate the general characteristics of the outflows and the effect of the outflow feedback onto the parent molecular clouds.

To achieve the objective described above, I conducted an exploration of ^{12}CO molecular outflows in the Orion A giant molecular clouds using ^{12}CO ($J = 1-0$) and ^{13}CO ($J = 1-0$) data obtained by the Nobeyama 45-m telescope. I identified 44 ^{12}CO outflows, (including 17 newly detected) based on the unbiased and systematic procedure of automatically decided the threshold of velocity range of the outflows and separated the cloud components and the outflow components. I detected 95% of the known outflows, except for the Orion Molecular Cloud 1 region, and identify 11 outflows in the OMC 4/5 region where no outflows had been detected, and as a result, increased the total number of the outflows in Orion A by a factor of ~ 1.5 . The detection rate of the outflows in our surveys decreases with the evolution of the protostars that driven the outflows, indicating that outflows tend to appear in earlier phases of the protostar evolution stage.

The optical depth of the ^{12}CO emission in the detected outflows is estimated to be ~ 5 typically. The total momentum and energy of the outflows, corrected by the optical depth, are estimated to be $1.6 \times 10^2 M_{\odot} \text{ km s}^{-1}$ and $1.5 \times 10^{46} \text{ erg}$, respectively. The physical properties of the individual outflows strongly depend on the luminosities of their driving protostars, and this suggest that the the power of the outflows actually originates from their central protostars. The total forces and luminosities of the outflows are estimated to be 36% and 235% of the total forces and luminosities of the cloud turbulence, respectively. Furthermore, the ejection rates of the outflows are comparable to those of the expanding molecular shells estimated by Feddersen et al, therefore the cloud turbulence cannot be sustained by the outflows and shells unless the energy conversion efficiency is as high as 20%.

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Chapter 1

Introduction

1.1 Overview of star formation

Stars are one of the most fundamental constituents of the universe, thus elucidation of the star formation process is essential issue in astrophysics. Over the years, many astronomers have assembled the star formation scenarios with observational and theoretical approaches. In this section, I first give a brief summary of the star formation scenario as an introduction to the thesis.

1.1.1 Molecular clouds

Stars are born in molecular clouds which can be categorized into giant molecular clouds (GMCs) and dark clouds. The molecular cloud consists of gas and dust in a mass ratio of 100 : 1. The main components of the gas are 70% hydrogen and 28% helium in mass (e.g., Cohen & Kuhi 1979) and dust is sub-micron or micron-sized solid particles. Table 1.1 summarizes the physical properties of each cloud type and dense cores. High-mass stars ($M_{\text{star}} > 8 M_{\odot}$) are thought to be born only in GMCs such as the Orion Molecular Clouds (OMCs). On the other hand, dark clouds such as Taurus and Perseus only make low-mass stars ($M_{\text{star}} \leq 1 M_{\odot}$). The cloud cores are the densest portions of the molecular clouds which the star formation occur in (e.g., see Myers & Benson 1983).

As can be seen in Table 1.1, the molecular clouds have low temperature of ~ 10 K, thus they does not emit radiation in the visible or infrared wavelength. However it is a sufficient temperature to cause the rotational transition of a molecule whose radiation is at millimeter or sub-millimeter wavelengths. Hydrogen and helium do not make rotational transitions at low temperatures, however, molecular clouds have been observed with carbon monoxide (CO) molecules which are the next most abundant in molecular clouds (e.g., see Wilson et al. 1970).

Table 1.1: Physical properties of molecular clouds and dense cores

Clouds type	Number density (cm ⁻³)	Size (pc)	Temperature (K)	Mass ($M_{\odot}$)
GMCs	100	50	15	10 ⁵
Dark clouds (complex)	500	10	10	10 ⁴
Dark clouds (individual)	10 ³	2	10	30
Cloud cores	10 ⁴	0.1	10	10

Adapted and modified from Table 3.1 of Steven & Francesco (2005).

1.1.2 Star formation scenario

For low to intermediate-mass ($M_{\text{star}} < 8 M_{\odot}$) stars, like Sun, the formation scenario from clouds to stars is well established. A star starts from the gravitational collapse of a dense cloud core that happens on the timescale of the free-fall time¹,

$$t_{\text{ff}} = \left(\frac{3\pi}{32G\rho} \right)^{1/2} \sim 10^6 \text{ yr} \left(\frac{n_{\text{tot}}}{10^3 \text{ cm}^{-3}} \right)^{-1/2}. \quad (1.1)$$

In equation 1.1, G is the gravitational constant, ρ is the medium density, and n_{tot} is the total number density. The densest portions of the molecular clouds produce stars through gravitational collapse since their masses are larger than the Jeans mass². The cores shrink to one millionth size to form the stars.

According to the numerical simulations (Masunaga et al. 1998 and Masunaga & Inutsuka 2000), the core contraction is initially isothermal, but eventually the number density rises to $5 \times 10^{10} \text{ cm}^{-3}$ at the center of the core, and when a dynamically balanced gas sphere is formed, the core becomes opaque to its radiation. This quasi-adiabatic object which mainly consists of H_2 is called the “first core” and its temperature is 1000 K, radius is 1 au, and mass is $0.01 M_{\odot}$. The first core forms by gravitational infall rotates significantly fast, and its magnetic fields drive energetically expels mass with a bipolar flow (e.g., see Arce et al. 2007 and Inutsuka 2012). This gas flow plays an important role in transporting angular momentum away from the core. Further mass gradually accretes on the first core, and as the mass increases, the temperature also increases, and the temperature reaches 2000 K, the hydrogen molecules dissociate. Since this reaction is an endothermic, the thermal equilibrium is broken, and contraction starts again. In this “second collapse” phase, the collapsing velocity becomes very large, thus a result, the first core only lasts for $\sim 10^3$ years. Through this second collapse phase, fully ionized hydrogen form the equilibrium core called the “second core”. The central density of this second core reaches $\sim 1 \text{ g cm}^{-3}$ which is comparable of the stellar values and central temperature of the core is 4000 K.

The resultant new protostars are embedded in dense envelopes of molecular clouds, thus they cannot be observed in visible or near infrared, but only in far infrared or longer wavelength radiation.

¹The time for spherical clouds to collapse to the center by self-gravity in the absence of pressure.

²The maximum mass supported by gas-pressure gradient in opposition to self-gravity.

These protostars, gradually shrink in size, blow off the envelope. This contraction proceeds slowly over Kelvin-Helmholtz timescale³,

$$t_{\text{KH}} \equiv \frac{GM_{\text{star}}^2}{R_{\text{star}}L_{\text{star}}} \sim 10^7 \text{ yr} \left(\frac{M_{\text{star}}}{M_{\odot}} \right)^2 \left(\frac{R_{\text{star}}}{R_{\odot}} \right)^{-1} \left(\frac{L_{\text{star}}}{L_{\odot}} \right)^{-1}, \quad (1.2)$$

where R_{star} and L_{star} is the stellar radius and luminosity, respectively, while maintaining mechanical equilibrium. For a star with 1 solar mass, the timescale is about 10^7 years. Stars in this process are called pre-main sequence (PMS) stars, and their temperature increases with contraction. Finally, when the temperature inside the star reaches 10^7 K, hydrogen fusion begins, a PMS star evolves into a main sequence star. This indicates the end of the star formation, and stars can be observed in visible.

The formation scenario of high-mass stars ($M_{\text{star}} > 8 M_{\odot}$) is not so well established as low-mass stars. This is caused by several observational difficulties. The high-mass star formation itself is rare because the population of stars falls precipitously with mass as expected by the initial mass function (IMF)⁴. As a result, the high-mass star forming regions usually distribute several kiloparsecs away from us, thus to study them in detail requires high-angular-resolution observations. In addition, the timescale of high-mass star evolution is much shorter than that of low-mass stars. Using Equation 1.2, t_{KH} of a $10 M_{\odot}$ mass star is less than 10^5 yr which is more than one order of magnitude shorter than that of low-mass stars. Therefore, I can observe fewer number of high-mass protostars than low-mass protostars. Such a short evolutionary timescale poses additional observational difficulties. Because the formation time scale of a high-mass star is so short, the star reaching the main sequence remains deeply embedded in the molecular gas and is not observed, not only at the visible, but also at the infra-red wavelength. Indirect observations of bright maser emissions that are thought to be excited in the vicinity of the protostars have been done (e.g., Fujisawa et al. 2014 and Sugiyama et al. 2017).

1.1.3 Classification of Young Stellar Object

The stages of YSOs evolution are categorized into four classes, Class 0, I, II, and III by Lada (1987) and by others (e.g., André et al. 1993 and André & Montmerle 1994) based on the slope of the spectral energy distribution (SED) between $2 \mu\text{m}$ and $25 \mu\text{m}$,

$$\alpha_{\text{IR}} = \frac{d \log \nu F_{\nu}}{d \log \nu} = \frac{d \log \lambda F_{\lambda}}{d \log \lambda}. \quad (1.3)$$

The definitions and characteristics of each Class are summarized in Table 1.2 and Figure 1.1.

³The time scale of contraction when a star contracts by gravity to emit photons and lose energy.

⁴The function that describes the initial distribution of masses for a population of stars.

Table 1.2: Classification of YSOs.

Class	SED slope	Mass property ^{*2}	Observational characteristic
0	-	$M_{\text{enve}} > M_{\text{star}} > M_{\text{disk}}$	No optical or near IR emission
I	$\alpha_{\text{IR}} > 0.3$	$M_{\text{star}} > M_{\text{enve}} \sim M_{\text{disk}}$	Generally optical observed
FS ^{*1}	$-0.3 < \alpha_{\text{IR}} < 0.3$		Intermediate between Class I and II
II	$-1.6 < \alpha_{\text{IR}} < -0.3$	$M_{\text{disk}}/M_{\text{star}} \sim 1\%, M_{\text{enve}} \sim 0$	Accreting disk; strong H_{α} and UV
III	$\alpha_{\text{IR}} < -1.6$	$M_{\text{disk}}/M_{\text{star}} \ll 1\%, M_{\text{enve}} \sim 0$	Passive disk; no or very weak accretion

¹ Flat Spectrum; introduced by Greene et al. (1994) in order to bridge Class I and II.

² M_{star} , M_{disk} , and M_{enve} represent mass of the star, disk, and envelope, respectively.

Adapted and modified from Table 1 of Williams and Cieza (2011).

Class 0

The Class 0 YSOs are seen at the earliest stage of cloud collapse. Although the protostar already forms at the center of the cloud, it cannot be observed even in the near-infrared because they are deeply embedded within the optically thick gas and dust. The Class 0 YSOs are typically considered as protostars accompanying active jets and outflows. The SED of the Class 0 YSOs shows that of a cold gray body with less than 30 K in temperature.

Class I

Class I YSOs are the most luminous at far-infrared around 100 μm . In this phase, the YSO is still embedded within an envelope of infalling material, which reradiates the emission from the protostar and disk toward longer wavelengths. Circumstellar disks with a size of ~ 100 au appear in this phase. Outflows and jets are also identified from these Class I YSOs.

Class II

Class II YSOs represent a later evolutionary phase when the envelope has largely been accreted. The SED of Class II phase can be understood as the sum of emission from the optically visible pre-main-sequence stars (PMSs) together with emission in the infrared and millimeter radio from a surrounding circumstellar disk. In addition, an excess of ultraviolet radiation greater than from naked stellar photosphere is also observed in this phase. This is due to accretion hotspots on the stellar surface as gas in the disk flows on to the stars. The Class II YSOs are referred to as classical T Tauri stars (CTTSs), which have an equivalent width of H_{α} 10 Å.

Class III

The YSOs with almost dissipated disk are classified as Class III phase. The Class III YSOs can still be distinguished from main sequence stars by their location in a Hertzsprung–Russell diagram or by

other features of young stars such as strong X-ray activity. They are often referred as weak-lined T Tauri stars (WTTs) that have an $H\alpha$ equivalent width smaller than 10 Å. Some Class III YSOs are accompanied by debris disks that are thought to have little or no gas. The emission of debris disks is thought to be caused by short-lived dust that is constantly regenerated by collisions of larger dust in orbit around the star.

1.2 Outflows and jets

In the early 1980s, in the vicinity of YSOs of early phase, molecular outflows and optical jets both of which are phenomena of expelling mass from the center of the star forming region to outer were detected one after another.

1.2.1 Outflows

The outflow was discovered for the first time in the L-1551 cloud of Taurus by Snell et al. (1980). ^{12}CO ($J = 1-0$) observations revealed a remarkable, double-lobed spectral structure in the velocity range of few to tens km s^{-1} , opposite directions from an infrared source IRS 5 (see Figure 1.2). Outflows are mainly identified through radio emission lines of CO molecule which have bipolar morphology (see Figure 1.3). Protostellar outflows are important tools for understanding star formation process, since they provide a fossil record of the mass loss histories (Arce et al. 2007 and Bally et al. 2007). They may play a significant role in determining final stellar masses and the IMF. Outflows may also take away some of the angular momentum of matter accreting onto the protostar and thus promote the evolution of the circumstellar disk. While the stage of the stellar evolution from a molecular cloud core to protostar, the angular momentum must be reduced by more than five orders of magnitude, but since the angular momentum is a conserved quantity, it must be released to the outside by some mechanism. Outflows and jets are one of those candidates, but the driving mechanisms of them are also not completely understood.

General properties

Molecular outflows have been well studied in the low to intermediate mass protostars (e.g., see Richer et al. 2000). Typical flow sizes are 0.1–1 pc, with outflowing gas velocities of 10–100 km s^{-1} . Typical mass outflow rate and outflow force are $10^{-6} M_{\odot} \text{ yr}^{-1}$ and $10^{-5} M_{\odot} \text{ km s}^{-1} \text{ yr}^{-1}$, respectively (Bontemps et al. 1996). These values correlate with the bolometric luminosities of the driving YSOs (e.g., see Bally and Lada 1983 and Wu et al. 2004). Outflows driven by B type massive stars have mass outflow rate of $10^{-5} M_{\odot} \text{ yr}^{-1}$ and force of $10^{-4} M_{\odot} \text{ km s}^{-1} \text{ yr}^{-1}$ (Arce et al. 2007). The outflow collimation and morphology varies with protostellar evolution (Lee et al. 2002). The youngest outflows are highly collimated, while the older ones present much lower collimation and wider opening angles. The correlation between collimation, morphology, kinematic properties of outflows and properties of outflow driving sources are still uncertain.

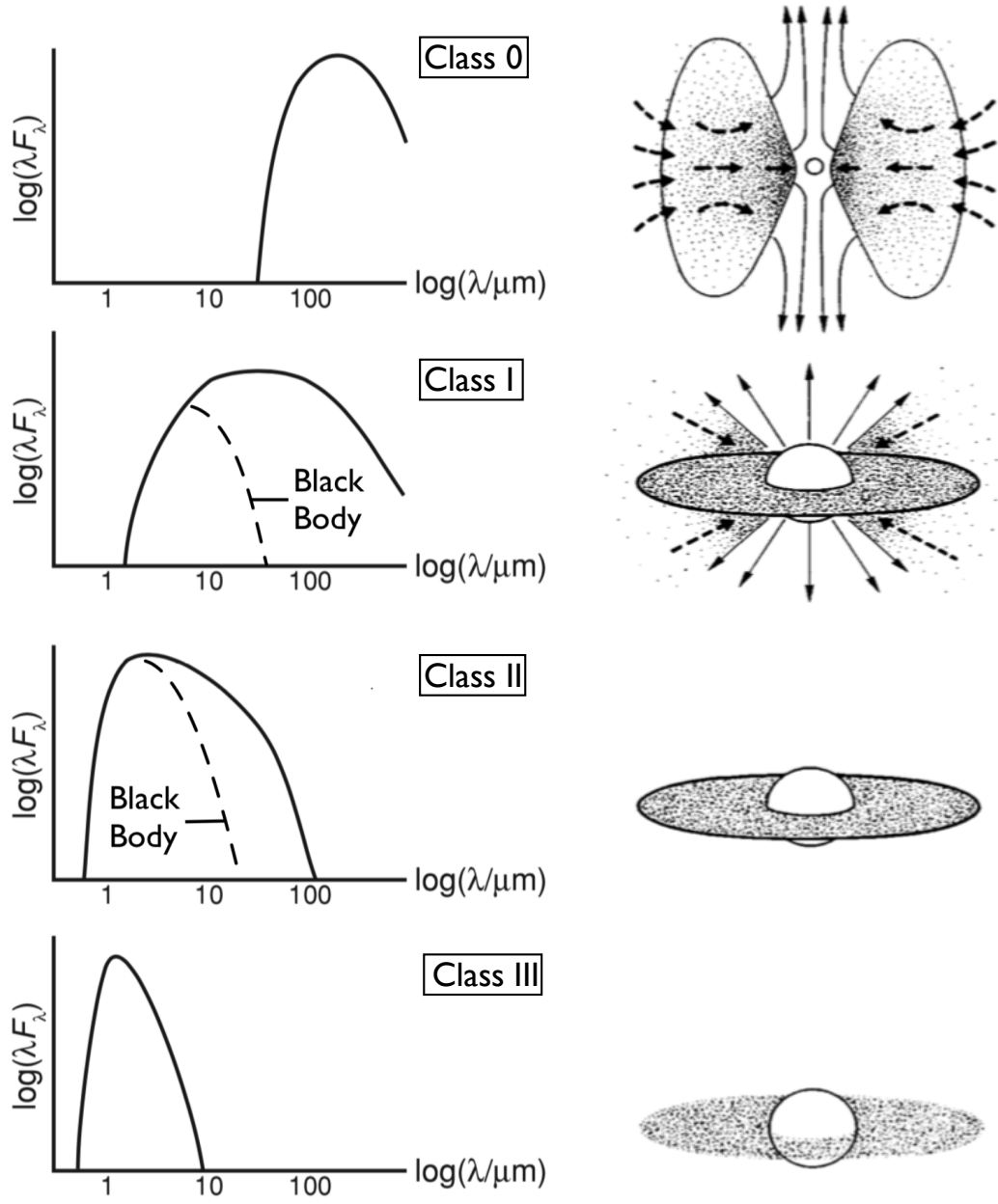


Figure 1.1. Classification scheme for YSOs, which shows the evolution of stars from the dense core to the start of nuclear fusion. The left plots show the SEDs of each class adapted and modified from Figure 2.1 in Armitage (2010). The right illustrations represent a star and its surrounding environment adapted from Figure 11 in Bachiller (1996).

1.2.2 Jets

Herbig (1951) and Haro (1952) independently found the first examples of nebulous objects, located close to NGC 1999 within the Orion A molecular clouds, which are now known as Herbig-Haro

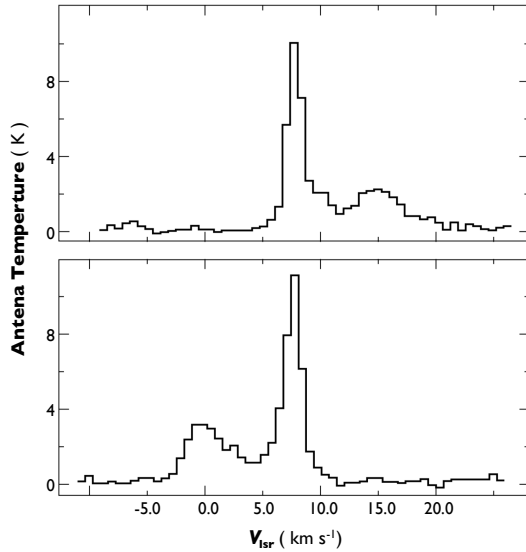


Figure 1.2. ^{12}CO ($J = 1-0$) molecular outflow spectra of L-1551/IRS 5. The upper panel shows the red-shifted lobe located in the north-east direction to IRS 5, while the lower one shows the blue-shifted lobe located at the south-west direction (see also Figure 1.3). Adapted and modified from Figure 1 in Snell et al. (1980).

(HH) objects. These objects were first thought to be young stars themselves or their associated reflection nebulae (Strom et al. 1974). However by the early 1980s, HH objects were proved to follow collimated jets driven by young stars (Dopita et al. 1982 and Mundt & Fried 1983) and have large proper-motion (Herbig & Jones 1981, see also Figure 1.4). Jet is also a phenomenon that releases mass like outflow and characterized by faster speeds (tens to hundreds km s^{-1}) and its high collimation. HH objects are now thought to be caused by shock waves generated by jets from YSOs collide with interstellar medium (Schwartz 1975). In the 1990s, many HH objects were imaged by sensitive CCD mounted on *Hubble space telescope* (*HST*) at high resolution (Figures 1.4 and 1.5), and more than a thousand HH objects are now cataloged (Bally 2016).

1.2.3 Theories on outflow's mechanism

Since the outflows and jets were found, their acceleration mechanism has been discussed, but is not yet fully understood. The most prominent theory at present is the acceleration model with magnetic lines penetrating the protostar and circumstellar disk (e.g., Pudritz 1986 and Shu et al. 1991). According to these models, the rotating protostellar system is strongly coupled to the magnetic fields to generate an Alfvén wave⁵ with a large angular momentum in the vertical direction, and the momentum is transmitted to the surrounding gas, releasing the gas in bipolar directions. It has not yet been known whether the high-speed jets and low-speed outflows are emitted by different mechanisms or not. The latest magnetohydrodynamics (MHD) simulation (Machida et al. 2007, 2008) has succeeded in portraying both faster and narrower jets and slower

⁵A transverse wave that travels along magnetic fields lines in a magnetic plasma.

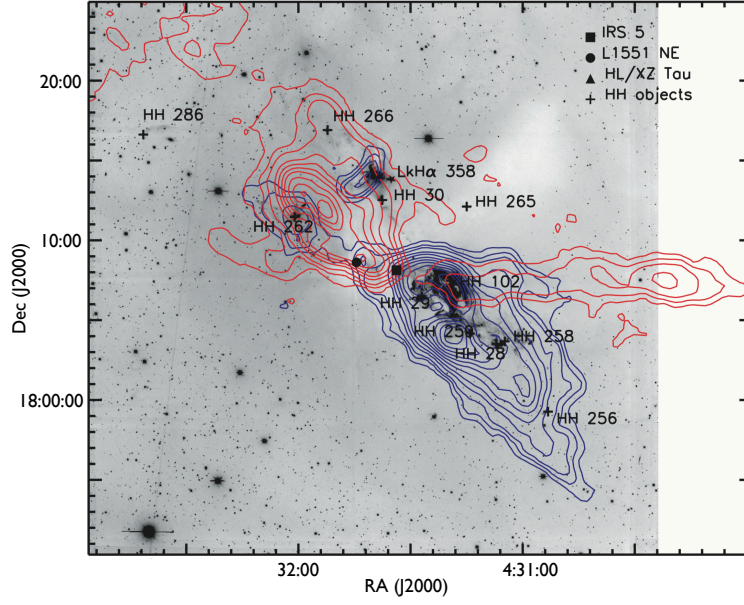


Figure 1.3. Outflowing ^{12}CO ($J = 1-0$) integrated intensity emission in L-1551 overlaid on optical $\text{H}\alpha$. The blue and red contours represent the blue- and red-shifted components, respectively. The integrated intensity velocity ranges are -20 km s^{-1} to 5 km s^{-1} for blue-shifted components and 8 km s^{-1} to 20 km s^{-1} for red-shifted components. Blue contours start at 3σ and are $1.5, 3, 4.5, 6, 9, 12, 16, 20, 24, 28, 32, 36, 40$, and 44 K km s^{-1} , and red contours start at 4.5σ and are $1.5, 3, 5, 9, 12, 15, 18, 22, 26, 30, 34, 38, 42$, and 46 K km s^{-1} . Adapted from Figure 1 in Stojimirović et al. (2006).

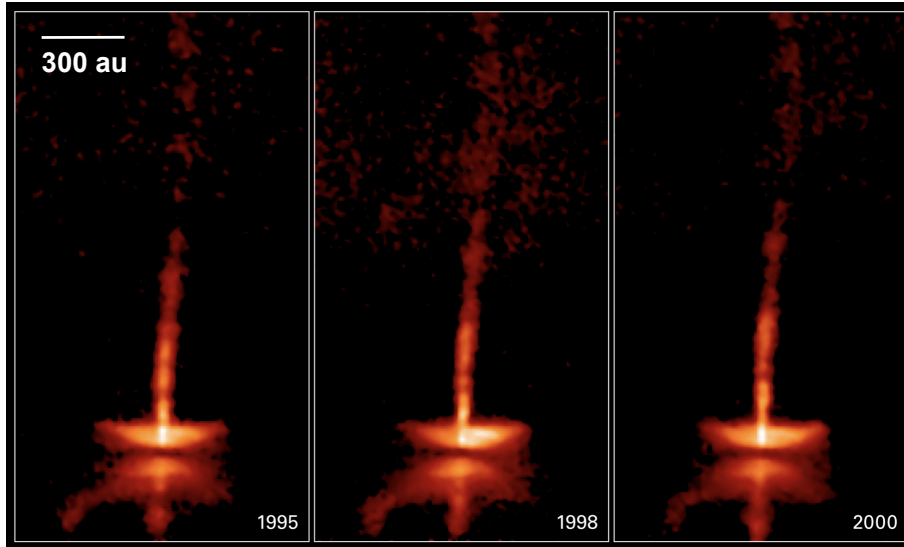


Figure 1.4. Jet and edge-on disk in HH 30 with wavelength of 675 nm imaged by the *HST* Wide Field Planetary Camera (WFPC) 2. These images show changes over only a five-year period in the jet of newborn star.



Figure 1.5. HH 1 and 2 objects imaged by *HST* WFPC 2. The cross express the location of the driving star VLA 1.

and wider outflows accelerated by different mechanisms. According to Machida et al. (2007, 2008), outflows are driven by the magnetic centrifugal force that from the first core of the early phase of the protostar, or from the outer edge of the protoplanetary disk of the late phase of the protostar. On the other hand, jets are driven by the magnetic pressure gradient force from the second core or inside the protoplanetary disk. In the observational aspects, high-resolution outflow surveys using the interferometer such as the Atacama Large Millimeter/sub-millimeter Array (ALMA) to capture the roots of the acceleration of outflows and jets are underway (e.g., Matsushita et al. 2019).

1.3 Outflow feedback

During the early phase of star formation, it is now considered that outflows and jets are ubiquitous phenomena both in the low- and high-mass star forming regions (e.g., Lada 1985 and Arce et al. 2007). Outflows and jets may give a remarkable impact on their surrounding environment. The terminal shocks in outflows dissociate molecules, sputter grains, and can reset the chemical evolution of clouds to an initial state (Steven & Francesco 2005). On the other hand, outflows and jets inject energy and momentum into the parent molecular clouds and may play an important role in the self-regulation of star formation (e.g., Norman & Silk 1980 and Bally 2016). The substantial energy of the outflows injected into its parent molecular clouds can affect the cloud structure and evolution (Solomon et al. 1981), sustaining the clouds against gravitational collapse (Shu et al. 1987 and Federrath 2015).

Molecular clouds are in turbulence with supersonic velocity width that increases with cloud's scale (Zukerman & Evans 1974 and Larson 1981), and this observational fact is called "Larson's law". According to the three dimensional MHD simulations conducted by Mac Low et al. (1998) and Stone et al. (1998), however, turbulence is instantly dissipated in the absence of some energy source. Energy feedback from outflows may maintain the turbulence in the molecular clouds (Shu et al. 1987 and Nakamura & Li 2007).

In the past decade, many authors investigated molecular outflows and their feedback in the parent molecular clouds by comparing the luminosity of the outflows and the energy dissipation

rates of the cloud turbulence. For example, Arce et al. (2010) conducted outflow surveys in Perseus, and concluded that the outflows have sufficient energy to maintain the observed turbulence in the entire Perseus cloud complex (see also Hatchell et al. 2007, 2009). Nakamura et al. (2011a, 2011b) investigated the outflows in L1688 in the ρ Ophiuchi and Serpens South, respectively, and found that the luminosity of outflows in each region are comparable to the energy dissipation rate of the cloud turbulence (see also White et al. 2015). Li et al. (2015) undertook the unbiased outflow surveys in Taurus and concluded that the outflow feedback is sufficient to maintain the observed turbulence in the current epoch. All these studies were conducted in relatively low-mass ($\leq 10^3 M_\odot$ (Nakamura & Li 2013)) molecular clouds, containing low-mass star forming regions. I investigate the feedback of outflows in the Orion A giant molecular clouds, containing high-mass star forming regions.

1.4 Observation target

Orion A giant molecular clouds (referred to simply as Orion A hereafter) is the nearest high-mass star forming region whose distance is estimated to be 414 ± 7 pc by Menten et al. (2007), and located in the Orion-Monoceros Cloud Complex (see Figure 1.6). Low-mass star formation occurs throughout the cloud (e.g., Strom et al. 1993 and Stanke et al. 2002), while high-mass stars form in the northern part of the cloud which is observed as the Orion Nebula in visible and infrared light. In addition, the Orion OB association 1a and 1b, the group of dozens massive stars, exists outside Orion A (Blaauw 1991; see Figure 1.6). These massive stars are expected to input substantial energy and gas pressure to the Orion A and B molecular clouds through their strong stellar wind. On the other hand, Megeath et al. (2012, hereafter M2012) cataloged 2818 YSOs, consisting of 2446 PMSs and 372 protostars using the InfraRed Array Camera (IRAC) and the Multiband Imaging Photometer for Spitzer (MIPS) instruments mounted on the *Spitzer Space Telescope* and the Two Micron All-Sky Survey (2MASS). The total mass of Orion A is estimated to be $5 \times 10^4 M_\odot$ and $3.9 \times 10^4 M_\odot$ by Bally et al. (1987) and Nakamura et al. (2019), respectively.

Orion A had been observed by various gas emission lines. Observations with ^{12}CO ($J = 1-0$) and ^{13}CO ($J = 1-0$) line, which are the tracers of low-density regions revealed that Orion A is elongated along the galactic plane and has a distinctive filamentary structure called as the "Integral shaped filament" (Bally et al. 1987). Observations of the tracers of high-density regions were also made. For example, C^{18}O ($J = 1-0$) (e.g., Dutrey et al. 1991), CS ($J = 1-0$) (e.g., Tatematsu et al. 1993), NH_3 (e.g., Cesaroni & Wilson 1994), and H^{13}CO^+ (e.g., Aso et al. 2000) can be mentioned. Orion A had been observed with dust continuum emission at $450 \mu\text{m}$ and $850 \mu\text{m}$ by Johnstone & Bally (1999). Shimajiri et al. (2015) also conducted a survey in 1.1 mm continuum emission and cataloged 619 dust cores in Orion A.

Orion A is often divided into several subregions (e.g., Feddersen et al. 2018). OMC 2/3 is located in the northernmost of Orion A and is known as an intermediate-mass star forming region (e.g., Chini et al. 1997; Lis et al. 1998). More than 500 young stellar objects (YSOs) have been found in this region by previous observations (e.g., Chini et al. 1997; M2012). OMC 1 has the brightest

intensity and the largest velocity width. This region contains the H II region M42 created by the Trapezium stars, as well as the Orion BN/KL Nebula (Becklin & Neugebauer 1967; Kleinmann & Low 1967). The Orion BN/KL Nebula is located about $1'$ northwest of the Trapezium and has a bolometric luminosity of about $10^5 L_{\odot}$ (O'Dell et al. 2008). In this region, evidence of active massive-star formation is obtained from detections of multiple strong infrared and radio sources. OMC 4/5 is located at south of the OMC 1. Shimajiri et al. (2015) identified 225 1.1mm dust cores in this region. L1641-N and NGC 1999 contain well-known young clusters such as L1641-N and V380 Ori, respectively. Approximately 80 YSOs are identified in L1641-N cluster (Fang et al. 2009). Nakamura et al. (2012) found that the collision of two different gas components (cloud-cloud collision) is taking place in this region. V380 Ori cluster contains many HH objects (e.g., see Allen & Davis 2008). High-mass stars are not formed in OMC 4/5, L1641-N, and NGC 1999 regions.

1.5 Outflows in Orion A

Previous outflow surveys in Orion A are limited to some specific subregion such as OMC 2/3 (e.g., Aso et al. 2000; Williams et al. 2003; Takahashi et al. 2008; Berné et al. 2014), OMC 1 (e.g., Kwan & Scoville 1976; Snell et al. 1984; Zapata et al. 2005; Bally et al. 2017), V380 Ori (Davis et al. 2000), and L1641-N (Stanke & Williams 2007; Nakamura et al. 2012).

The OMC 2/3 regions had been observed comparatively well so far. Aso et al. (2000) and Williams et al. (2003) conducted the outflow surveys toward OMC 2/3 in ^{12}CO ($J = 1-0$) with the angular resolutions of $\sim 20''$ with the Nobeyama 45m telescope and $\sim 10''$ with the FCRAO 14m telescope and Berkeley-Illinois-Maryland Association (BIMA) array, respectively. They identified 8 and 9 outflows. Williams et al. (2003) found that the luminosity of the outflows is comparable to the energy dissipation rate of the cloud turbulence in OMC 2/3. Chini et al. (1997) and Takahashi et al. (2008A) also conducted the survey toward the same region using ^{12}CO ($J = 3-2$) with NRAO 12m telescope and with the Atacama Submillimeter Telescope Experiment (ASTE), respectively. Takahashi et al. (2008A) detected 14 outflows. Shimajiri et al. (2008, 2009) conducted the survey of the outflows with the Nobeyama Millimeter Array (NMA) in the OMC 2 FIR 3, 4, 5, 6 regions.

In the OMC 1 region, extremely high velocity outflows associated with KL objects were found by Kwan & Scoville (1976). Bally et al. (2017) showed more than a hundred ^{12}CO ($J = 2-1$) outflowing streamers with velocities extending from $V_{\text{lsr}} = -150 \text{ km s}^{-1}$ to $+145 \text{ km s}^{-1}$ with ALMA.

The OMC 4/5 region was poorly studied and no systematic search of outflows were conducted. Therefore, no outflows was identified in this region.

Stanke & Williams (2007) and Nakamura et al. (2012) found several outflows driven by deeply embedded protostellar sources in L1641-N cluster using the ^{12}CO ($J = 2-1$) line taken by the IRAM 30m telescope and ^{12}CO ($J = 1-0$) line taken by the Nobeyama 45-m telescope, respectively.

In the NGC 1999 region, a well-collimated CO outflow associated with V380 Ori-NE was identified by previous searches (e.g., Davis et al. 2000 (^{12}CO ($J = 3-2$) and ($J = 4-3$); Choi et al. 2017 (SiO ($v=0$, $J=1-0$))). Moro-Martín et al. (1999) revealed several outflows around HH 1/2 in

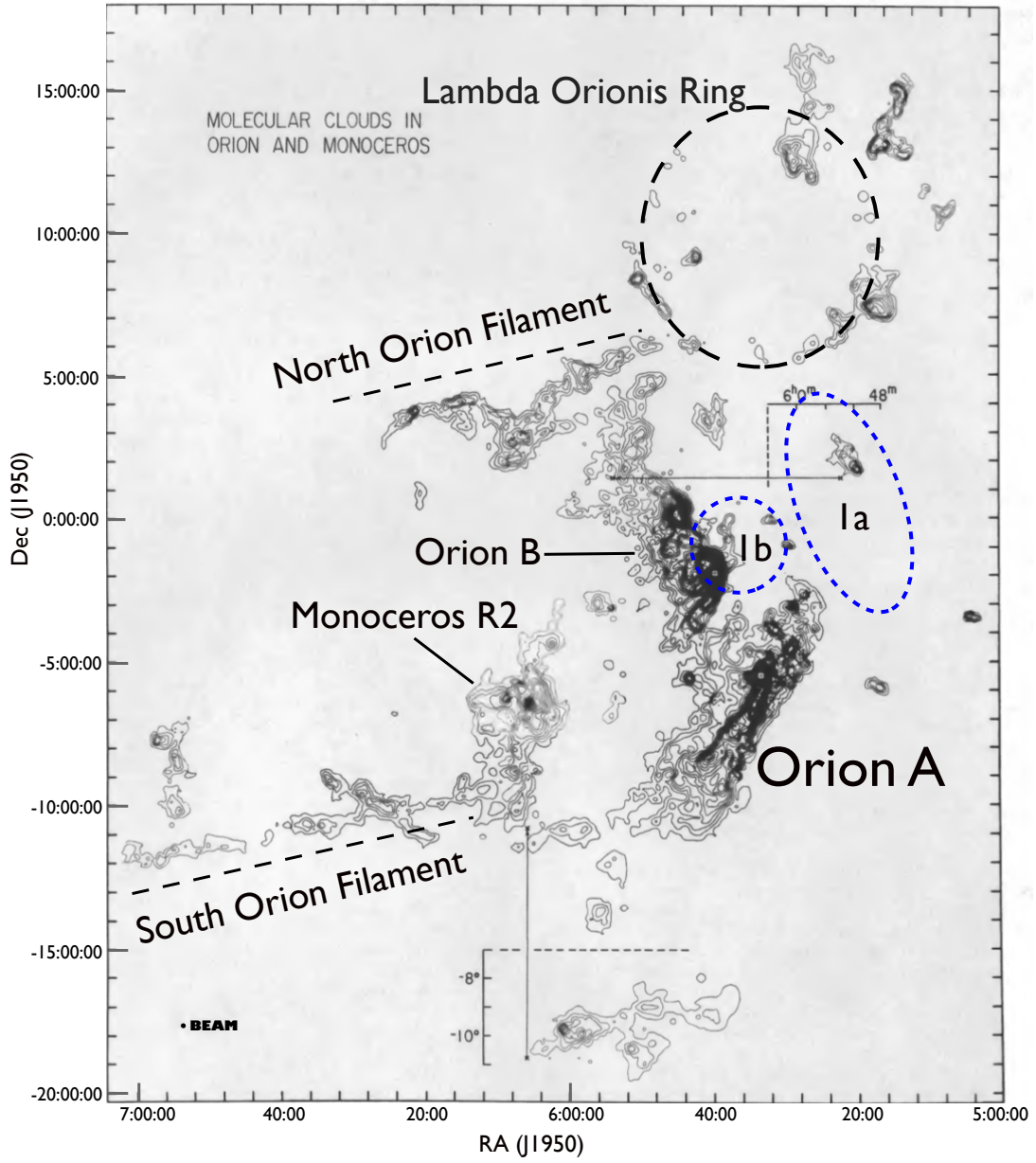


Figure 1.6. Large scale gas distribution of Orion-Monoceros Cloud Complex indicated by contour map of integrated intensity of ^{12}CO ($J = 1-0$) line emission. The contour intervals are 2.56 K km s^{-1} starting at 1.28 K km s^{-1} . The blue dashed circles represent the OB association 1a and 1b. Adapted and modified from Figure 2 in Maddalena et al. (1986).

NGC 1999 using the ^{12}CO ($J = 1-0$) and ($J = 2-1$) lines.

1.6 The aim of this study

The observational studies of this thesis have been performed by the following main aims.

1. To conduct the comprehensive outflow survey of Orion A including the poorly studied OMC 4/5 region where no outflows were previously identified, with the systematic procedure.
2. To investigate the general properties of the outflows which contain the correlation between the physical properties of the outflows and the parameters of the protostars that drive the outflows.
3. To derive whether the outflows and other protostellar feedback can maintain the turbulence of Orion A.

1.7 Outline

The outline of this thesis is as follows. Chapter 2 describes the detail of our Nobeyama 45-m observations and obtained data. In chapter 3, I present the systematic search procedure to identify the outflows. The results of outflow searches and the physical properties of the outflows are given in chapter 4. In chapter 5, I discuss the two things: the comparison of the parameters of the outflows and that of the protostars which driving the outflows, and impact of the outflows and other protostellar feedback into parent Orion A. In chapter 6, I summarize the main results of this study and describe the feature work.

Chapter 2

Observations and data

2.1 Observations and data reduction

2.1.1 FOREST Observations

I conducted mapping observations of ^{12}CO ($J = 1-0$, 115.271202 GHz) and ^{13}CO ($J = 1-0$, 110.201354 GHz) toward Orion A with FOREST, four-beam dual polarization, sideband separating SIS receiver (Minamidani et al. 2016) mounted on the National Radio Observatory (NRO) 45-m telescope. The observations were made between 2014 December and 2017 March. I set a digital spectrometer, SAM45, that has 16 sets of 4096-channel arrays, as the backend receiver. The observation area is separated into small boxes with a size of $10' \times 10'$. I employed the On-The-Fly (OTF) scan mode (Sawada et al. 2008) for the mapping observations and the position of the emission-free area is $(\alpha_{\text{J2000}}, \delta_{\text{J2000}}) = (05^{\text{h}}29^{\text{m}}00^{\text{s}}.0, -5^{\circ}25'30''.0)$. The telescope beam size (HPBW) is $\sim 15''$ and the main beam efficiency is $\sim 45\%$ at 115 GHz. The typical pointing accuracy is $3''$ by observing the SiO maser line from Orion KL $(\alpha_{\text{J2000}}, \delta_{\text{J2000}}) = (05^{\text{h}}34^{\text{m}}14^{\text{s}}.16, -5^{\circ}22'21''.0)$ every one hour. The system noise temperatures of ^{12}CO and ^{13}CO observations are typically 350 K and 150 K, respectively. The chopper-wheel method was used to determine the temperature scale.

2.1.2 Combined with BEARS

To improve sensitivity and coverage, I combined the FOREST data and with previously published data taken with the BEARS receiver (Sunada et al. 2000). BEARS observations of ^{12}CO ($J = 1-0$) and ^{13}CO ($J = 1-0$) were conducted between 2007 December and 2010 January, and between 2012 April and 2013 May, respectively. These data were published by Shimajiri et al. (2011, 2014, 2015b) and Nakamura et al. (2012), and the intensity scales of the ^{12}CO ($J = 1-0$) and ^{13}CO ($J = 1-0$) were corrected into the main beam temperature scale (T_{MB}). Thus the calibrations of the intensity scales of the ^{12}CO and ^{13}CO data taken with FOREST were done by comparing those of BEARS data. I adopted a spheroidal function with a spatial grid size of $7''.5$ as a convolution function. The combined maps of the ^{12}CO and ^{13}CO have an effective resolution of $\sim 22''$ in FWHM, corresponding

to ~ 0.05 pc at a distance of 414 pc, and an effective velocity resolution of ~ 0.2 km s $^{-1}$. The typical rms noise levels of the ^{12}CO and ^{13}CO are 0.47 K and 0.18 K in units of T_{MB} , respectively. Table 2.1 summarizes the observations and data sensitivities. The coverages of the final maps is about $0.7^\circ \times 2^\circ$ and figure 2.1 shows the mapping regions of ^{12}CO and ^{13}CO superposed on the H_2 column density map of Orion A. Our mapping areas cover the entire of the star-forming regions of Orion A.

Table 2.1: Observed lines and data sensitivity

Molecule	Transition	Rest Frequency (GHz)	Effective Resolution (arcmin)	Δv (km s $^{-1}$)	Noise level (K)
^{12}CO	$J = 1-0$	115.271202	21.6	0.20	0.47
^{13}CO	$J = 1-0$	110.201354	22.0	0.22	0.18

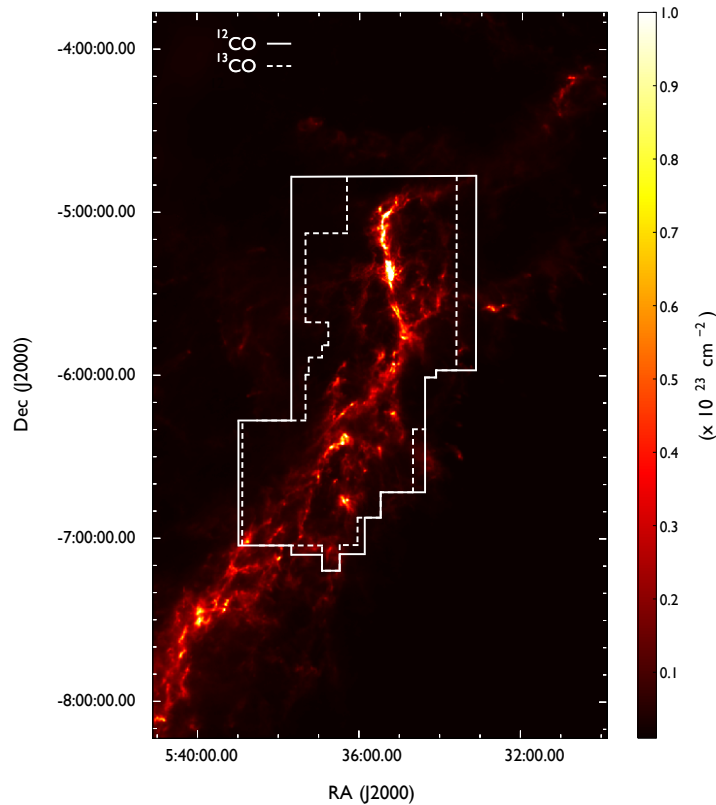


Figure 2.1. The coverage of the maps of ^{12}CO and ^{13}CO superposed on the H_2 column density map of Orion A. The background image is taken by *Herschel Space Observatory* (Lombardi et al. 2014).

2.2 Data

2.2.1 Integrated intensity map

Figures 2.2 and 2.3 show the total integrated intensity maps of the ^{12}CO ($J = 1-0$) and ^{13}CO ($J = 1-0$) emission of Orion A, respectively. The integrated velocity range is from 2.0 km s^{-1} to 20.0 km s^{-1} in v_{LSR} in both maps. Five subregions and several well-known structures are labeled. The integral-shaped filament detected by many previous surveys (e.g., Bally et al. 1987 and Nagahama et al. 1998) and some cavity-like structures are clearly seen in both maps. Overall, both the ^{12}CO ($J = 1-0$) and ^{13}CO ($J = 1-0$) emissions become weak toward the south, and I cannot detect the filament structure in the L1641-N and NGC 1999 regions. In the both maps, the brightest emission located at the center of OMC 1 ($\alpha_{\text{J2000}}, \delta_{\text{J2000}} = (05\text{h}35\text{m}15\text{s}, -5^\circ22'22'')$) is from the Orion KL nebula and the rod-like structure located at the southwest of Orion KL is referred to as the Orion Bar. The Orion Bar is highly irradiated by ultraviolet photons from the massive stars in Orion KL Nebula (e.g., Walmsley et al. 2000 and O'Dell et al. 2001). Such regions are usually referred to as photodissociation regions (PDRs). The strip-like emission located at the east of OMC 1 is the Kelvin-Helmholtz (KH) ripples that are thought to be in the foreground of the Orion A (Berné et al. 2010). In the ^{13}CO map, several clumpy structures of about 1 pc size can be seen in the integral-shaped filament, L1641-N region, and NGC 1999 region.

2.2.2 Channel map

Figures 2.4 to 2.6 and 2.7 to 2.8 show the sample channel maps of the ^{12}CO ($J = 1-0$) and ^{13}CO ($J = 1-0$) emission of Orion A, respectively. The velocity ranges are $+2.30 \text{ km s}^{-1}$ to $+17.90 \text{ km s}^{-1}$ for ^{12}CO and $+3.39 \text{ km s}^{-1}$ to $+14.61 \text{ km s}^{-1}$ for ^{13}CO . I show here the channel maps smoothed by every three channels in both ^{12}CO and ^{13}CO , thus the velocity resolution of ^{12}CO and ^{13}CO are 0.60 km s^{-1} and 0.66 km s^{-1} , respectively. The rms noise levels are 0.27 K for ^{12}CO and 0.10 K for ^{13}CO . Both maps clearly express a large scale velocity gradient along the south to north direction. According to Bally et al. (1987) and Wilson et al. (2005), the origin of this large scale velocity gradient is the condensation of the cloud by the wind from the supernovae in the Orion OB association located to the 3° north of the Orion A (see Figure 1.6). In the ^{12}CO ($J = 1-0$) channel map, the emission from KL Nebula appears beyond the observed velocity range (from -2 km s^{-1} to 20 km s^{-1}). According to Bally et al. (2017), the ^{12}CO ($J = 1-0$) emission in the KL Nebula extend over the velocity range of $\pm 100 \text{ km s}^{-1}$.

2.2.3 Spectral feature

Figure 2.9 shows the averaged line profiles of the ^{12}CO and ^{13}CO in each subregion. The peak velocities of the ^{12}CO and ^{13}CO spectra in Figure 2.9 shift from 11 km s^{-1} to 8 km s^{-1} across the north to south of the cloud. The averaged velocity width at OMC 2/3, OMC 1, OMC 4/5, L1641-N, and NGC 1999 are $3.1, 4.7, 3.8, 4.0,$ and 3.3 km s^{-1} for ^{12}CO and $2.1, 4.0, 3.1, 3.5,$ and 2.8 km s^{-1} for ^{13}CO . These values are obtained from single-Gaussian fitting to each spectrum

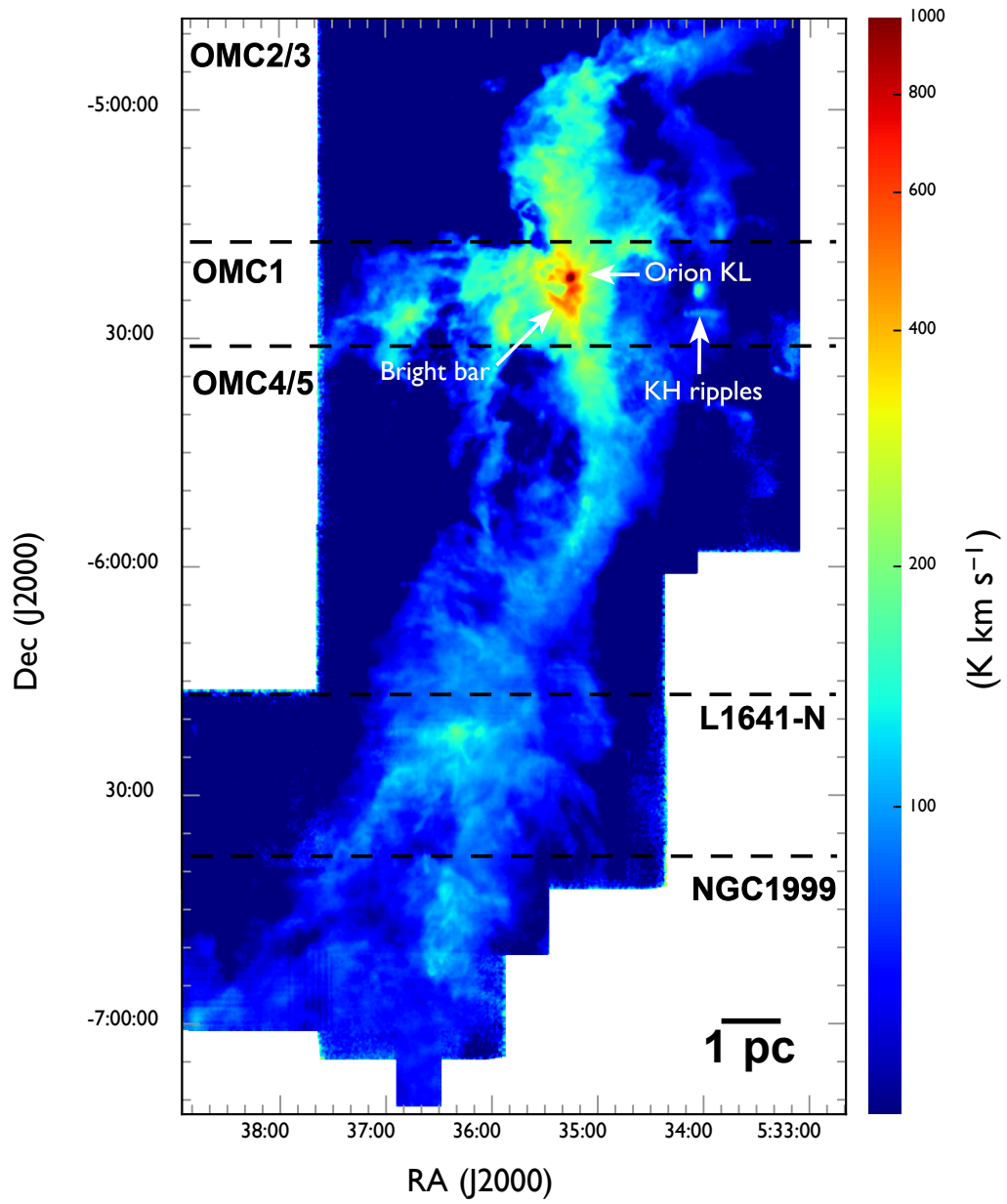


Figure 2.2. ^{12}CO ($J=1-0$) total integrated intensity map of Orion A.

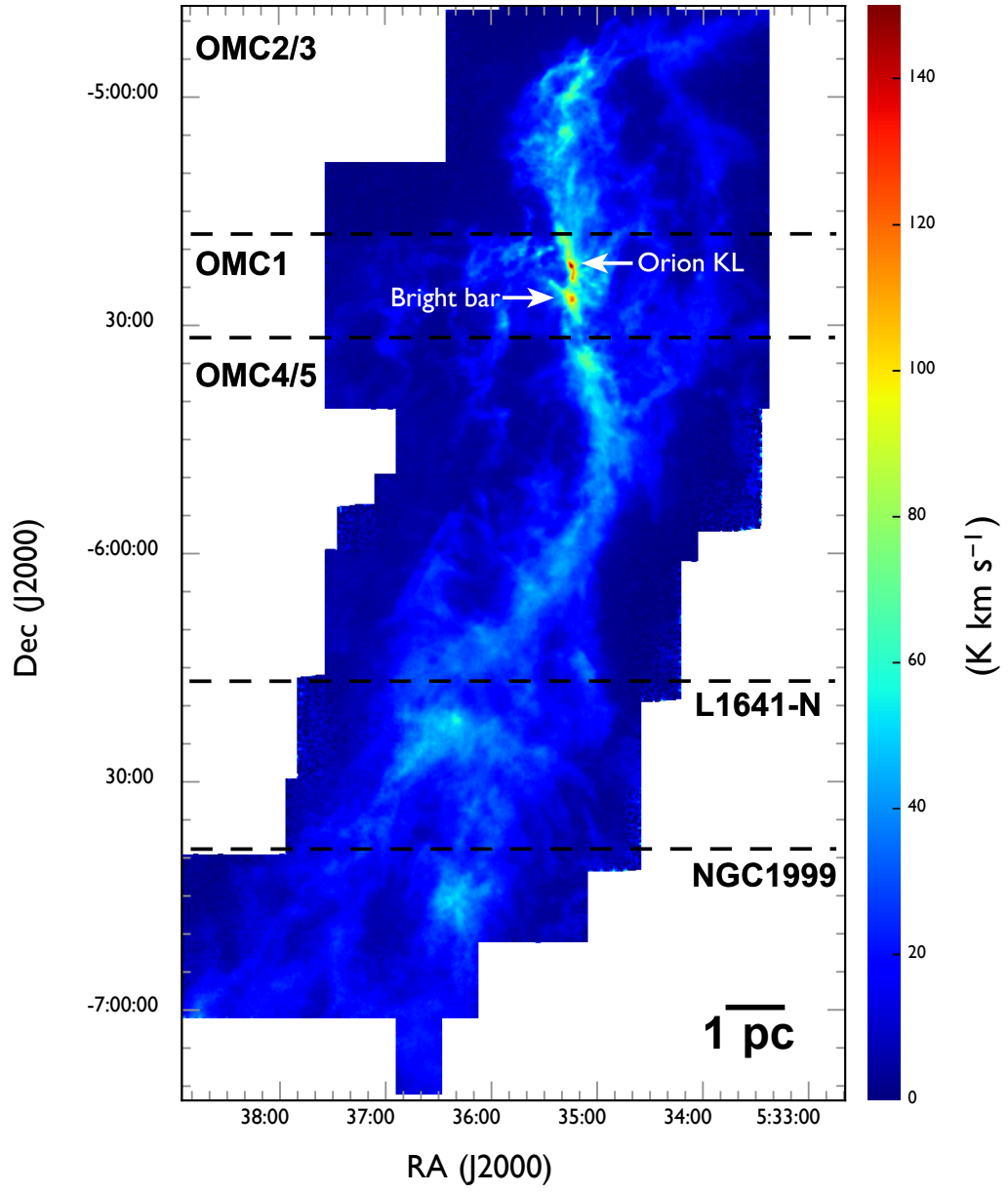


Figure 2.3. ^{13}CO ($J = 1-0$) total integrated intensity map of Orion A.

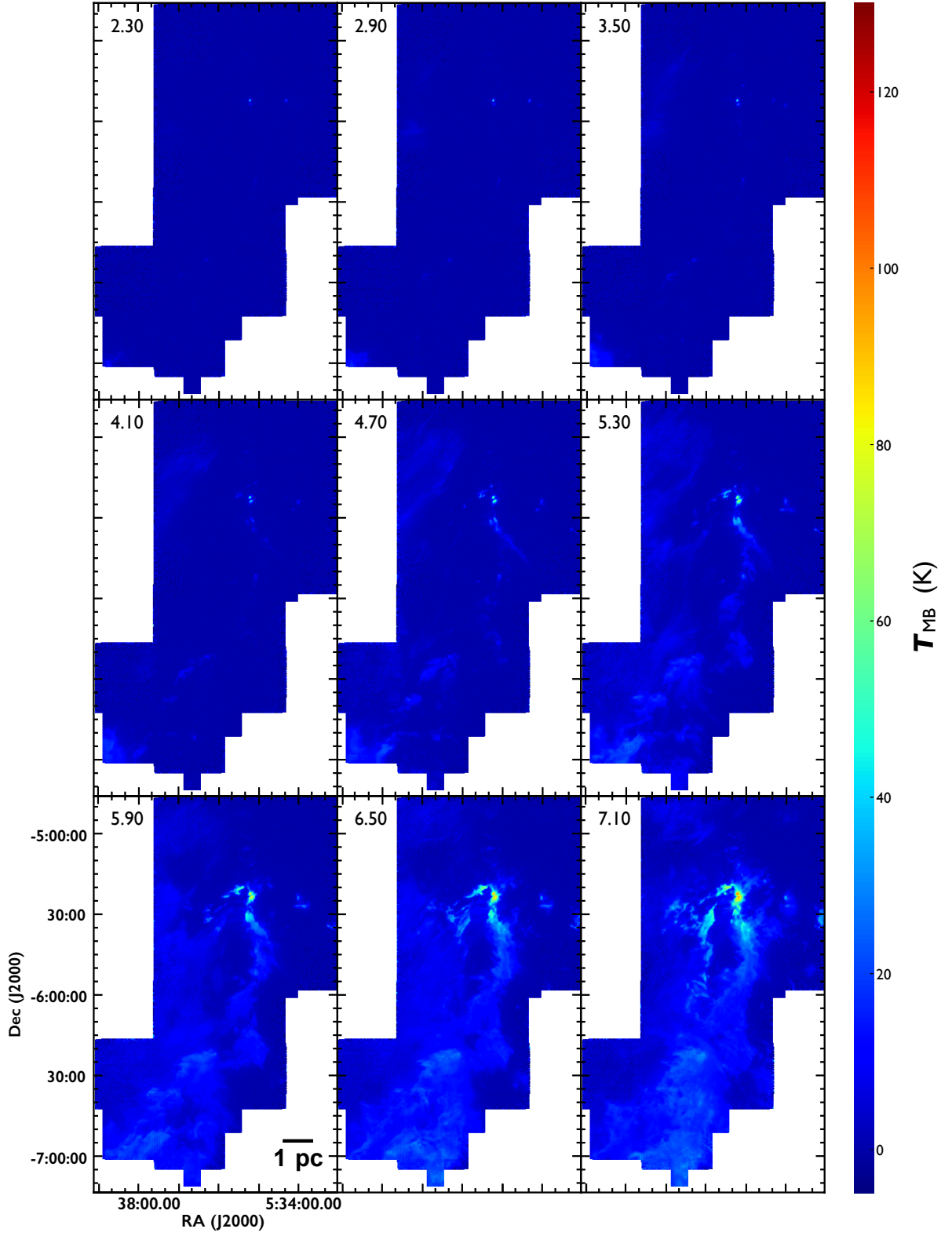


Figure 2.4. Channel maps of ^{12}CO ($J=1-0$). The lsr velocity is shown in the top left of each panel in the unit of km s^{-1} .

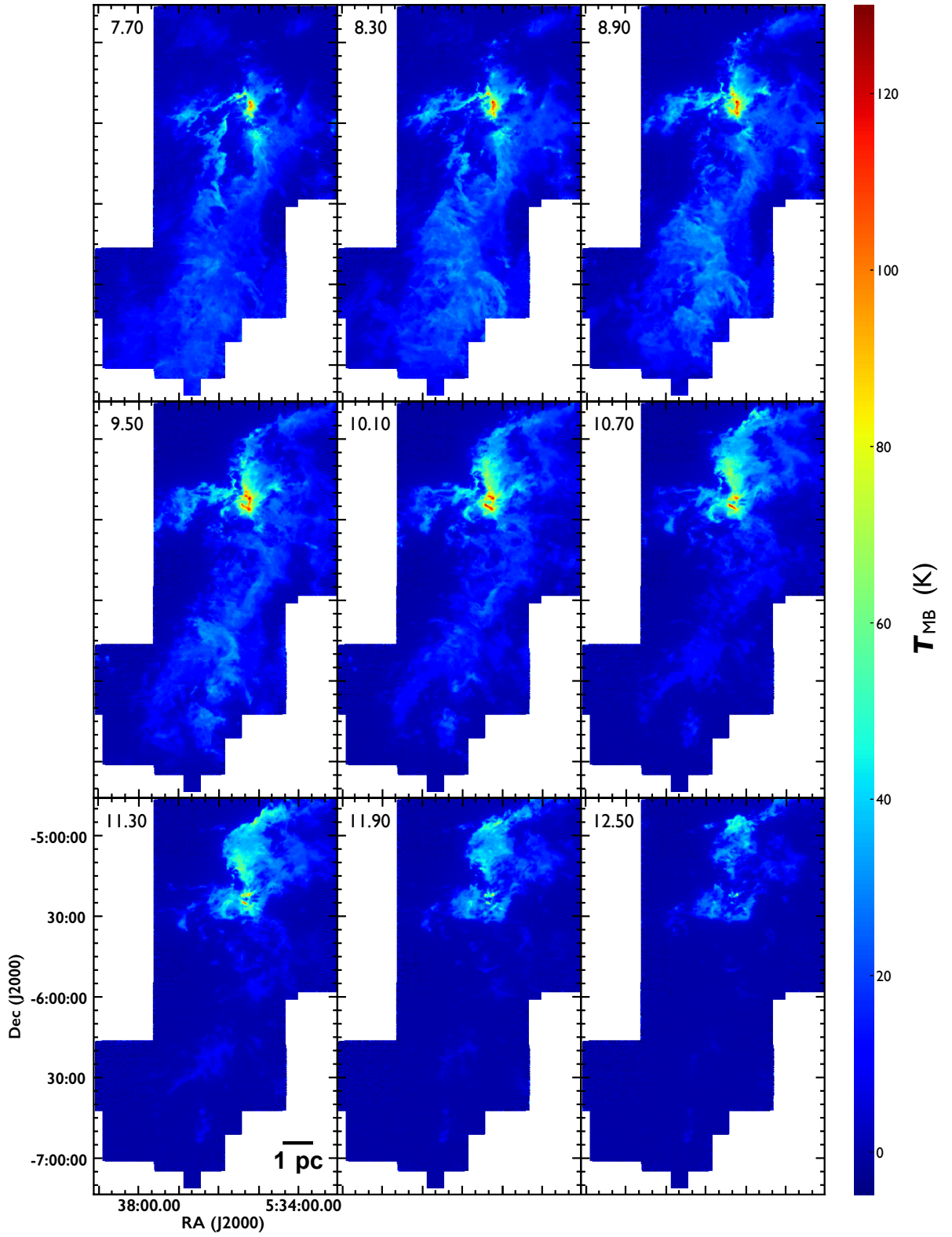


Figure 2.5. Channel maps of ^{12}CO ($J = 1-0$), continued from Figure 2.4.

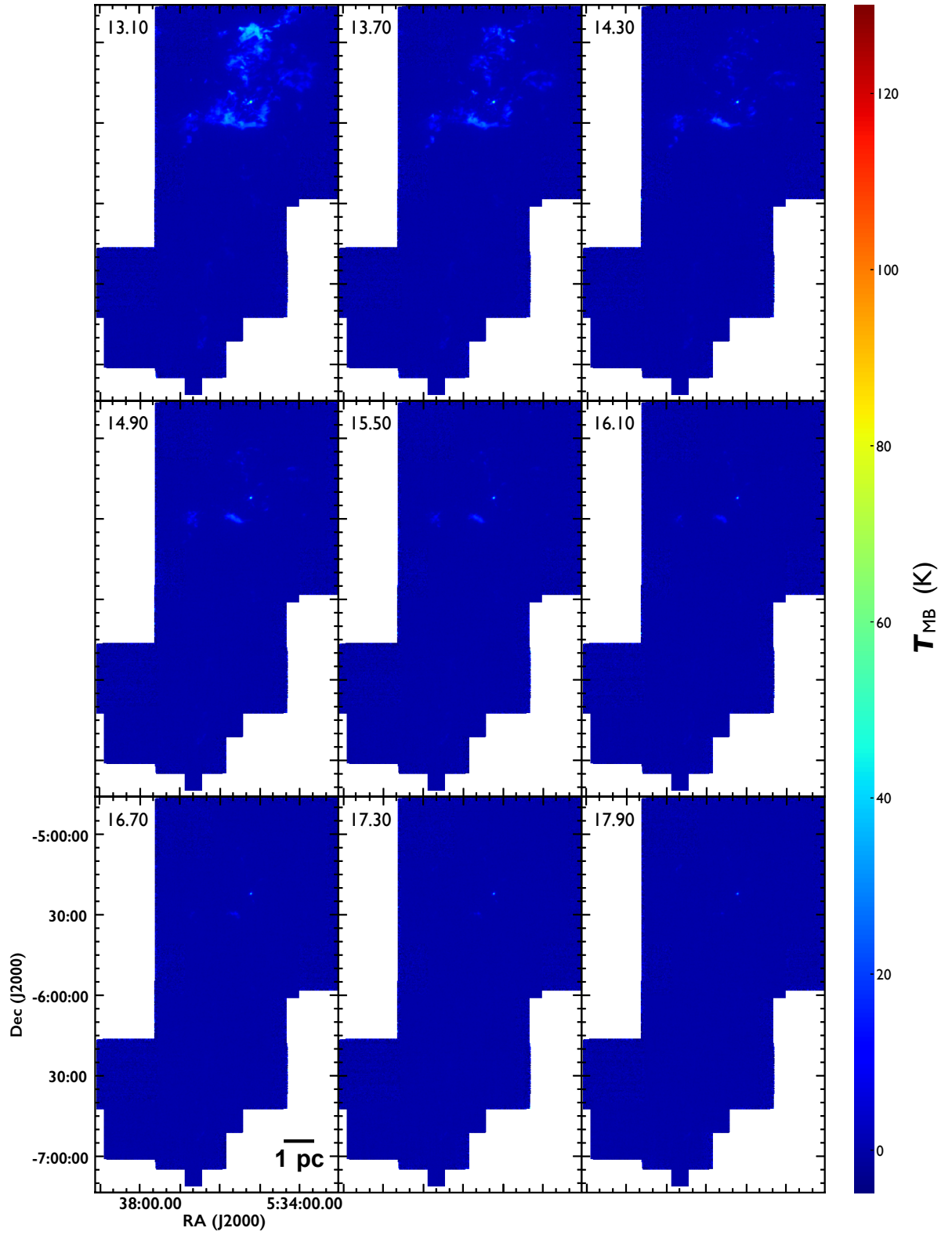


Figure 2.6. Channel maps of ^{12}CO ($J = 1-0$), continued from Figure 2.5.

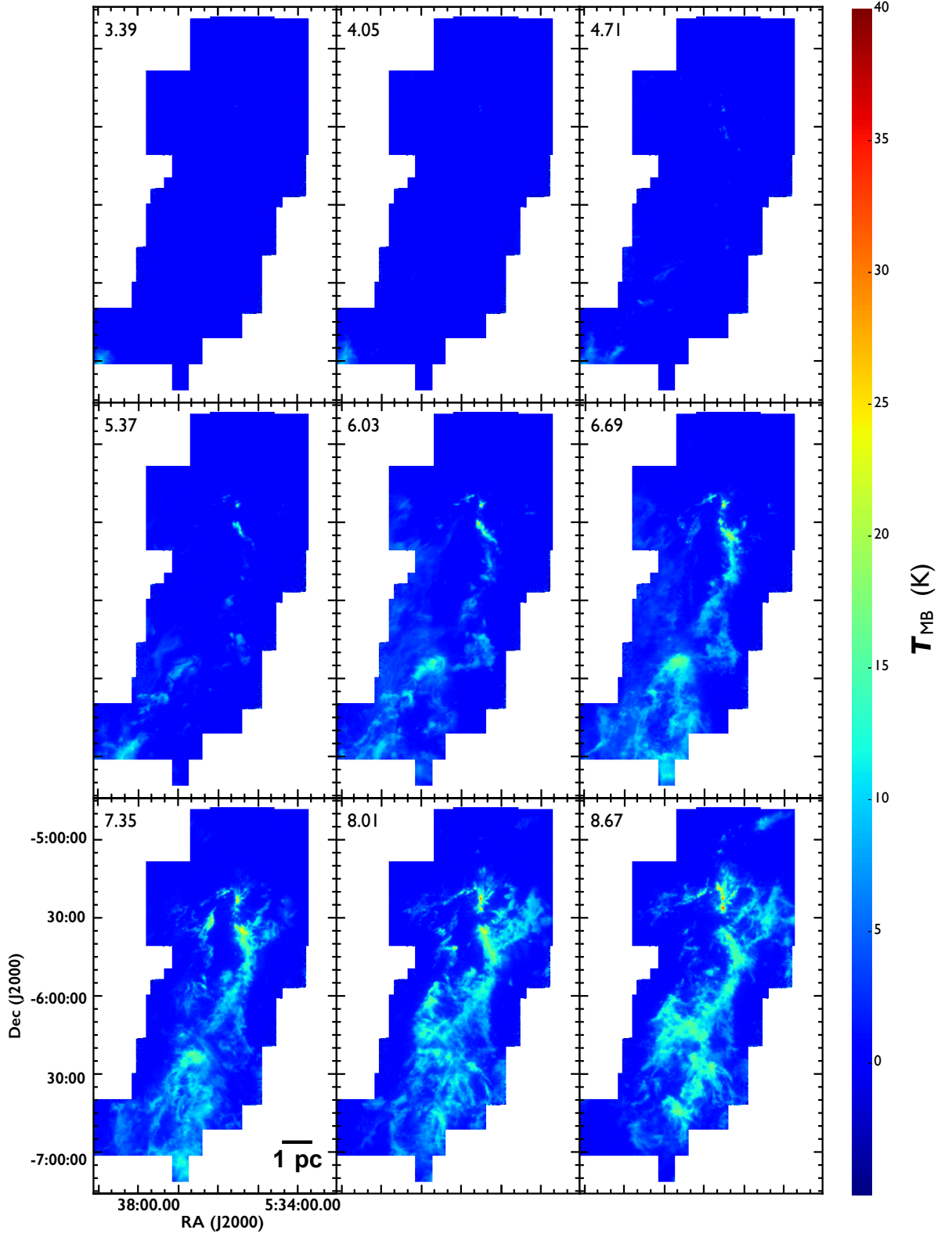


Figure 2.7. Channel maps of ^{13}CO ($J = 1-0$). The lsr velocity is shown in the top left of each panel in the unit of km s^{-1} .

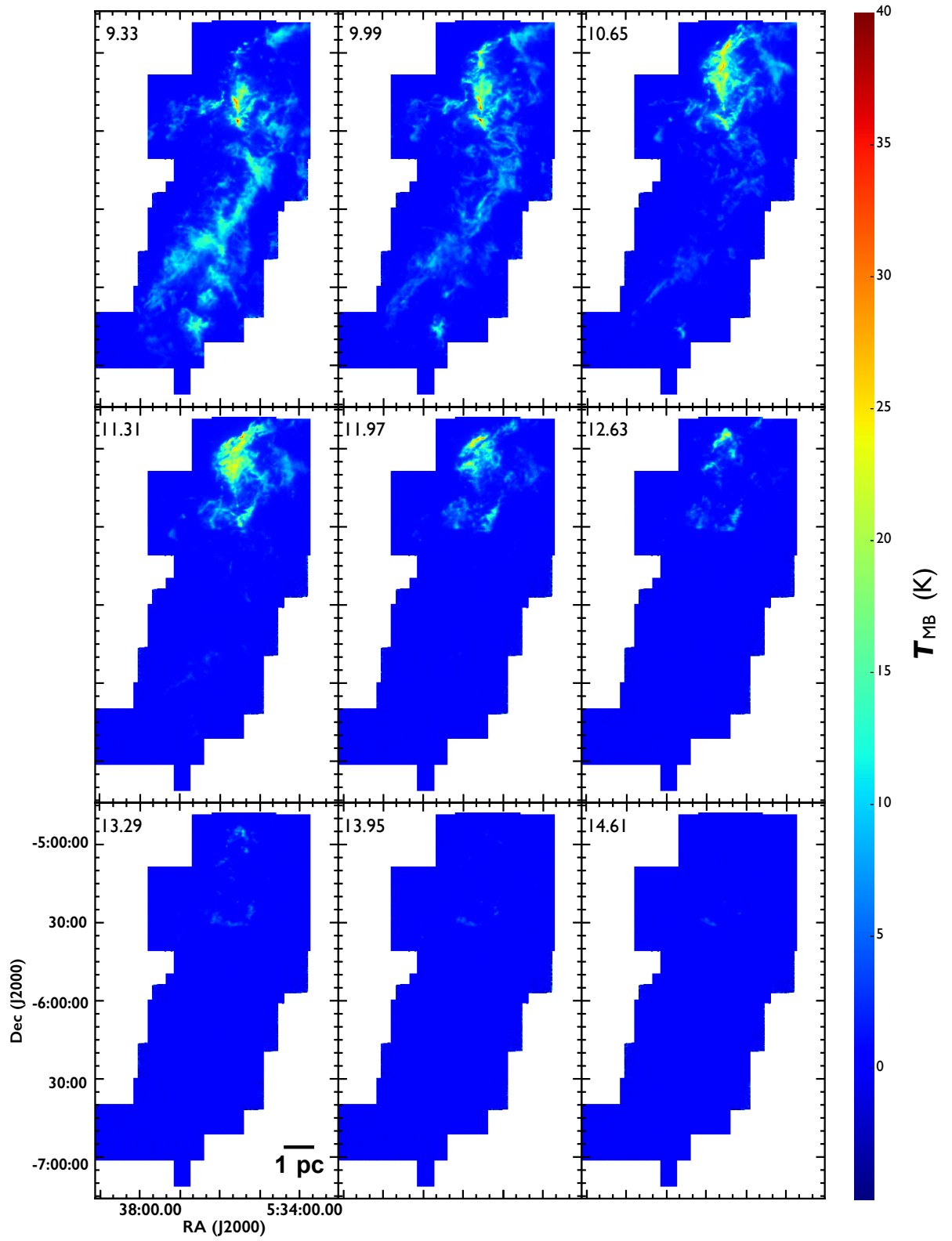


Figure 2.8. Channel maps of ^{13}CO ($J = 1-0$), continued from Figure 2.7.

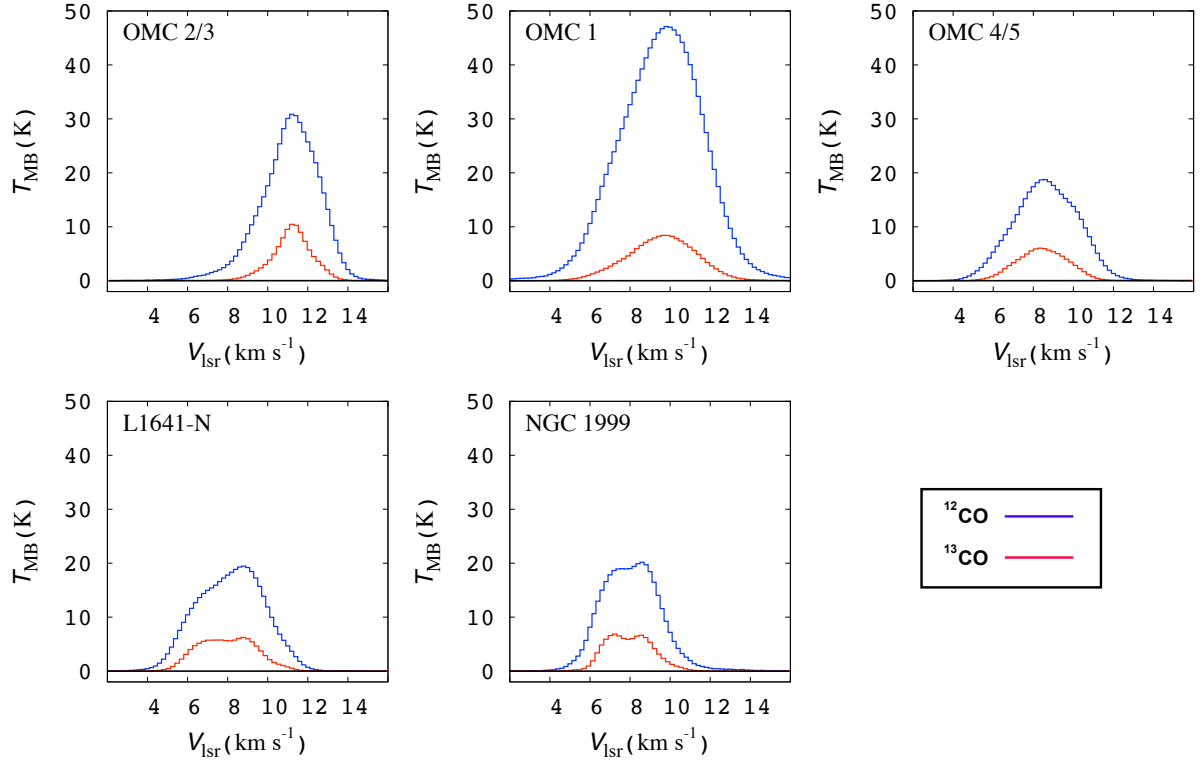


Figure 2.9. Averaged spectrum of ^{12}CO ($J=1-0$) (blue) and ^{13}CO ($J=1-0$) (red) in each subregion. All spectra are presented for the emission detected above 5σ .

shown in Figure 2.9. The large velocity width at OMC 1 is from extremely high velocity outflow components associated with BN/KL object. The double peaks appearing in L1641-N and NGC 1999 are consequent upon the cloud-cloud collisions (Nakamura et al. 2012).

Chapter 3

Method for identifying molecular outflows

To investigate the outflow feedback into the parent cloud, I identify the CO outflows and estimate their physical properties based on the data cube of the ^{12}CO ($J = 1-0$) emission line. In this chapter, I describe the procedure of outflow search.

3.1 Outflow driving source candidates

To identify the molecular outflows in the vicinity of YSOs, I summarize a list of YSO candidates in our observed region. I made a sample of candidates for outflow driving sources from the YSO catalog produced by M2012 using IRAC and MIPS mounted on the *Spitzer Space Telescope* and 2MASS. The YSOs are divided into two categories based on their mid-infrared photometry: protostars and PMS stars with a protoplanetary disk. I selected the protostars as candidates for driving sources of outflows because the outflows tend to appear in an early phase of star formation. In our observed region, M2012 identified 198 protostars.

I also supplement the candidates with sources that appear to drive H_2 jets. Davis et al. (2009) made an unbiased survey of molecular hydrogen emission line of $v = 1-0$ S(1) at a wavelength of $2.12\ \mu\text{m}$ originating from shocks in outflows (see also Stanke et al. 2002). Davis et al. (2009) also identified driving sources of H_2 jets from the *Spitzer* YSO catalog based on their morphology and/or alignment, arguing that 65 YSOs are associated with H_2 jets in our observed region. Among the 65 YSOs, 53 are categorized as protostars and 12 are categorized as PMS stars, respectively.

Eventually, I focus on 210 candidates for outflow driving sources selected from M2012's catalog, 65 of which are also listed in Davis's as H_2 jet associated with a YSO. Table 3.1 summarizes the number of candidates in each category, and Figure 3.1 shows all the candidates of the driving sources of the outflows superposed on the ^{12}CO integrated intensity map.

Table 3.1: Categorization of candidates for outflow driving sources

		Categories		
		Protostar	PMS star	Total
H ₂ jet	Yes	53	12	65
	No	145	0	145
	Total	198	12	210

3.2 The search procedure

I searched for ¹²CO molecular outflows around candidates of driving sources by the procedure as follows.

First, I produced the ¹²CO spectrum averaged over the area around each candidate with a radius of 30'' (~ 0.06 pc) and applied a least square fitting using a Gaussian function described by;

$$f(v_{\text{lsr}}) = T_{\text{peak}} \exp [-(v_{\text{lsr}} - v_{\text{sys}})^2 / 2\sigma_v^2]^1. \quad (3.1)$$

With the fitting, I obtained three parameters, T_{peak} in K, v_{sys} in km s⁻¹, and the standard deviation σ_v in km s⁻¹. Other sources may be present within a radius of 30'', but their effects are not taken into account.

Next, I produced the integrated intensity maps (10'' $\times$ 10'' of the blue-shifted emission ($v_{\text{lsr}} - v_{\text{sys}} \geq 2\sigma_v$) and the red-shifted emission ($v_{\text{lsr}} - v_{\text{sys}} \leq -2\sigma_v$). I defined the blue- or red-shifted emission above 5σ as high velocity blue- or red-shifted emission associated with each YSO candidate. Note that we neglected the emission if the extent is less than the beamsize. I estimated the position angles of the blue- and red-shifted emissions by the directions to the peak of ¹²CO emission from the candidate YSOs.

Then, I compared the position angle of the high-velocity emissions to that of H₂ jets identified by Davis et al. (2009). I identified the blue- and red-shifted emissions as an outflow associated with the candidate only when the position angles of the emission and H₂ jet coincide within $\pm 20^\circ$ with each other. For the high-velocity emissions not to be associated with the H₂ jets, we simply regarded them as the outflow.

I show, in Figure 3.2, an example of the outflow search by the above procedure. Figure 3.2 (a) shows the ¹²CO integrated intensity map centered on the protostar MMS 5, ($\alpha_{\text{J2000}}, \delta_{\text{J2000}} = (05\text{h}35\text{m}22\text{s}.43, -5^\circ1'14''.1)$), and Figure 3.2 (b) shows the spectrum averaged over the area 30'' in radius around MMS 5 and the results of the Gaussian fitting. Figure 3.2 (c) presents the integrated intensity maps of blue- and red-shifted emission. The distributions of the blue- and red-shifted components are quite similar to those of the MMS 5 outflow identified by previous studies (e.g., Aso et al. 2000; Williams et al. 2003; Takahashi et al. 2008).

¹The fitting range is from -2 km s⁻¹ to 20 km s⁻¹.

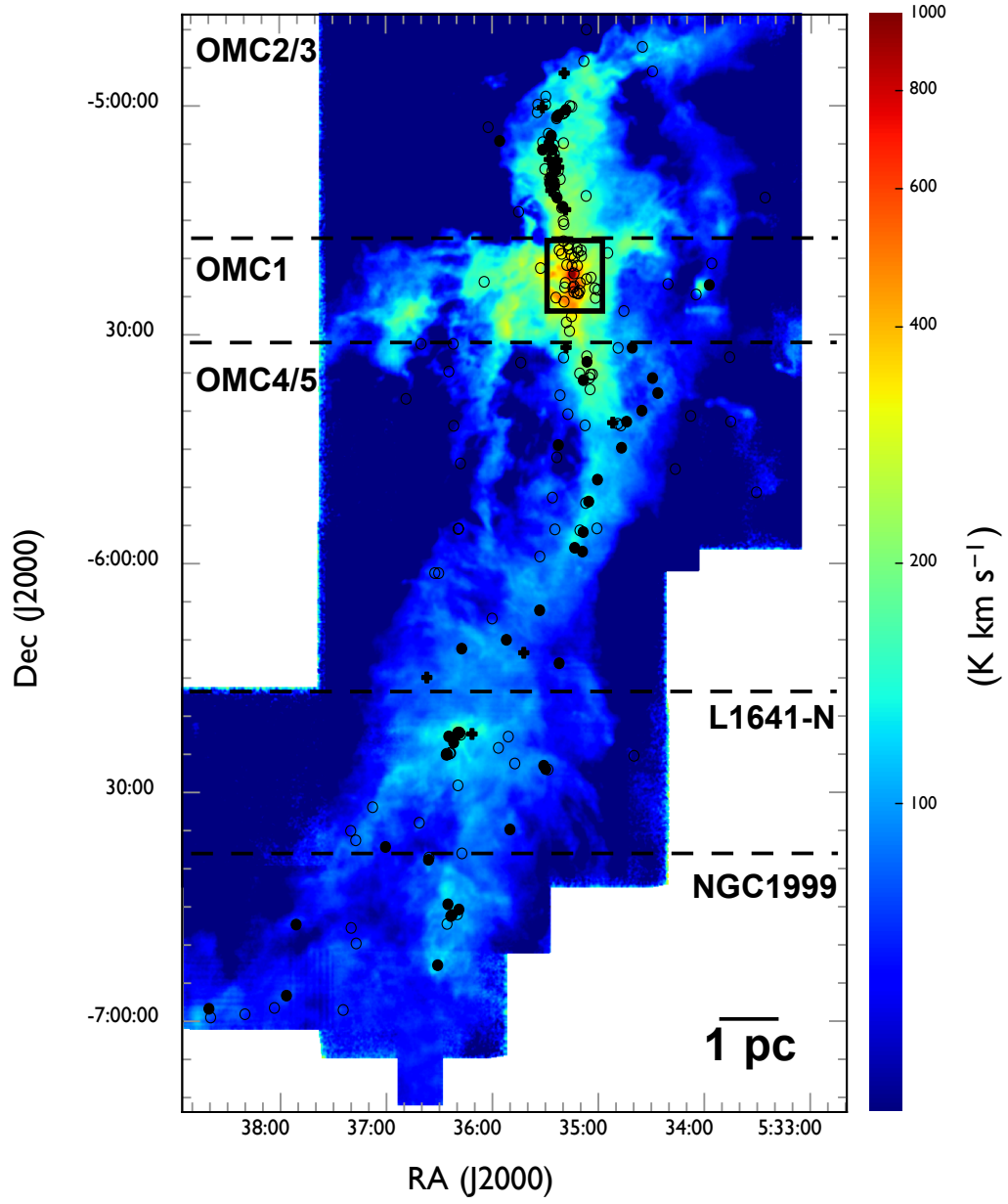


Figure 3.1. The outflow driving source candidates superposed on ^{12}CO integrated intensity map. The open circle, filled circle, and filled cross indicate the positions of the protostars without H_2 jets, protostars with H_2 jets, and pre-main-sequence stars with H_2 jets, respectively (M2012 and Davis et al. 2009). The black square shows the region of the center of OMC 1.

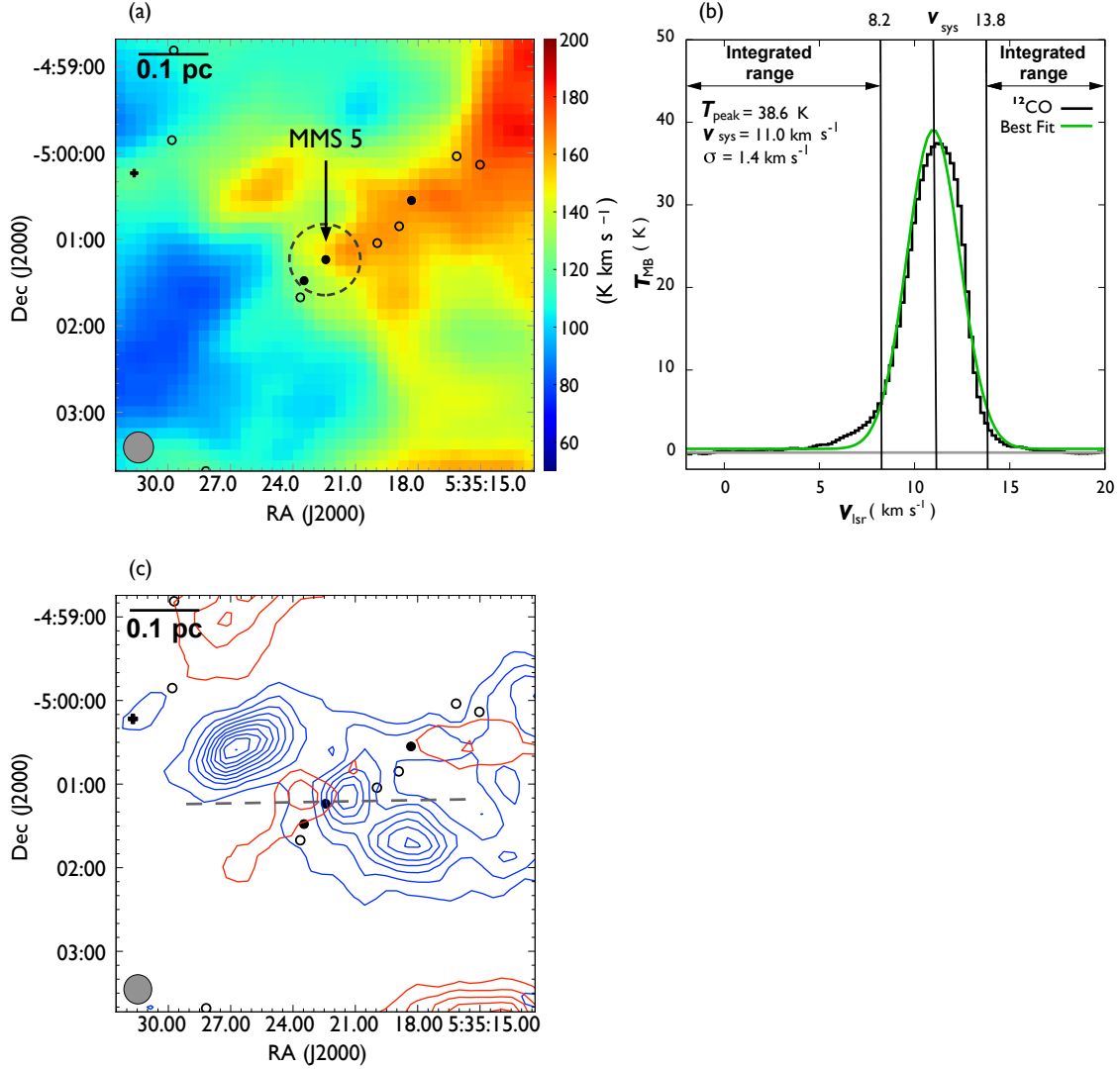


Figure 3.2. Results of our outflow search procedure for MMS 5. (a) Outflow driving source candidates overlaid on the ^{12}CO integrated intensity map. (b) Average spectrum of the ^{12}CO emission over the $30''$ radius area around the center of the left panel and the result of Gaussian fitting. (c) ^{12}CO integrated intensity maps for the distributions of blue- and red-shifted components. In panels (a) and (c), the filled and open circles represent the same as in Figure 2.2, and the effective angular resolution is indicated in the bottom-left. The area where the ^{12}CO spectrum is averaged in panel (b) is indicated by the dashed circle in panel (a). In panel (b), three parameters for the fitting are indicated on the left, and the integrated velocity range for the blue- and red-shifted components is indicated by arrows. In panel (c), the blue and red contours show the distributions of the blue- and red-shifted components integrated from $v_{\text{LSR}} = -1.2$ km s⁻¹ to 8.2 km s⁻¹ and from 13.8 km s⁻¹ to 20.2 km s⁻¹, respectively. The contour intervals are 3 K km s⁻¹ ($\sim 5\sigma$) starting at 3 K km s⁻¹. The gray dashed line represents the axis of the outflow. In this example, I focus on the one candidate located at the center of panels (a) and (c), but I apply the same procedure independently for all other candidates. For example, the peaks located to the north and south of MMS 5 in panel (c) are regarded as outflows associated with different sources (see Figures A.2 and A.4).

Chapter 4

Results

4.1 Identified outflows

4.1.1 Overview of identified outflows

Following the procedure described in section 3.2, I identify 44 CO outflows in ^{12}CO ($J = 1-0$) line, of which 17 are newly detected. To distinguish them from those detected in ^{13}CO ($J = 1-0$) line, hereafter I refer to them as ^{12}CO outflows (or more simply refereed as outflows). Our survey increases the number of outflows in Orion A by a factor of ~ 1.5 . Notably, I identify 11 outflows in the OMC 4/5 region where no outflows had been detected. Figures 4.1 and 4.2 show the locations of the detected outflows and their position angles, and Table 4.2 lists all the outflows identified in this survey. I identify 25 outflows consisting of a pair of blue- and red-shifted lobes, and 19 outflows with a single lobe (13 blue-shifted and 6 red-shifted). As shown in Figure 3.1, some of the protostars are identified at the edge of the clouds, although all the outflows are only detected near the center of the cloud, such as the integral shaped filament and clamps. The individual outflows of newly detected and known are shown in section 4.1.4 and appendix A, respectively. All newly detected outflows are associated with the H_2 jets.

4.1.2 Comparison with previous outflow searches

In OMC 2/3, all outflows detected by Chini et al. (1997), Aso et al. (2000), and Williams et al. (2003) are also detected by this study. I detect 12 out of 14 outflows detected in ^{12}CO ($J = 3-2$) by Takahashi et al. (2008). In the two outflows not detected by this study, the velocity range detected as an outflow in (3-2) line is buried in ambient in our (1-0) line.

In OMC 4/5, no systematic search of outflows had been conducted previously. Thus, all 11 outflows identify in this region are new detections.

Our results for the outflow surveys in the central region of L1641-N agree with the previous observations conducted by Stanke and Williams (2007) and Nakamura et al. (2012). In addition, I find three new outflows in this region.

In NGC 1999, I also detect a collimated CO outflow associated with V380 Ori-NE that had already been identified by previous searches (e.g., Davis et al. 2000; Choi et al. 2017). Our results around HH 1/2 in NGC 1999 agree with the surveys conducted by Moro-Martín et al. (1999). I reveal that a faint blue-shifted emission located at $\sim 2'$ east of HH 1/2 is an outflow driven by IRS 121. In addition, I find a new outflow in this region.

In the center of OMC 1 region (see Figure 3.1), I identify no individual outflows associated with YSOs. In this region, as can be seen in Figure 3.1, YSOs are so crowded that the identification of which outflows are associated with a particular YSO is not reliable. In addition, the local velocity width of the molecular clouds around the each YSO in this region is so broad that I could not separate the outflow components from the main cloud components. Thus I exclude the center of OMC 1 including 32 protostars from the following discussion. Therefore, our driving source sample shown in Table 3.1 is revised as shown in Table 4.1. Eventually, I succeed in detecting known outflows at a high rate of 93% in the region except the center of OMC 1.

Table 4.1: Categorization of candidates for outflow driving sources excluding the center of OMC 1

		Categories		
		Protostar	PMS star	Total
H ₂ jet	Yes	53	12	65
	No	113	0	113
	Total	166	12	178

4.1.3 Detection rate of outflows

Table 4.3 lists the numbers and detection rates of the outflows for the driving sources in each category. The detection rate of molecular outflows for protostars with H₂ jets is 62.3%, which is ~ 20 times higher than that in the protostars without H₂ jets (3.5%).

In Table 4.3, out of the 65 YSOs with H₂ jet, 40 YSOs (62%) are also associated with outflows, and out of the 44 YSOs associated with outflows, only 4 YSOs (9%) are not accompanied by H₂ jets. These correlations imply that the molecular outflows and H₂ jets occur in almost the same phase of star formation.

Table 4.4 lists the number and detection rates of outflows in each subregion. The detection rates of the outflows among the each subregion are consistent with each other within a factor of two, except for OMC 1. Note that I exclude the 32 YSOs distributed in the center of OMC 1, and the detection rate of the outflows in OMC 1 is 0% to represent an incomplete sample.

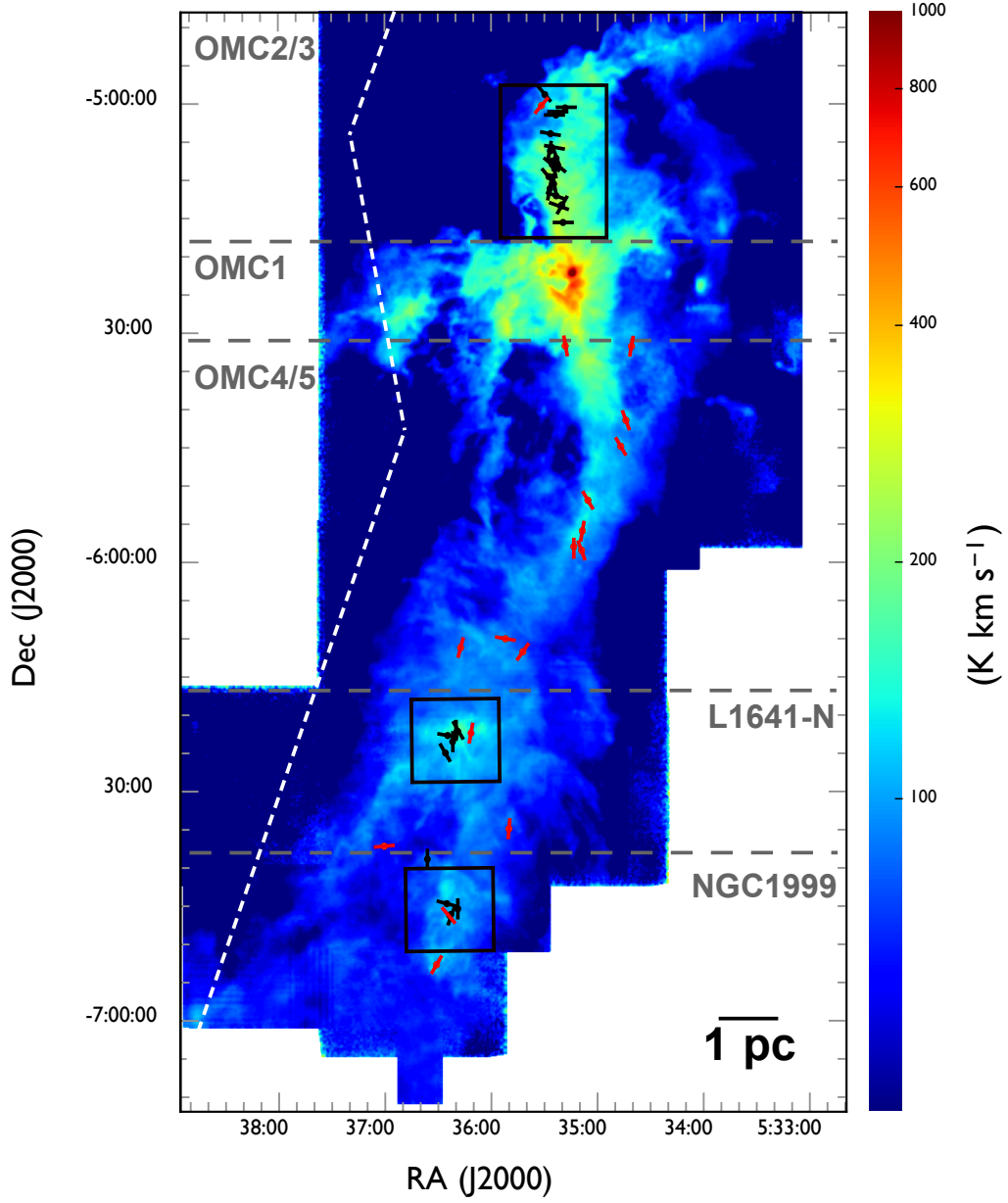


Figure 4.1. Locations of the detected outflows overlaid on the ^{12}CO ($J=1-0$) total integrated intensity map which is the same as in Figure 2.2. The red and black filled circles indicate the positions of newly detected and known outflow driving sources. Each solid line indicates the position angles of an outflow and does not indicate outflow length. White dashed lines represent the direction of the filaments in the clouds considered in this study (section 4.2.3). The black squares indicate OMC 2/3, L1641-N and NGC1999, for which close-up views are presented in Figure 4.2.

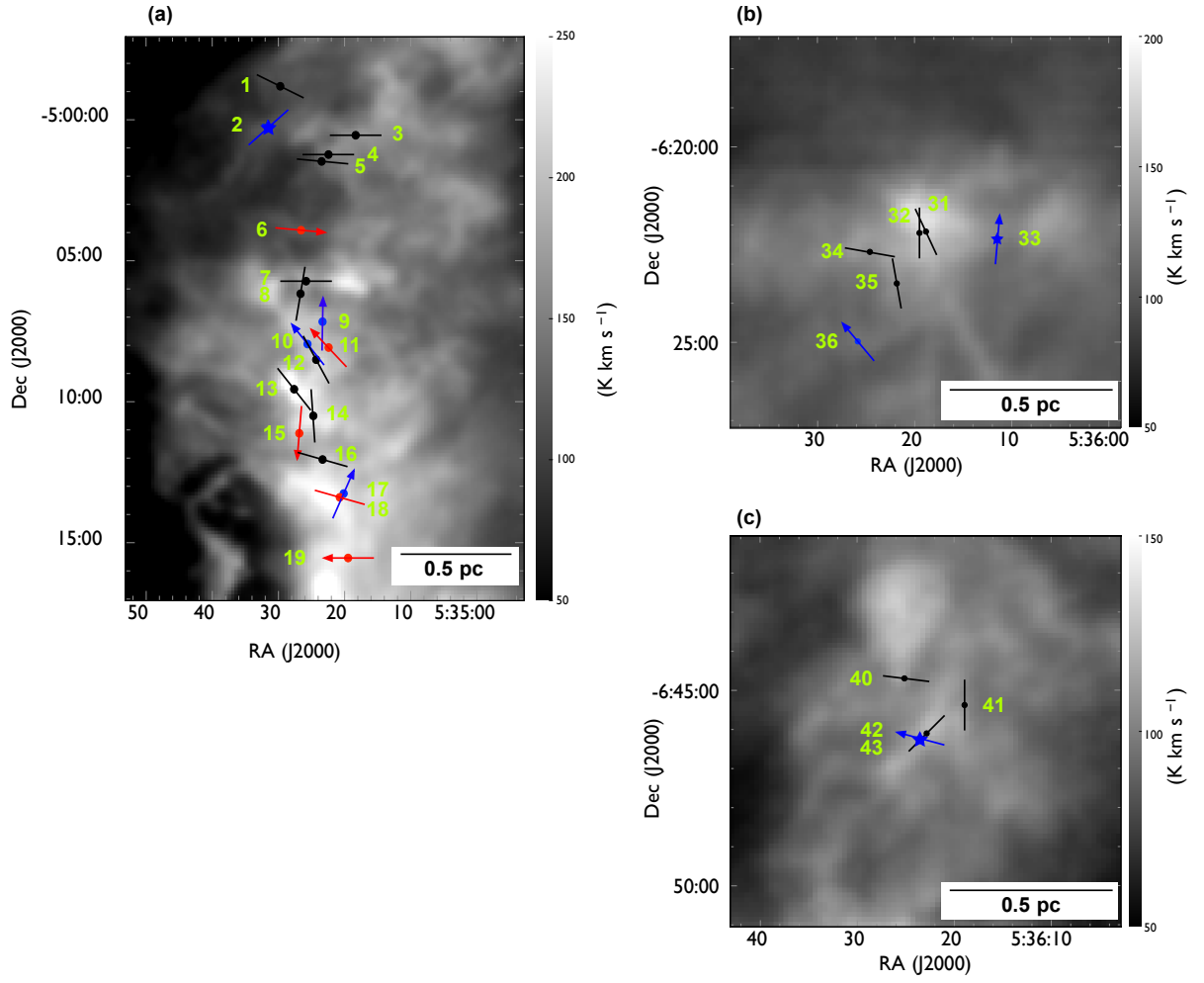


Figure 4.2. Close-up views of the detected outflows in (a) OMC 2/3 , (b) L1641-N, and (c) NGC 1999. Filled circles and star symbols indicate the positions of known and newly detected outflow driving sources, respectively. The solid lines and arrows indicate the position angles of the each outflow. The black, blue, and red colors represent blue- and red-shifted pairs of, single blue-shifted, and single red-shifted outflows, respectively. The direction of arrows indicate the directions of single outflow lobes. The background grayscale image is a total integrated intensity of ^{12}CO ($J = 1-0$).

Table 4.2: List of outflows

No.	α^1 (J2000.0)	δ^1 (J2000.0)	Source category* ²	Common name	HOPS No.	Velocity shift* ³	PA* ⁴	New detection	Reference
OMC 2/3									
1	05 35 29.72	-04 58 48.8	P		96	BR	65	-	1
2	05 35 31.62	-05 00 14.0	PMSJ		-	B	130	Yes	-
3	05 35 18.32	-05 00 33.0	PJ	MMS 2	92	BR	90	-	1,2,3
4	05 35 22.43	-05 01 14.1	PJ	MMS 5	88	BR	90	-	1,2,3
5	05 35 23.47	-05 01 28.7	PJ	MMS 6	87	BR	85	-	1,3
6	05 35 26.57	-05 03 55.1	PJ	MMS 7	84	BR	90	-	1,2,3
7	05 35 25.82	-05 05 43.6	PJ	MMS 9	78	BR	90	-	1,2,3
8	05 35 26.66	-05 06 10.3	P		75	BR	170	-	1,2,3
9	05 35 23.33	-05 07 09.8	PMSJ	MMS 11	-	B	160	-	1
10	05 35 25.61	-05 07 57.3	PJ	MMS 14	71	B	40	-	1,2
11	05 35 22.41	-05 08 04.8	PMSJ	MMS 15	70	R	45	-	1,2
12	05 35 24.30	-05 08 30.6	PJ	MMS 103	68	BR	30	-	1,2
13	05 35 27.63	-05 09 33.5	PJ	FIR 3	370	BR	40	-	1,2,4
14	05 35 24.73	-05 10 30.2	PJ	VLA 13	368	BR	5	-	1,4
15	05 35 26.85	-05 11 07.3	PMSJ		-	R	175	-	1
16	05 35 23.33	-05 12 03.1	PJ	FIR 6 b	60	BR	75	-	1,5
17	05 35 20.14	-05 13 15.5	PJ	FIR 6 d	59	B	155	-	5
18	05 35 20.73	-05 13 23.6	P	FIR 6 c	-	R	75	-	1,5
19	05 35 19.47	-05 15 32.7	P	CSO 33	56	R	90	-	1
OMC 4/5									
20	05 35 18.28	-05 31 42.1	PMSJ		-	B	15	Yes	-
21	05 34 40.91	-05 31 44.4	PJ		50	BR	145	Yes	-
22	05 34 44.06	-05 41 25.9	PJ		30	BR	40	Yes	-
23	05 34 46.94	-05 44 50.9	PJ		24	B	30	Yes	-
24	05 35 05.49	-05 51 54.4	PJ		18	B	30	Yes	-
25	05 35 08.60	-05 55 54.3	PJ		12	B	160	Yes	-
26	05 35 13.41	-05 57 58.1	PJ	Ori 2-6	11	BR	0	Yes	-
27	05 35 09.00	-05 58 27.6	PJ		10	BR	25	Yes	-
28	05 35 52.00	-06 10 01.8	PJ		194	B	60	Yes	-
29	05 36 17.26	-06 11 11.0	PJ		191	BR	165	Yes	-
30	05 35 42.18	-06 11 43.8	PMSJ		-	R	135	Yes	-
L1641-N									
31	05 36 18.83	-06 22 10.2	PJ		182	BR	25	-	6,7
32	05 36 19.50	-06 22 12.3	PJ		181	BR	0	-	6,7
33	05 36 11.45	-06 22 22.1	PMSJ		-	B	175	Yes	6,7
34	05 36 24.61	-06 22 41.3	PJ		178	BR	80	-	6,7
35	05 36 21.84	-06 23 29.8	PJ		179	BR	10	-	6,7
36	05 36 25.86	-06 24 58.7	PJ		174	B	40	-	6,7
37	05 35 50.02	-06 34 53.4	PJ		177	R	175	Yes	-
38	05 37 00.45	-06 37 10.5	PJ		164	B	95	Yes	-
NGC 1999									
39	05 36 36.10	-06 38 52.0	PJ	V380 Ori-NE	169	BR	0	-	8,9
40	05 36 25.13	-06 44 41.8	PJ	IRS 63	166	BR	80	-	10
41	05 36 18.93	-06 45 22.7	PJ	VLA 3	168	BR	0	-	10
42	05 36 22.84	-06 46 06.2	PJ	VLA 1/2	203	BR	140	-	10
43	05 36 23.54	-06 46 14.5	PJ	IRS 121	165	B	75	Yes	10
44	05 36 30.97	-06 52 40.9	PJ		162	BR	150	Yes	-

¹ The locations of the driving source of outflows.² Category of the outflow driving sources. "P", "PJ" and "PMSJ" represent Protostar without H₂ jet, Protostar with H₂ jet and PMS star with H₂ jet, respectively.³ The velocity shifts of outflows. "BR," "B," and "R" represent a blue and red-shifted pair of, single blue-shifted, and single red-shifted outflow, respectively.⁴ Outflow position angle on the plane of the sky (5° bin).

References– 1 Takahashi et al. (2008); 2 Williams et al. (2003); 3 Aso et al. (2000); 4 Shimajiri et al. (2008); 5 Shimajiri et al. (2009); 6 Nakamura et al. (2012); 7 Stanke & Williams (2007); 8 Davis et al. (2000); 9 Choi et al. (2017); 10 Moro-Martín et al. (1999).

Table 4.3: Outflow detection rate sorted by category of driving sources

Category	Number of outflows	Number of candidates	Detection rate
Protostar without jet	4	113	3.5%
Protostar with jet	33	53	62.3%
PMS star with jet	7	12	58.3%
Total	44	178	24.7%

Table 4.4: Outflow detection rate in each subregion

Subregion	Number of outflows	Number of candidates	Detection rate
OMC 2/3	19	62	30.6%
OMC 4/5	11	59	18.6%
L1641-N	8	27	29.6%
NGC 1999	6	19	31.6%
OMC 1* ¹	0	11	0%

¹Excluding the center of OMC 1.

4.1.4 Newly detected outflows

I present in this subsection, the integrated images and position-velocity (P-V) diagrams of newly detected outflows. Those of known outflows are shown in Appendix A.

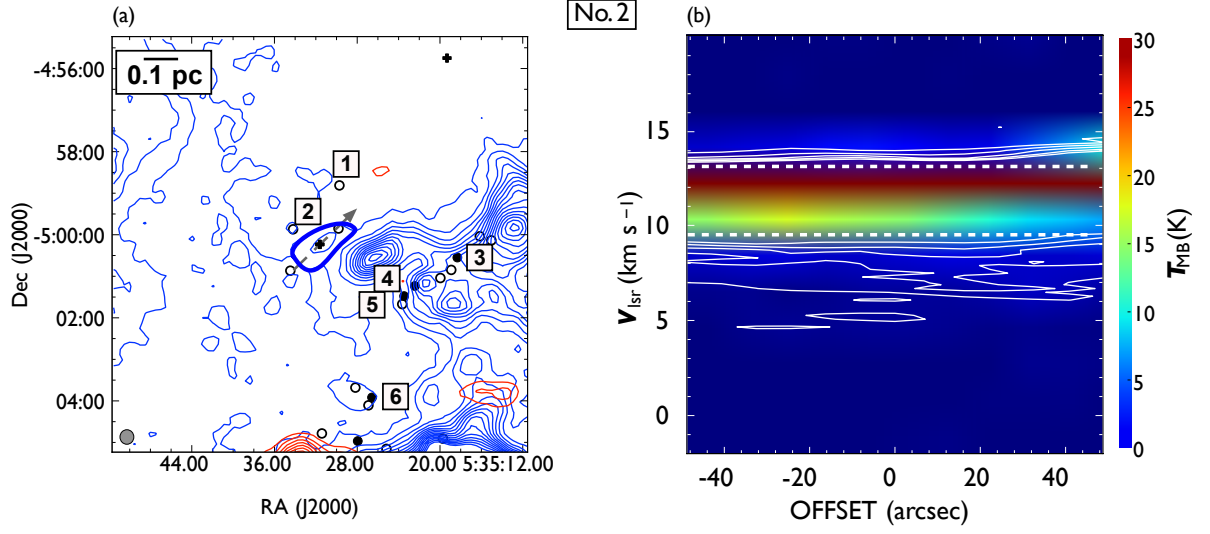


Figure 4.3. (a) The distribution of outflow No. 2, driven by a PMS star with a jet located in the northern part of OMC 3, and (b) the P-V diagram along the outflow axis. Contour levels and symbols shown in panel (a) are the same as those in Figure 3.2 (d), and the thick contour represents the projected area where I estimated the mass of the outflow. In panel (a), the integrated velocity ranges of blue- and red-shifted components are 2.0 km s^{-1} to 9.5 km s^{-1} and 13.8 km s^{-1} to 20.2 km s^{-1} , respectively. The upper (lower) limit for the blue and red ranges are indicated by the dashed lines in panel (b). The gray dashed arrow in panel (a) represents the cut along which the P-V diagram in panel (b) was obtained and also represents the position angle of the outflow. The direction of the arrow indicates the positive offset direction in the P-V diagram. The effective angular resolution of the ^{12}CO data is shown in the lower left corner. In panel (b), the contour intervals are 1, 2, 3, 4, and 5 K in T_{MB} . While the blue-shifted lobe can be seen with a north-west to south-east elongation, the red-shifted component is not detected.

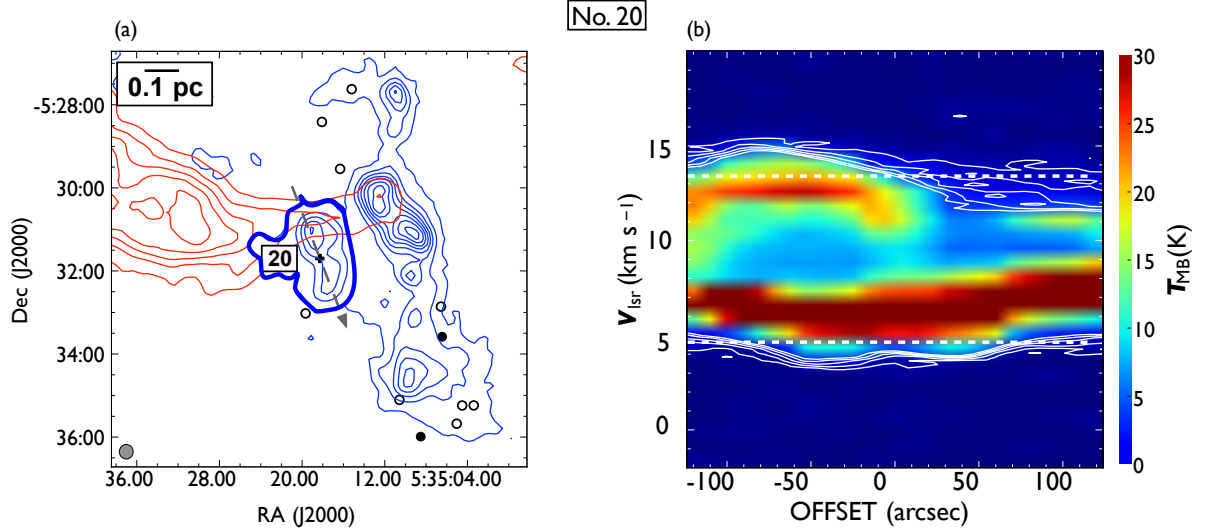


Figure 4.4. The same as in Figure 4.3 but for outflow No. 20. In panel (a), the blue- and red-shifted integrated intensity velocity ranges are -1.9 km s^{-1} to 4.8 km s^{-1} and 13.1 km s^{-1} to 20.2 km s^{-1} , respectively. This outflow, located at about $10'$ south of the center of OMC 1, has only a blue-shifted lobe and is driven by a PMS star with a jet.

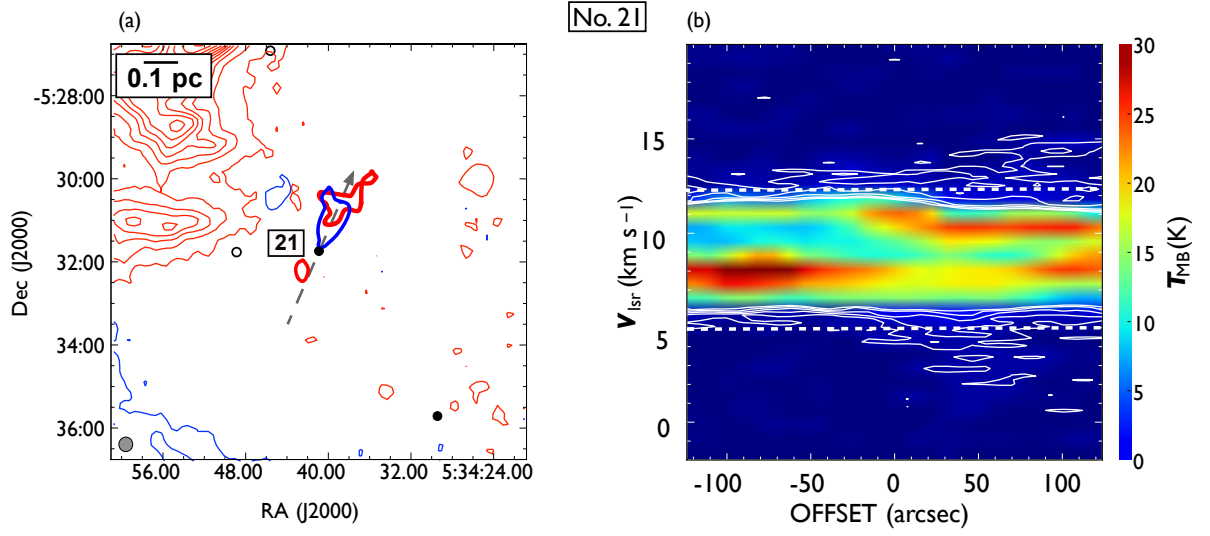


Figure 4.5. The same as in Figure 4.3 but for outflow No. 21. In panel (a), the blue- and red-shifted integrated intensity velocity ranges are -1.9 km s^{-1} to 4.8 km s^{-1} and 12.1 km s^{-1} to 20.2 km s^{-1} , respectively. It can be seen that the blue-shifted lobe and red-shifted lobe have a north-west elongation; the red-shifted lobe also has a south-east elongation.

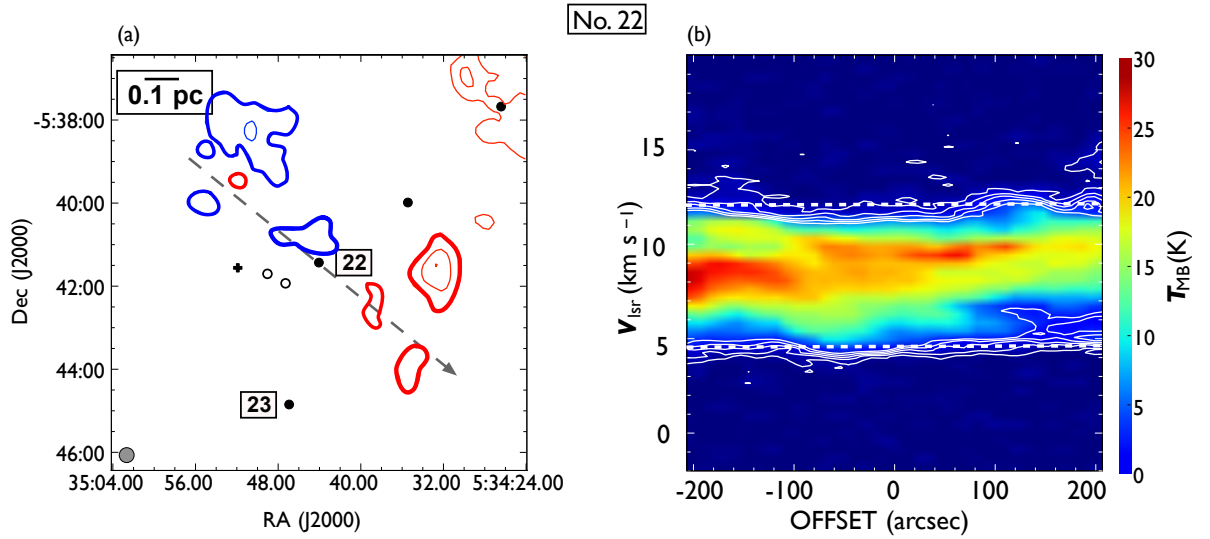


Figure 4.6. The same as in Figure 4.3 but for outflow No. 22. In panel (a), the blue- and red-shifted integrated intensity velocity ranges are -1.9 km s^{-1} to 4.4 km s^{-1} and 12.2 km s^{-1} to 20.2 km s^{-1} , respectively. This bipolar outflow has multiple blue- and red-shifted lobes with a north-east to south-west elongation.

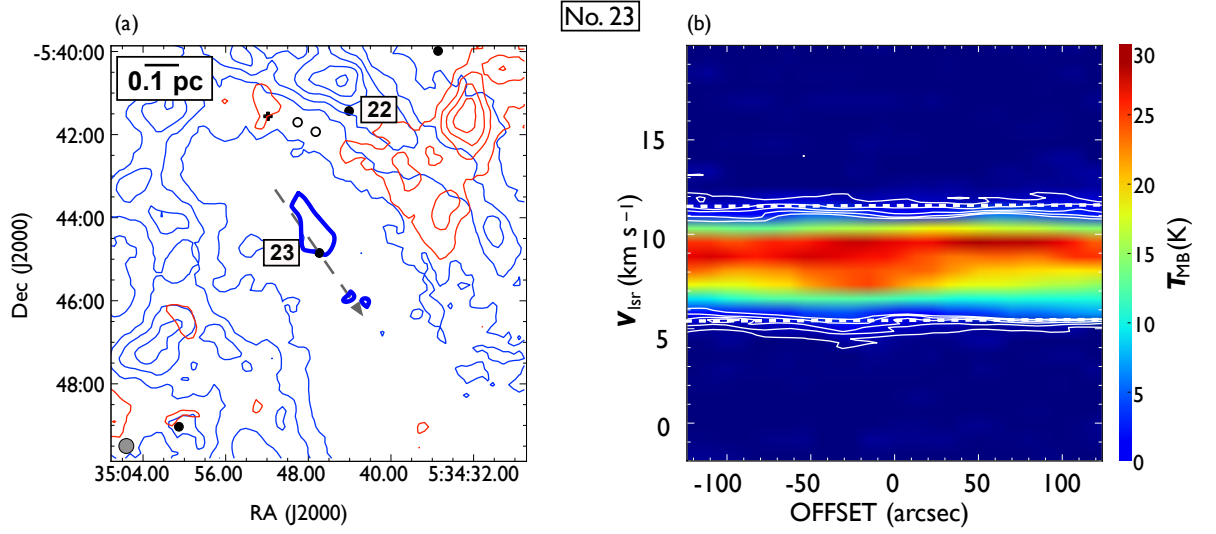


Figure 4.7. The same as in Figure 4.3 but for outflow No. 23. In panel (a), the blue- and red-shifted integrated intensity velocity ranges are -1.9 km s^{-1} to 5.4 km s^{-1} and 11.5 km s^{-1} to 20.2 km s^{-1} , respectively.

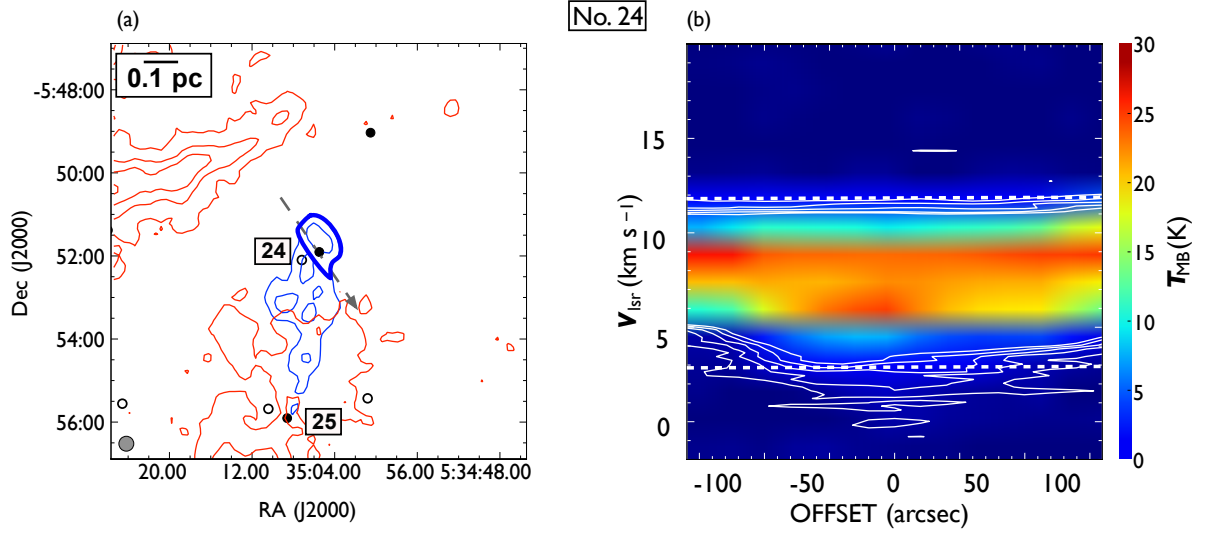


Figure 4.8. The same as in Figure 4.3 but for outflow No. 24. In panel (a), the blue- and red-shifted integrated intensity velocity ranges are -1.9 km s^{-1} to 3.8 km s^{-1} and 11.8 km s^{-1} to 18.0 km s^{-1} , respectively. This blue-single outflow has a strong blue-shifted lobe with a north-east to south-west elongation. The blue-shifted emission south of the central source is considered to be part of outflow No. 25.

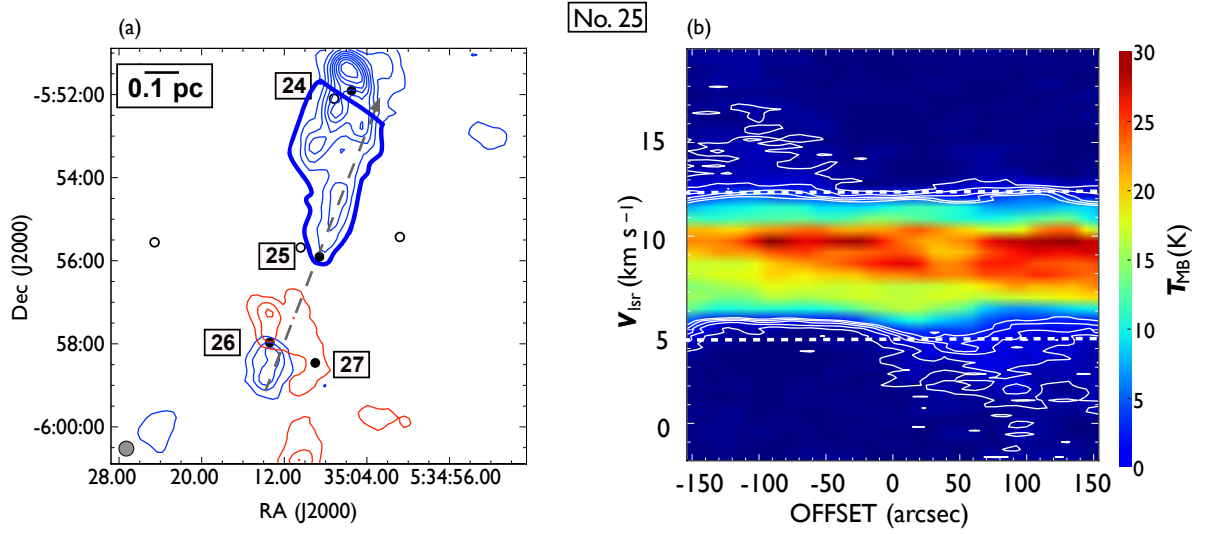


Figure 4.9. The same as in Figure 4.3 but for outflow No. 25. In panel (a), the blue- and red-shifted integrated intensity velocity ranges are -1.9 km s^{-1} to 4.6 km s^{-1} and 12.2 km s^{-1} to 20.2 km s^{-1} , respectively. This blue-single outflow has the strong blue-shifted lobe in a noethen direction. The red-shifted emission south of the central source is considered to be part of outflow No. 27.

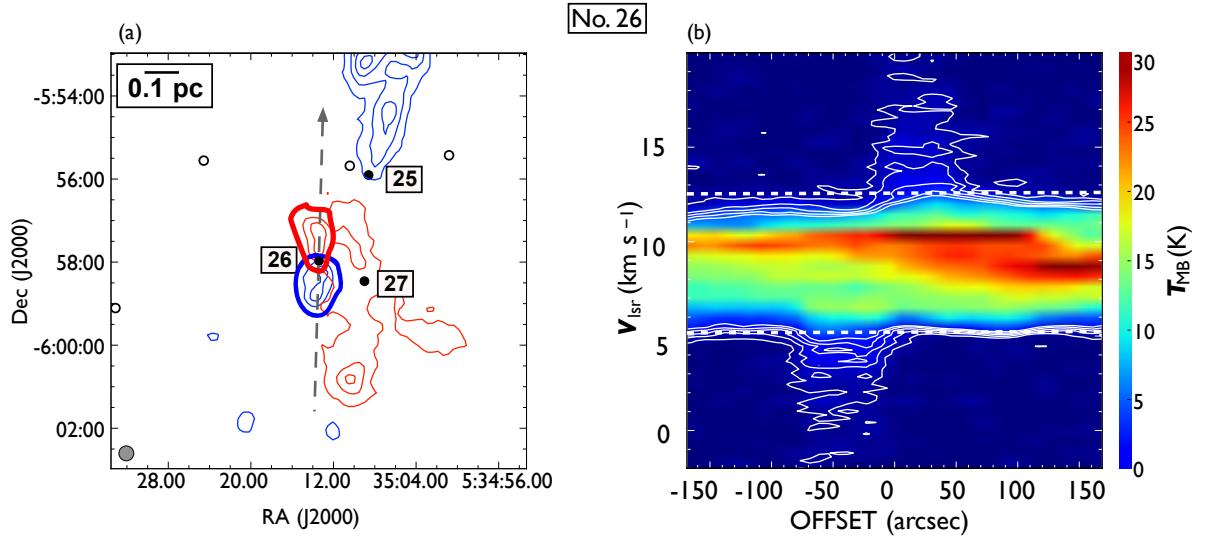


Figure 4.10. The same as in Figure 4.3 but for outflow No. 26. In panel (a), the blue- and red-shifted integrated intensity velocity ranges are -1.9 km s^{-1} to 4.9 km s^{-1} and 12.8 km s^{-1} to 20.2 km s^{-1} , respectively. The blue-shifted lobe in the south and the red-shifted lobe in the north are clearly can be seen.

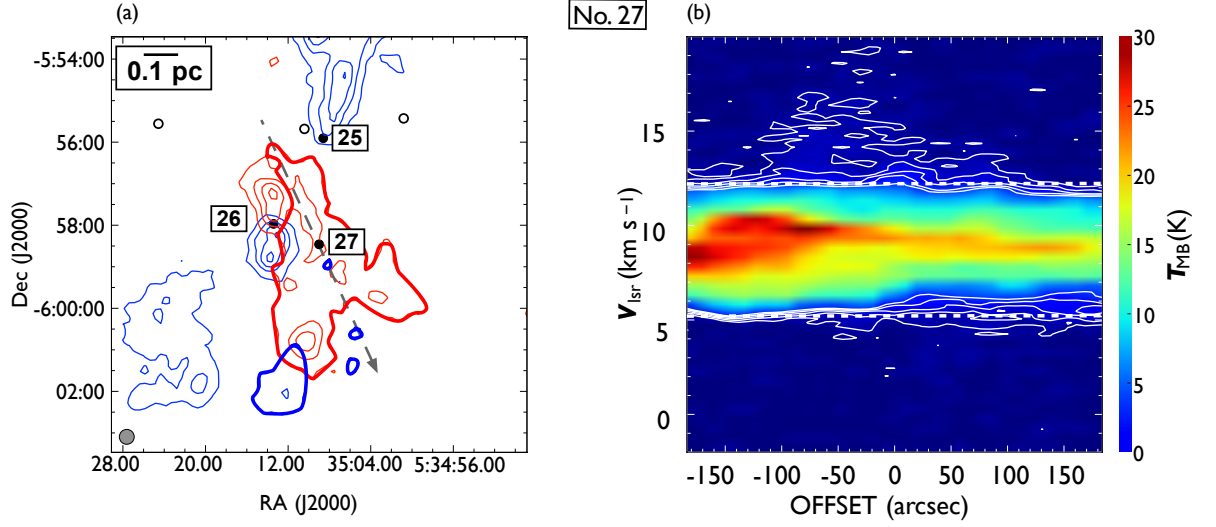


Figure 4.11. The same as in Figure 4.3 but for outflow No. 27. In panel (a), the blue- and red-shifted integrated intensity velocity ranges are -1.9 km s^{-1} to 5.2 km s^{-1} and 12.0 km s^{-1} to 20.2 km s^{-1} , respectively. This outflow has strong red-shifted lobes with a north-east to south-west elongation and faint blue-shifted lobes with a south-west elongation.

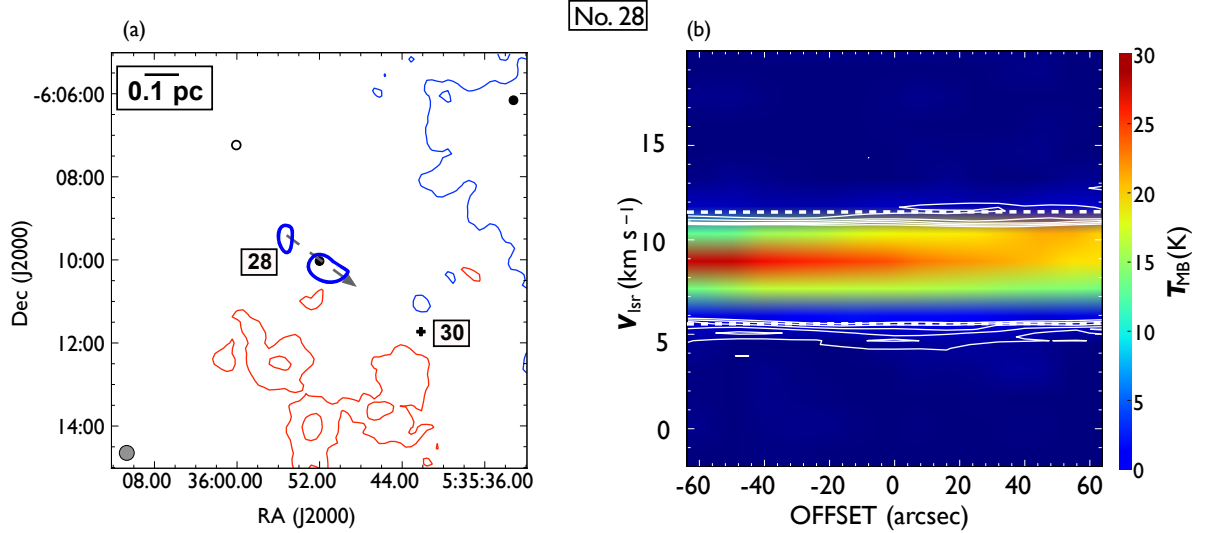


Figure 4.12. The same as in Figure 4.3 but for outflow No. 28. In panel (a), the blue- and red-shifted integrated intensity velocity ranges are -1.9 km s^{-1} to 5.5 km s^{-1} and 11.4 km s^{-1} to 20.2 km s^{-1} , respectively.

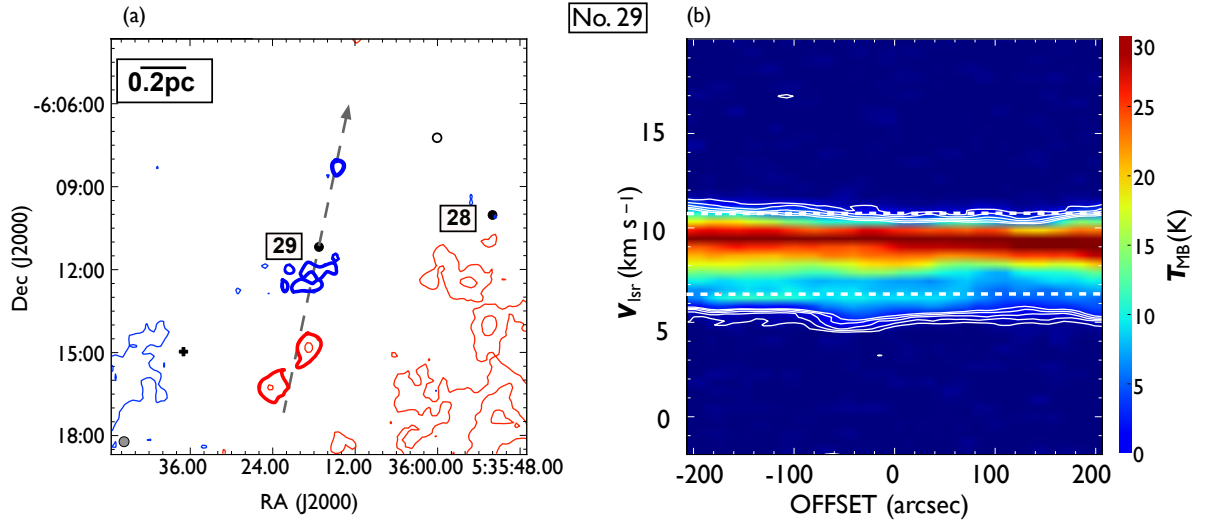


Figure 4.13. The same as in Figure 4.3 but for outflow No. 29. In panel (a), the blue- and red-shifted integrated intensity velocity ranges are -1.9 km s^{-1} to 6.7 km s^{-1} and 10.9 km s^{-1} to 20.2 km s^{-1} , respectively. This outflow is a faint bipolar outflow, which has the plural lobes in the north to south.

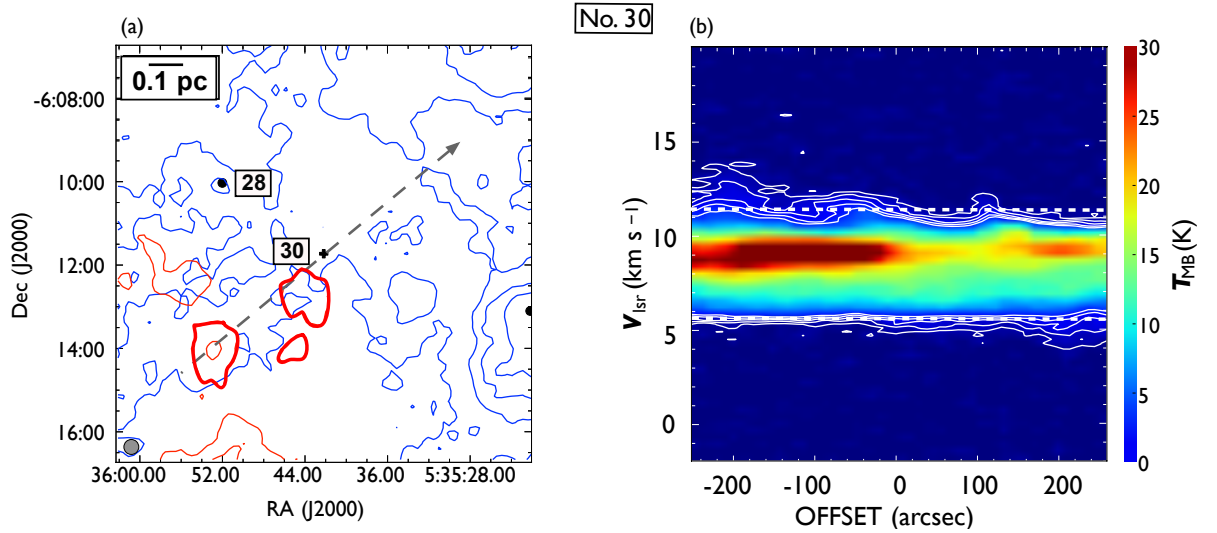


Figure 4.14. The same as in Figure 4.3 but for outflow No. 30. In panel (a), the blue- and red-shifted integrated intensity velocity ranges are -1.9 km s^{-1} to 5.7 km s^{-1} and 11.5 km s^{-1} to 20.2 km s^{-1} , respectively. This red-single outflow has the plural red-shifted lobes with a north-west elongation.

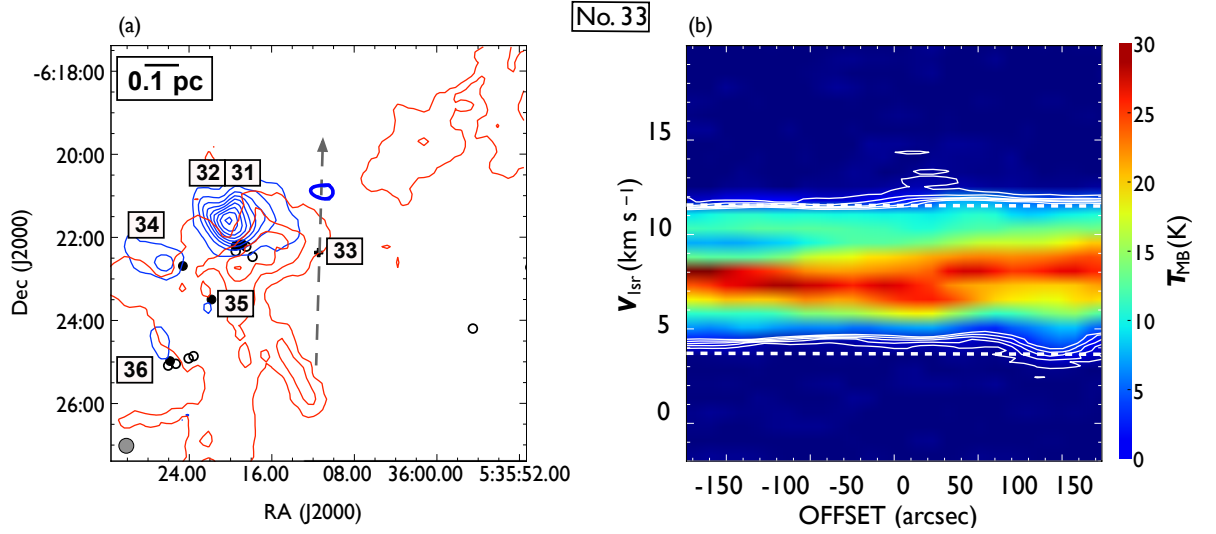


Figure 4.15. The same as in Figure 4.3 but for outflow No. 33. In panel (a), the blue- and red-shifted integrated intensity velocity ranges are -1.9 km s^{-1} to 3.7 km s^{-1} and 11.5 km s^{-1} to 18.0 km s^{-1} , respectively. This faint blue-single outflow is driven by the central L1641 region PMS star with a jet.

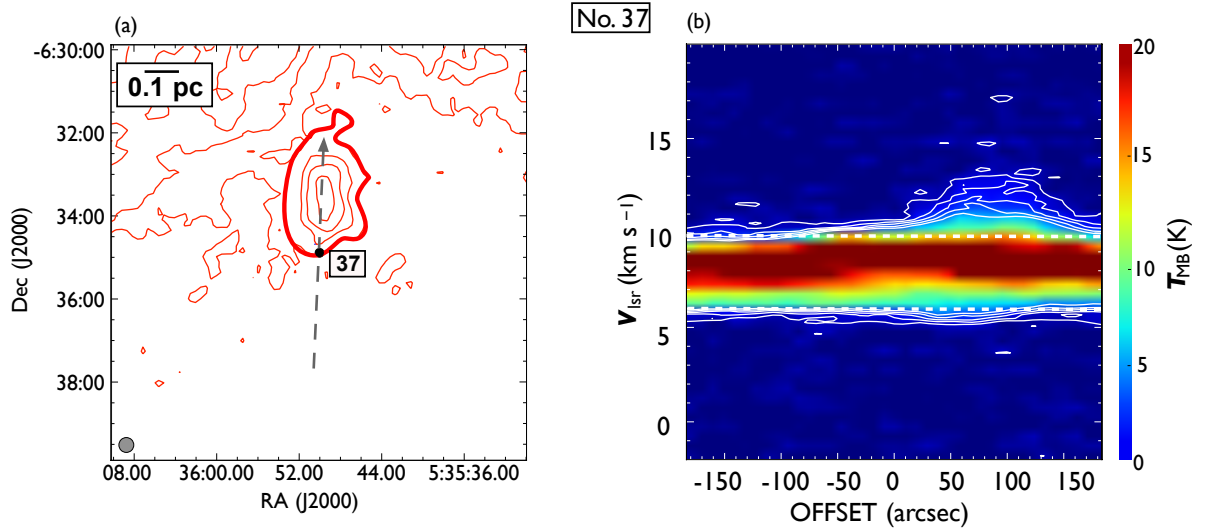


Figure 4.16. The same as in Figure 4.3 but for outflow No. 37. In panel (a), the blue- and red-shifted integrated intensity velocity ranges are -1.9 km s^{-1} to 6.0 km s^{-1} and 10.9 km s^{-1} to 20.2 km s^{-1} , respectively. The red-shifted lobe clearly can be seen in the north.

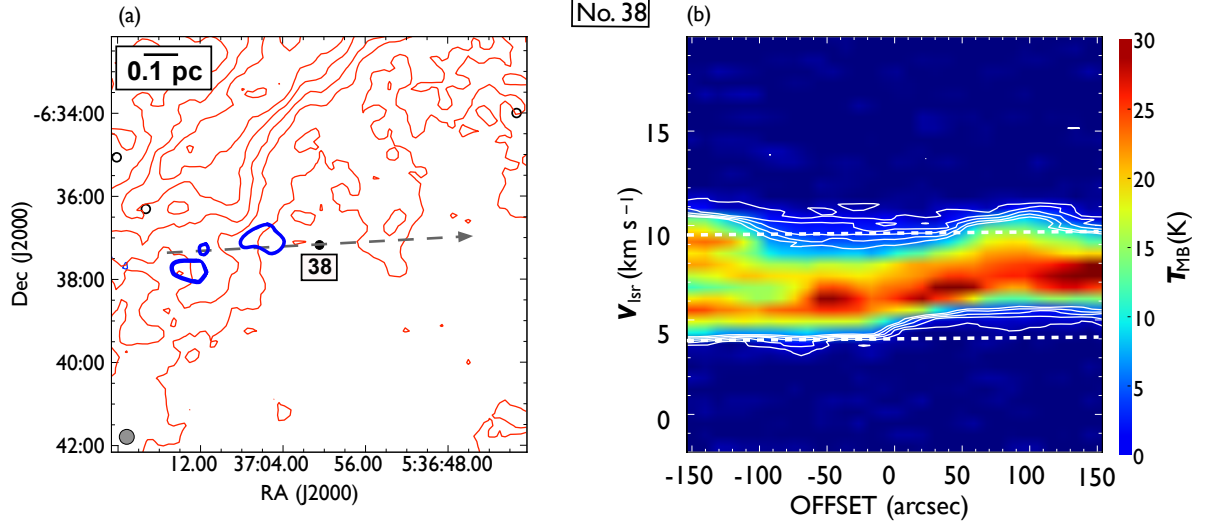


Figure 4.17. The same as in Figure 4.3 but for outflow No. 38. In panel (a), the blue- and red-shifted integrated intensity velocity ranges are -1.9 km s^{-1} to 3.9 km s^{-1} and 9.5 km s^{-1} to 18.0 km s^{-1} , respectively. This faint blue-single outflow has the three blue-shifted components in the east.

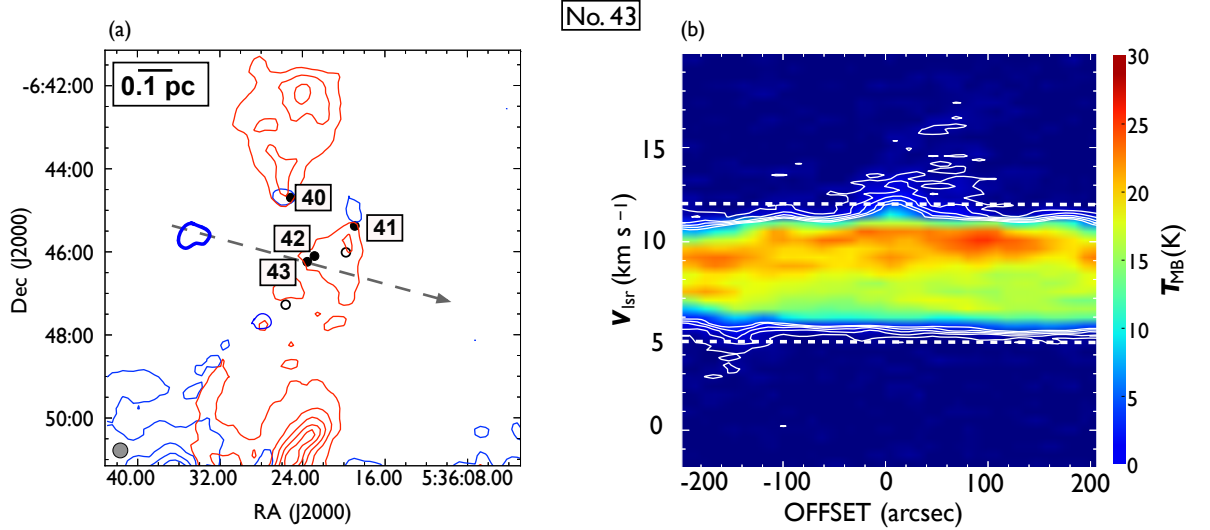


Figure 4.18. The same as in figure 4.3 but for outflow No. 43. In panel (a), the blue- and red-shifted integrated intensity velocity ranges are -1.9 km s^{-1} to 4.8 km s^{-1} and 12.1 km s^{-1} to 20.2 km s^{-1} , respectively. This blue-single outflow is driven by the protostar just to the south of the HH 1/2 VLA source.

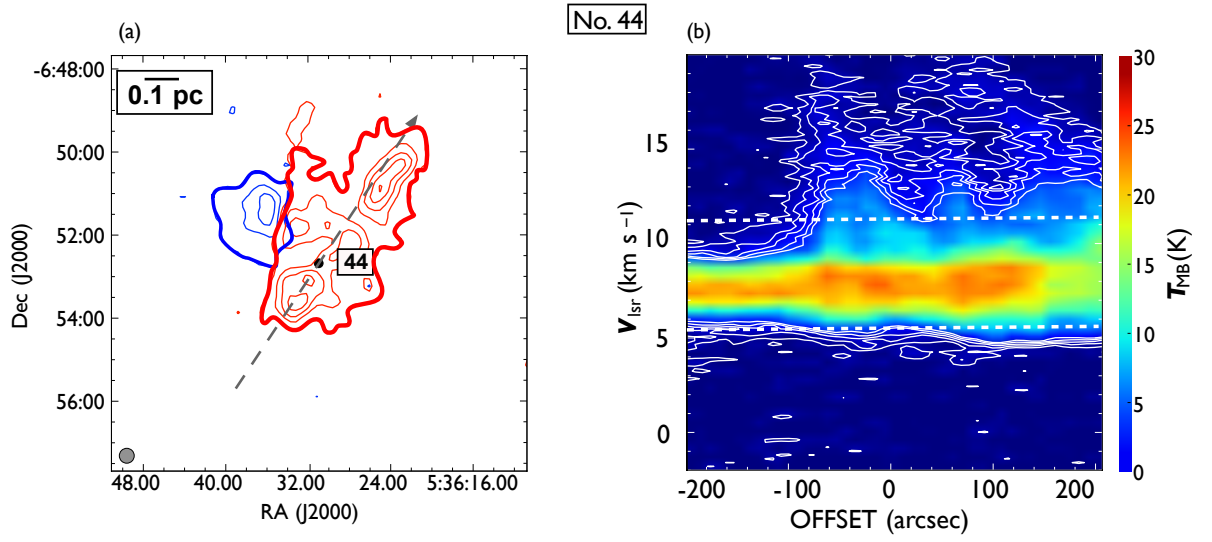


Figure 4.19. The same as in Figure 4.3 but for outflow No. 44. In panel (a), the blue- and red-shifted integrated intensity velocity ranges are -1.9 km s^{-1} to 5.4 km s^{-1} and 11.2 km s^{-1} to 20.2 km s^{-1} , respectively. This outflow has a strong red-shifted component with a north-west to south-east elongation and a faint blue-shifted component with a north-east elongation. I define the position angle of No. 44 as the direction of the red-shifted component.

4.2 Outflow properties

4.2.1 Optical depth of outflows

To estimate the optical depth of ^{12}CO ($J = 1-0$) outflows, I also search for outflows in ^{13}CO ($J = 1-0$) map at the locations where I identify ^{12}CO ($J = 1-0$) outflows. I make the ^{13}CO integrated intensity map with the same velocity range as ^{12}CO , (i.e., $|v_{\text{lsr}} - v_{\text{sys}}| \geq 2\sigma_v$). The ^{13}CO outflows are identified as the regions where the ^{13}CO integrated intensities are above 3σ and the peak of the ^{13}CO integrated intensity is located within the ^{12}CO outflow lobe. The results are shown in Figure 4.20. I identified three outflows in ^{13}CO ($J = 1-0$) map (hereafter I call them ^{13}CO outflows): the blue and red lobes of outflow No. 7, and the blue lobes of outflow Nos. 31 and 32. In these outflows, I estimate the optical depth using the following equation:

$$\frac{I_{12\text{CO}}}{I_{13\text{CO}}} = \frac{1 - \exp(-\tau_{12\text{CO}})}{1 - \exp(-\tau_{13\text{CO}})}, \quad (4.1)$$

where $I_{12\text{CO}}$ is the averaged integrated intensity of ^{12}CO inside the 5σ level, and $I_{13\text{CO}}$ is the averaged integrated intensity of ^{13}CO within the contour of the 5σ level of ^{12}CO . $\tau_{12\text{CO}}$ and $\tau_{13\text{CO}}$ are the averaged optical depths of the ^{12}CO and ^{13}CO lines. This equation can be used when ^{12}CO and ^{13}CO are in local thermal equilibrium (LTE) with the same excitation temperature. Assuming $\tau_{12\text{CO}}/\tau_{13\text{CO}} = 62$ taking from the value of $[^{12}\text{C}]/[^{13}\text{C}]$ (Langer & Penzias 1993), equation 4.1 provides us with $\tau_{12\text{CO}}$ of the outflow, as listed in Table 4.5. The average of the $\tau_{12\text{CO}}$ for the four lobes of the outflows is ~ 5 , suggesting that the optical depth of ^{12}CO is not small in the detected outflows. Hereafter, I adopt $\tau_{12\text{CO}} = 5$ in other outflows. The assumption of $\tau_{12\text{CO}} = 5$ is possible for outflows without ^{13}CO detection; ^{12}CO ($J = 1-0$) brightness temperature in outflows with ^{13}CO detection is lower than outflows with ^{13}CO detection, and I cannot give any stringent constraint on $\tau_{12\text{CO}}$.

Table 4.5: Optical depth of outflows

No.	Lobe	$\tau_{13\text{CO}}$	$\tau_{12\text{CO}}$
7	Blue	0.075	4.65
7	Red	0.097	6.01
31-32	Blue	0.076	4.71

4.2.2 Physical parameters of outflows

To estimate the physical parameters of each detected outflow, I assume that the ^{12}CO molecules are in LTE. The results are summarized in Table 4.6, but I do not correct for the inclination angle of outflows. When the outflows are distributed randomly, the average of inclinations is 57.3° , thus the velocity of outflows and timescale of outflows will be higher by a factor of 1.85 and 0.64, respectively.

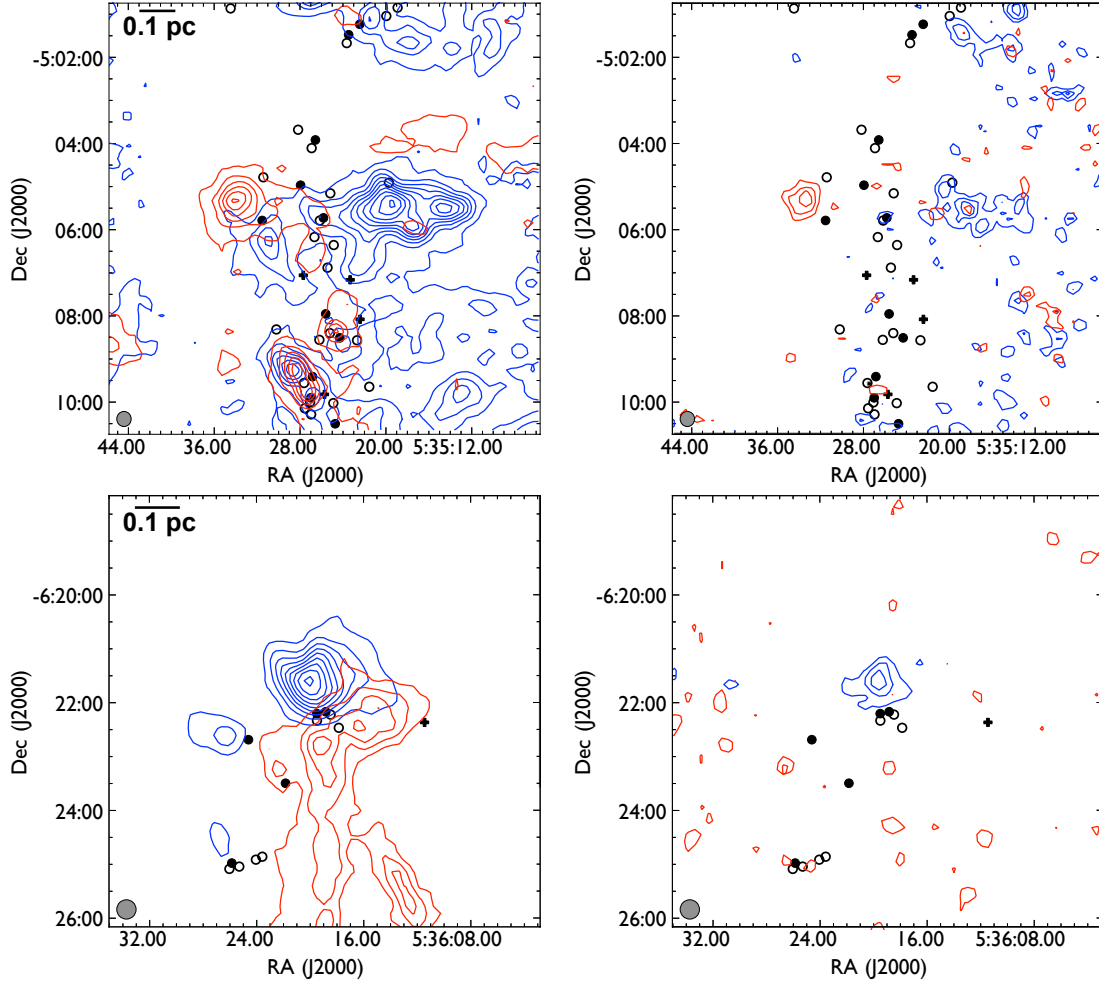


Figure 4.20. The pair of ^{12}CO and ^{13}CO outflows. Panel (a) and (c) show ^{12}CO outflows following procedure described in section 3.2. Contours and markers are the same as those of Figure 3.2 (d). Panel (b) and (d) show ^{13}CO outflows with the same velocity ranges as (a) and (c), respectively. The contour intervals are 0.3 K km s^{-1} ($\sim 1\sigma$) starting at 0.9 K km s^{-1} ($\sim 3\sigma$).

The uncertainty arising from unknown inclination angle of outflows is large. For example, a rather extreme case of 80° , these values will be higher by a factor of 5.76 and 0.18, respectively.

I adopt T_{peak} , derived from the Gaussian fitting with equation (3.1), as the excitation temperature (T_{ex}) of each outflow. The average value of T_{peak} of all the outflows in our sample is 36 K. Note that in the high velocity wings, T_{ex} may be higher than T_{peak} derived from Gaussian fitting. If T_{ex} for all the outflows is $2.0 \times T_{\text{peak}}$, for example, the mass of the outflows and other quantities proportional to mass will be higher by a factor of 1.9. The column density of ^{12}CO at each position and at each velocity component is expressed by

Table 4.6: $^{12}\text{CO}(1-0)$ Outflow properties

No.	Lobe	M_{flow} ($M_{\odot}$)	P_{flow} ($M_{\odot} \text{ km s}^{-1}$)	E_{flow} (10^{43} erg)	Δv_{max} (km s^{-1})	R_{max} (pc)	t_{d} (10^4 yr)	$\dot{M}_{\text{flow}}$ *1	$\dot{P}_{\text{flow}}$ *2	$\dot{E}_{\text{flow}}$ *3
OMC 2/3										
1	B	0.07 $\pm$ 0.03	0.26 $\pm$ 0.11	1.00 $\pm$ 0.45	5.3	0.13	2.4	3.0	10.6	13.1
	R	0.11 $\pm$ 0.04	0.24 $\pm$ 0.10	0.63 $\pm$ 0.27	3.9	0.23	5.9	1.5	4.0	3.5
2	B	0.16 $\pm$ 0.07	0.61 $\pm$ 0.27	2.40 $\pm$ 1.15	6.6	0.08	1.2	14.1	50.3	65.9
3	B	0.03 $\pm$ 0.02	0.13 $\pm$ 0.09	0.64 $\pm$ 0.45	6.4	0.06	0.9	2.5	14.1	21.1
	R	0.16 $\pm$ 0.06	0.55 $\pm$ 0.21	1.96 $\pm$ 0.79	6.2	0.19	3.0	5.0	18.6	20.6
4	B	0.20 $\pm$ 0.07	0.96 $\pm$ 0.37	4.87 $\pm$ 1.72	6.7	0.08	1.1	17.6	87.0	136.8
	R	0.07 $\pm$ 0.03	0.23 $\pm$ 0.11	0.79 $\pm$ 0.29	5.9	0.06	1.0	6.0	22.6	24.6
5	B	0.37 $\pm$ 0.14	1.92 $\pm$ 0.79	10.54 $\pm$ 4.04	10.3	0.32	3.1	12.1	61.9	108.6
	R	0.01 $\pm$ 0.01	0.02 $\pm$ 0.01	0.06 $\pm$ 0.05	3.7	0.05	1.2	0.5	1.5	1.5
6	B	0.01 $\pm$ 0.01	0.02 $\pm$ 0.01	0.04 $\pm$ 0.02	3.5	0.08	2.2	0.4	0.9	0.6
	R	1.04 $\pm$ 0.23	4.34 $\pm$ 1.04	18.23 $\pm$ 4.78	7.4	0.55	7.3	14.6	59.4	79.5
7	B	2.29 $\pm$ 0.36	10.60 $\pm$ 2.09	53.39 $\pm$ 11.54	13.0	0.42	3.1	73.2	341.8	539.4
	R(west)	1.55 $\pm$ 0.30	5.80 $\pm$ 1.63	22.70 $\pm$ 5.85	8.4	0.34	4.0	39.2	145.2	181.4
	R(east)	0.13 $\pm$ 0.04	0.46 $\pm$ 0.15	1.61 $\pm$ 0.52	4.0	0.27	6.1	1.5	7.5	5.0
8	B	0.14 $\pm$ 0.05	0.72 $\pm$ 0.28	3.76 $\pm$ 1.60	7.9	0.13	1.6	9.1	45.3	73.9
	R	0.20 $\pm$ 0.05	0.74 $\pm$ 0.18	2.83 $\pm$ 0.73	4.7	0.13	2.7	7.0	27.7	32.7
9	B	0.14 $\pm$ 0.04	0.69 $\pm$ 0.22	3.51 $\pm$ 1.17	6.8	0.10	1.4	9.6	49.3	77.5
10	B	0.63 $\pm$ 0.16	2.68 $\pm$ 0.71	11.36 $\pm$ 3.30	6.9	0.34	4.8	13.1	55.8	73.9
11	R	0.18 $\pm$ 0.04	0.66 $\pm$ 0.17	2.51 $\pm$ 0.55	5.2	0.09	1.7	10.1	38.7	46.3
12	B	0.10 $\pm$ 0.05	0.46 $\pm$ 0.24	2.13 $\pm$ 1.16	6.3	0.06	0.9	10.6	51.3	72.9
	R	0.31 $\pm$ 0.10	1.30 $\pm$ 0.44	5.76 $\pm$ 1.99	7.7	0.08	1.0	30.2	130.3	178.6
13	B(north)	0.40 $\pm$ 0.15	2.29 $\pm$ 0.97	14.32 $\pm$ 6.81	12.7	0.14	1.1	36.7	208.2	419.5
	B(south)	0.30 $\pm$ 0.10	1.54 $\pm$ 0.54	8.20 $\pm$ 3.19	8.5	0.12	1.4	21.6	110.2	187.6
	R(north)	0.36 $\pm$ 0.11	1.69 $\pm$ 0.57	8.30 $\pm$ 3.17	9.1	0.13	1.4	26.2	120.7	188.6
	R(south)	0.32 $\pm$ 0.10	1.48 $\pm$ 0.50	7.07 $\pm$ 2.70	9.1	0.10	1.1	30.2	134.3	208.7
14	B(south)	0.09 $\pm$ 0.03	0.39 $\pm$ 0.14	1.76 $\pm$ 0.69	5.8	0.08	1.4	6.5	28.2	40.7
	R(south)	0.13 $\pm$ 0.05	0.59 $\pm$ 0.24	2.73 $\pm$ 1.19	6.3	0.10	1.6	8.6	36.7	54.8
15	R	0.16 $\pm$ 0.06	0.64 $\pm$ 0.26	2.57 $\pm$ 1.10	5.0	0.26	5.1	3.0	12.6	16.1
16	B	0.38 $\pm$ 0.12	1.70 $\pm$ 0.56	7.60 $\pm$ 2.80	6.9	0.22	3.1	12.1	54.8	76.5
	R	0.22 $\pm$ 0.08	0.87 $\pm$ 0.35	3.70 $\pm$ 1.48	7.0	0.24	3.4	6.0	25.7	34.7
17	B	0.49 $\pm$ 0.19	2.36 $\pm$ 0.98	11.78 $\pm$ 5.01	8.3	0.54	6.3	7.5	37.2	58.9
18	R	0.27 $\pm$ 0.12	1.25 $\pm$ 0.55	5.83 $\pm$ 2.72	6.7	0.12	1.8	15.1	69.4	105.6
19	R	0.36 $\pm$ 0.13	1.80 $\pm$ 0.68	8.93 $\pm$ 3.55	6.8	0.16	2.3	15.6	78.0	122.2

¹ ($10^{-6} M_{\odot} \text{ yr}^{-1}$)² ($10^{-6} M_{\odot} \text{ km s}^{-1} \text{ yr}^{-1}$)³ ($10^{30} \text{ erg s}^{-1}$)

Table 4.6: continued

No.	Lobe	M_{flow} ($M_{\odot}$)	P_{flow} ($M_{\odot} \text{ km s}^{-1}$)	E_{flow} (10^{43} erg)	Δv_{max} (km s^{-1})	R_{max} (pc)	t_{d} (10^4 yr)	$\dot{M}_{\text{flow}}$	$\dot{P}_{\text{flow}}$	$\dot{E}_{\text{flow}}$
OMC 4/5										
20	B	0.06 $\pm$ 0.02	0.32 $\pm$ 0.09	1.64 $\pm$ 0.47	5.7	0.12	2.1	3.0	15.1	24.6
21	B	0.04 $\pm$ 0.02	0.12 $\pm$ 0.08	0.44 $\pm$ 0.30	5.6	0.15	2.7	1.3	4.5	5.1
	R	0.05 $\pm$ 0.03	0.29 $\pm$ 0.17	1.93 $\pm$ 1.16	7.6	0.17	2.2	2.0	13.3	28.1
22	B	0.07 $\pm$ 0.03	0.30 $\pm$ 0.12	1.30 $\pm$ 0.50	5.0	0.28	5.5	1.2	5.4	7.5
	R	0.04 $\pm$ 0.03	0.22 $\pm$ 0.15	1.22 $\pm$ 0.34	7.0	0.51	7.1	0.5	3.0	5.4
23	B	0.09 $\pm$ 0.03	0.29 $\pm$ 0.11	0.99 $\pm$ 0.38	4.0	0.18	4.5	1.9	6.5	7.0
24	B	0.18 $\pm$ 0.09	1.29 $\pm$ 0.67	9.47 $\pm$ 5.17	11.7	0.25	2.1	8.6	61.9	144.9
25	B	0.24 $\pm$ 0.11	1.27 $\pm$ 0.61	7.02 $\pm$ 2.23	10.1	0.28	2.7	9.0	47.3	83.0
26	B	0.13 $\pm$ 0.07	0.70 $\pm$ 0.38	4.06 $\pm$ 1.68	10.7	0.14	1.3	9.8	53.2	97.4
	R	0.22 $\pm$ 0.11	1.25 $\pm$ 0.67	8.60 $\pm$ 5.05	12.3	0.15	1.2	18.3	102.4	223.0
27	B	0.07 $\pm$ 0.04	0.26 $\pm$ 0.16	1.07 $\pm$ 0.63	4.6	0.25	5.3	1.2	5.0	6.4
	R	0.45 $\pm$ 0.26	2.33 $\pm$ 1.41	12.83 $\pm$ 4.77	12.4	0.35	2.7	16.6	85.2	148.9
28	B	0.05 $\pm$ 0.03	0.18 $\pm$ 0.11	0.62 $\pm$ 0.38	4.1	0.16	3.8	1.3	4.6	5.2
29	B	0.08 $\pm$ 0.04	0.32 $\pm$ 0.18	1.33 $\pm$ 0.73	4.7	0.38	7.9	1.0	4.1	5.3
	R	0.05 $\pm$ 0.02	0.16 $\pm$ 0.07	0.49 $\pm$ 0.22	3.7	0.40	10.7	0.5	1.5	1.4
30	R	0.22 $\pm$ 0.10	0.80 $\pm$ 0.37	2.99 $\pm$ 1.47	5.6	0.30	5.3	4.1	15.1	18.0
L1641-N										
31	B(NE)	0.36 $\pm$ 0.09	2.09 $\pm$ 0.65	13.66 $\pm$ 5.06	19.8	0.17	0.8	43.3	261.4	528.5
	R(SE)	0.14 $\pm$ 0.08	0.77 $\pm$ 0.46	4.48 $\pm$ 2.72	8.2	0.65	7.8	2.0	10.1	18.1
	B(east)	0.05 $\pm$ 0.02	0.24 $\pm$ 0.07	1.19 $\pm$ 0.35	5.4	0.16	2.8	1.5	8.6	13.1
32	B(north)	0.36 $\pm$ 0.08	1.94 $\pm$ 0.49	10.92 $\pm$ 3.19	11.0	0.19	1.7	21.4	114.5	203.4
	R(south)	0.48 $\pm$ 0.28	2.73 $\pm$ 1.66	16.07 $\pm$ 10.19	15.4	1.01	6.3	7.5	42.8	79.5
33	B	0.02 $\pm$ 0.01	0.07 $\pm$ 0.04	0.29 $\pm$ 0.15	4.7	0.15	3.1	0.5	2.5	3.0
34	B	0.04 $\pm$ 0.02	0.16 $\pm$ 0.08	0.74 $\pm$ 0.30	5.6	0.15	2.6	1.3	6.0	9.0
	R	0.03 $\pm$ 0.01	0.12 $\pm$ 0.04	0.55 $\pm$ 0.07	5.8	0.08	1.3	1.8	9.0	14.0
35	B	0.01 $\pm$ 0.01	0.03 $\pm$ 0.02	0.13 $\pm$ 0.08	4.7	0.04	0.8	0.9	3.6	4.9
	R	0.02 $\pm$ 0.01	0.12 $\pm$ 0.07	0.72 $\pm$ 0.34	9.9	0.06	0.5	4.0	22.0	41.7
36	B	0.01 $\pm$ 0.01	0.04 $\pm$ 0.03	0.19 $\pm$ 0.12	5.0	0.08	1.6	0.6	2.6	3.7
37	R	0.42 $\pm$ 0.08	1.00 $\pm$ 0.23	2.60 $\pm$ 0.73	4.9	0.25	5.1	8.2	19.6	16.1
38	B	0.04 $\pm$ 0.02	0.11 $\pm$ 0.05	0.33 $\pm$ 0.14	3.6	0.22	5.8	0.6	1.9	1.8
NGC 1999										
39	B	0.32 $\pm$ 0.13	1.63 $\pm$ 0.81	9.62 $\pm$ 4.13	11.6	0.23	1.9	16.0	85.5	157.5
	R	0.16 $\pm$ 0.09	0.85 $\pm$ 0.49	4.94 $\pm$ 2.24	9.3	0.22	2.3	7.0	36.5	68.0
40	B	0.02 $\pm$ 0.01	0.07 $\pm$ 0.05	6.38 $\pm$ 0.17	4.9	0.06	1.2	1.5	5.5	6.5
	R	0.27 $\pm$ 0.12	1.34 $\pm$ 0.61	6.83 $\pm$ 1.71	8.3	0.14	1.6	11.5	83.0	132.0
41	B	0.01 $\pm$ 0.01	0.04 $\pm$ 0.03	0.11 $\pm$ 0.08	3.0	0.06	2.0	0.5	2.0	2.0
	R	0.08 $\pm$ 0.05	0.44 $\pm$ 0.27	2.53 $\pm$ 1.65	8.8	0.22	2.5	3.5	17.5	32.0
42	B	0.07 $\pm$ 0.03	0.27 $\pm$ 0.13	1.15 $\pm$ 0.55	4.2	0.46	10.7	0.5	2.5	3.5
	R	0.10 $\pm$ 0.06	0.44 $\pm$ 0.29	2.09 $\pm$ 0.39	6.6	0.46	6.9	1.5	6.5	9.5
43	B	0.04 $\pm$ 0.02	0.16 $\pm$ 0.10	0.73 $\pm$ 0.47	6.0	0.37	6.0	0.5	2.5	4.0
44	B	0.07 $\pm$ 0.04	0.30 $\pm$ 0.14	1.26 $\pm$ 0.58	4.7	0.34	7.1	1.0	4.0	5.5
	R	1.42 $\pm$ 0.53	9.13 $\pm$ 3.77	63.03 $\pm$ 20.54	13.3	0.46	3.4	41.5	267.0	585.0
Total		21.5	84.2	439.7				728.9	3585.0	6024.8

$$N(v) = \frac{3k^2}{8\pi^3 h B (J+1) \nu \mu^2} f_\tau T_{\text{ex}} \exp\left(\frac{hB(J+1)(J+2)}{kT_{\text{ex}}}\right) T_{\text{B}}(v) \Delta v, \quad (4.2)$$

where k , h , B , ν , μ , Δv are the Boltzmann constant, the Planck constant, the rotational constant of ^{12}CO , the rest frequency of the $(J=1-0)$ transition, the dipole moment of the ^{12}CO molecule, and Δv is the velocity channel width of the cube, respectively. f_τ is the correction factor for the optical depth given by

$$f_\tau = \frac{\tau_{^{12}\text{CO}}}{1 - \exp(-\tau_{^{12}\text{CO}})}, \quad (4.3)$$

where $\tau_{^{12}\text{CO}}$ is the optical depth of ^{12}CO derived in section 4.2.1. The mass of each outflow can be estimated from the channel maps integrated in the velocity ranges $|v_{\text{lsr}} - v_{\text{sys}}| \geq 2\sigma_v$,

$$M_{\text{flow}} = \sum_{|v_{\text{lsr}} - v_{\text{sys}}| \geq 2\sigma_v} m(v), \quad (4.4)$$

where $m(v)$ is the mass of each velocity component, given by

$$m(v) = 4.33 \times 10^{13} \frac{\bar{\mu} m_{\text{H}}}{\chi_{^{12}\text{CO}}} \left(\frac{s(v)}{\text{cm}^2}\right) f_\tau \left(\frac{T_{\text{ex}}}{\text{K}}\right) \exp\left(\frac{5.53}{T_{\text{ex}}}\right) \left(\frac{\overline{T_{\text{B}}}(v)}{\text{K}}\right) \left(\frac{\Delta v}{\text{km s}^{-1}}\right). \quad (4.5)$$

In the equation (4.5), $\bar{\mu} = 2.4$ is the mean molecular weight, m_{H} is the atomic hydrogen mass, $\chi_{^{12}\text{CO}} = 10^{-4}$ (Frerking et al. 1982) is the abundance of ^{12}CO relative to H_2 , $\overline{T_{\text{B}}}(v)$ is the averaged brightness temperature of all pixels in $s(v)$, and $s(v)$ is the projected area above the 3σ level, given by

$$s(v) = n_{\text{pix}} \left\{ 1.5 \times 10^{13} \left(\frac{D}{\text{pc}}\right) \left(\frac{\Delta\theta}{\text{arcsec}}\right) \right\}^2 [\text{cm}^2], \quad (4.6)$$

where n_{pix} is the number of pixels in $s(v)$, D is the distance to Orion A, and $\Delta\theta = 7''.5$ is the pixel size. After deriving $m(v)$, I calculate the outflow momentum, P_{flow} , and the outflow energy, E_{flow} , using

$$P_{\text{flow}} = \sum_{|v_{\text{lsr}} - v_{\text{sys}}| \geq 2\sigma_v} m(v) |v_{\text{lsr}} - v_{\text{sys}}| \quad (4.7)$$

and

$$E_{\text{flow}} = \frac{1}{2} \sum_{|v_{\text{lsr}} - v_{\text{sys}}| \geq 2\sigma_v} m(v) |v_{\text{lsr}} - v_{\text{sys}}|^2. \quad (4.8)$$

The maximum velocity of each outflow (Δv_{max}) is taken from $|v_{\text{max}} - v_{\text{sys}}|$, where v_{max} is the highest velocity of each outflow whose emission is above 3σ . The maximum size of each outflow (R_{max}) is measured in the integrated map. The dynamical timescale of each outflow (t_{d}) is defined by $R_{\text{max}}/\Delta v_{\text{max}}$. The mass outflow rate is calculated by $\dot{M}_{\text{flow}} = M_{\text{flow}}/t_{\text{d}}$, the outflow force is by $\dot{P}_{\text{flow}} = P_{\text{flow}}/t_{\text{d}}$, and the outflow luminosity is by $\dot{E}_{\text{flow}} = E_{\text{flow}}/t_{\text{d}}$.

Figure 4.21 shows the histogram of mass, momentum, energy, mass outflow rate, force, and luminosity for all the outflows, and dynamical timescale for all the outflow lobes. The average

values of mass, momentum, energy, mass outflow rate, force, and luminosity of all the outflows in our sample are $4.8 \times 10^{-1} M_{\odot}$, $1.9 M_{\odot} \text{ km s}^{-1}$, $1.0 \times 10^{44} \text{ erg}$, $1.7 \times 10^{-5} M_{\odot} \text{ yr}^{-1}$, $8.1 \times 10^{-5} M_{\odot} \text{ km s}^{-1} \text{ yr}^{-1}$, and $1.4 \times 10^{32} \text{ erg s}^{-1}$, respectively. The average dynamical timescale of all the outflow lobes is $3.8 \times 10^4 \text{ year}$.

4.2.3 Position angle of outflows

Protostars formed in filamentary structures may have a characteristic outflow direction to a filament: parallel or perpendicular (Stephens et al. 2017). According to Stephens et al. (2017), the projected angles between the outflows and filaments in the Perseus molecular cloud complex are not consistent with being either mostly parallel or perpendicular; they are consistent with being random or a mix of parallel and perpendicular. I also compare the position angles of the outflows to the direction of the cloud filament in Orion A. For simplification, I define the direction of the cloud filament on the plane of the sky as $\text{PA} = -20^\circ$ for $\delta \geq -5^\circ 0' 00'' 00$ (J2000.0), $\text{PA} = 10^\circ$ for $-5^\circ 0' 00'' 00$ (J2000.0) $> \delta \geq -5^\circ 40' 00'' 00$ (J2000.0) and $\text{PA} = -20^\circ$ for $\delta \leq -5^\circ 40' 00'' 00$ (J2000.0) (see Figure 4.1), and I determine the relative position angles of the outflows with respect to the cloud filament. The results are shown in Figure 4.22. There is no clear significant difference between the north and the south of the clouds, and the results do not show any correlation between the position angles of the outflows and elongations of the cloud filaments.

4.3 Cloud properties

Using the ^{13}CO ($J = 1-0$) line emission, I estimate the cloud kinetic properties in each subregion by the following method, and the results are summarized in Table 4.7. An excitation temperature is calculated for each pixel by assuming that the ^{12}CO line is optically thick and using the equation from Rohlfs & Wilson (1996),

$$T_{\text{ex}} = \frac{5.53}{\ln(1 + [5.53/(T_{\text{peak}}(^{12}\text{CO}) + 0.82)])} [\text{K}], \quad (4.9)$$

where T_{peak} is the peak intensity of ^{12}CO at each pixel. In the region where ^{13}CO is detected above 5σ , I calculate the optical depth of the ^{13}CO ($J = 1-0$) line with the equation

$$\tau_{^{13}\text{CO}}(\nu) = -\ln \left[1 - \frac{T_{^{13}\text{CO}}(\nu)}{T_{^{12}\text{CO}}(\nu)} \right]. \quad (4.10)$$

The total column density of ^{13}CO can be expressed by

$$N_{^{13}\text{CO}} = 4.74 \times 10^{13} T_{\text{ex}} \exp \left(\frac{5.29}{T_{\text{ex}}} \right) \int f_{\tau}(\nu) \left(\frac{T_B(\nu)}{\text{K}} \right) \left(\frac{dv}{\text{km s}^{-1}} \right) [\text{cm}^{-2}]. \quad (4.11)$$

In equation 4.11, $f_{\tau}(\nu)$ is the correction factor for the opacity defined as

$$f_{\tau}(\nu) = \frac{\tau_{^{13}\text{CO}}(\nu)}{1 - \exp(-\tau_{^{13}\text{CO}}(\nu))}. \quad (4.12)$$

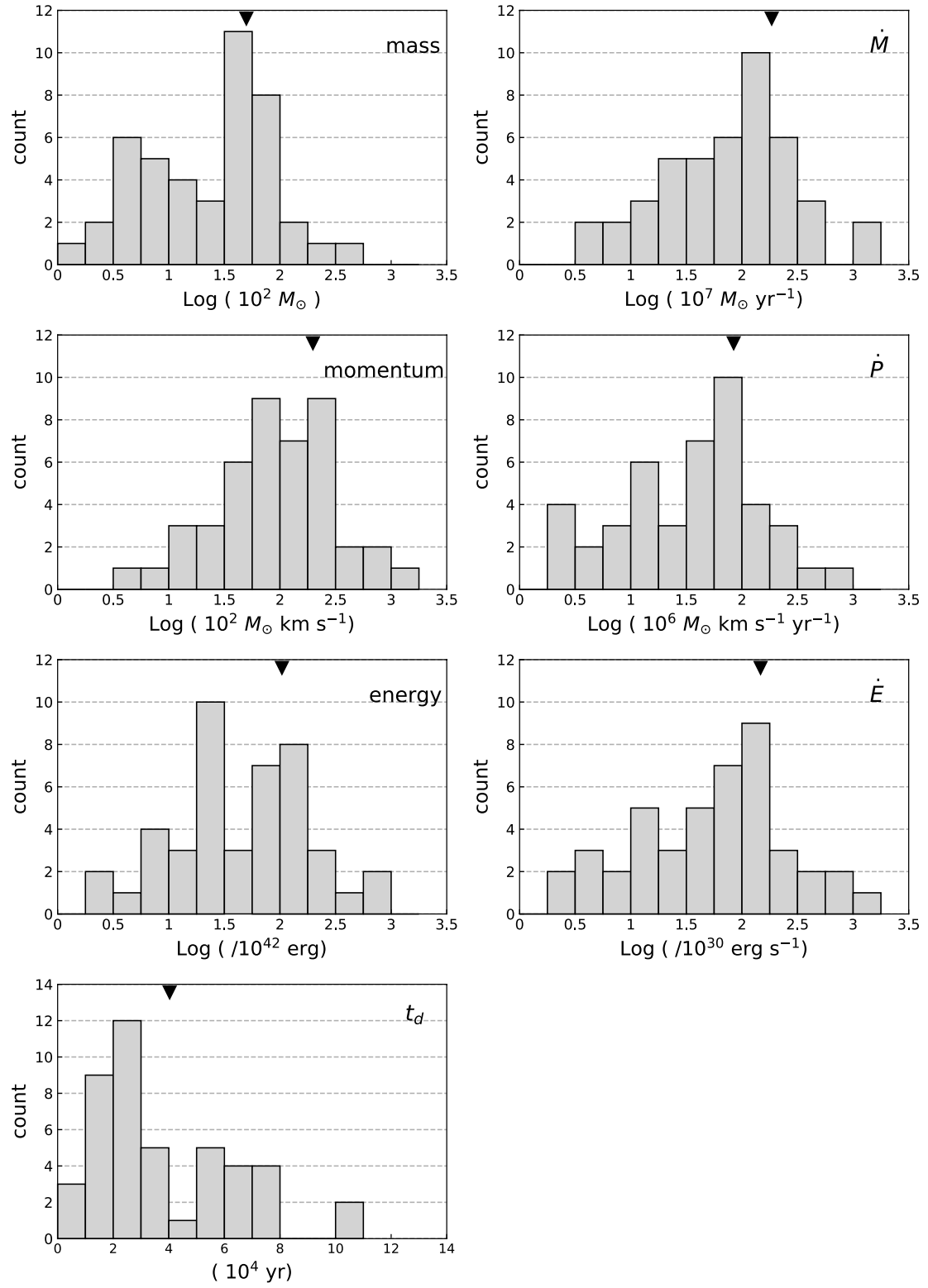


Figure 4.21. Histograms of the distribution of the outflow properties. The triangles represent the average of each property.

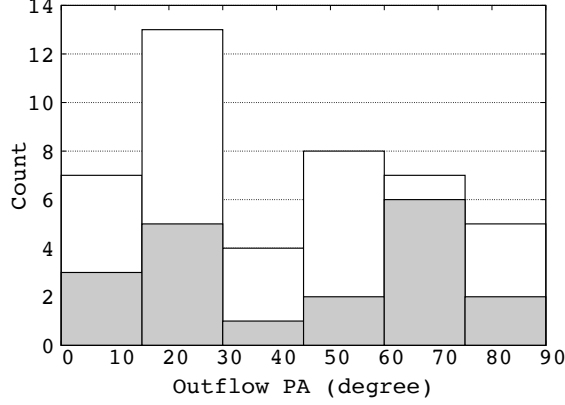


Figure 4.22. Distribution of the observed angle between outflow position angle and the cloud filament (15° bins) for all outflows in Orion A (white filled) and for northern OMC 2/3 outflows (gray filled).

The mass in each pixel is given by

$$m_{\text{cl}} = N_{^{13}\text{CO}} \frac{\bar{\mu} m_{\text{H}}}{\chi_{^{13}\text{CO}}} \left\{ 1.5 \times 10^{13} \left(\frac{D}{\text{pc}} \right) \left(\frac{\Delta\theta}{\text{arcsec}} \right) \right\}^2 [\text{g}], \quad (4.13)$$

where $\chi_{^{13}\text{CO}}$ is the abundance of ^{13}CO relative to H_2 , $\chi_{^{13}\text{CO}} = (1/67) \times 10^{-4}$. I estimate the cloud mass for all pixels with ^{13}CO emission above 5 sigma, and find that the total mass of each subregion, $M_{\text{cl}} = 5.8, 7.1, 9.6, 5.0$, and $4.5 \times 10^3 M_\odot$ for the OMC 2/3, OMC 1, OMC 4/5, L1641-N, and NGC 1999 subregions, respectively. Figure 4.23 shows the maps of excitation temperature and column density of ^{13}CO .

I also estimate the turbulent energy of the Orion A cloud following the method presented in Li et al. (2015). The turbulent energy of the cloud of each pixel is given approximately by

$$e_{\text{turb}} = \frac{1}{2} m_{\text{cl}} \sigma_{3\text{d}}^2, \quad (4.14)$$

where $\sigma_{3\text{d}}$ is the ^{13}CO three-dimensional turbulent velocity dispersion of each pixel, which is assumed to be

$$\sigma_{3\text{d}} = \sqrt{3} \sigma_v. \quad (4.15)$$

The total turbulent energy of the cloud is then given by

$$\mathcal{E}_{\text{turb}} = \sum e_{\text{turb}}. \quad (4.16)$$

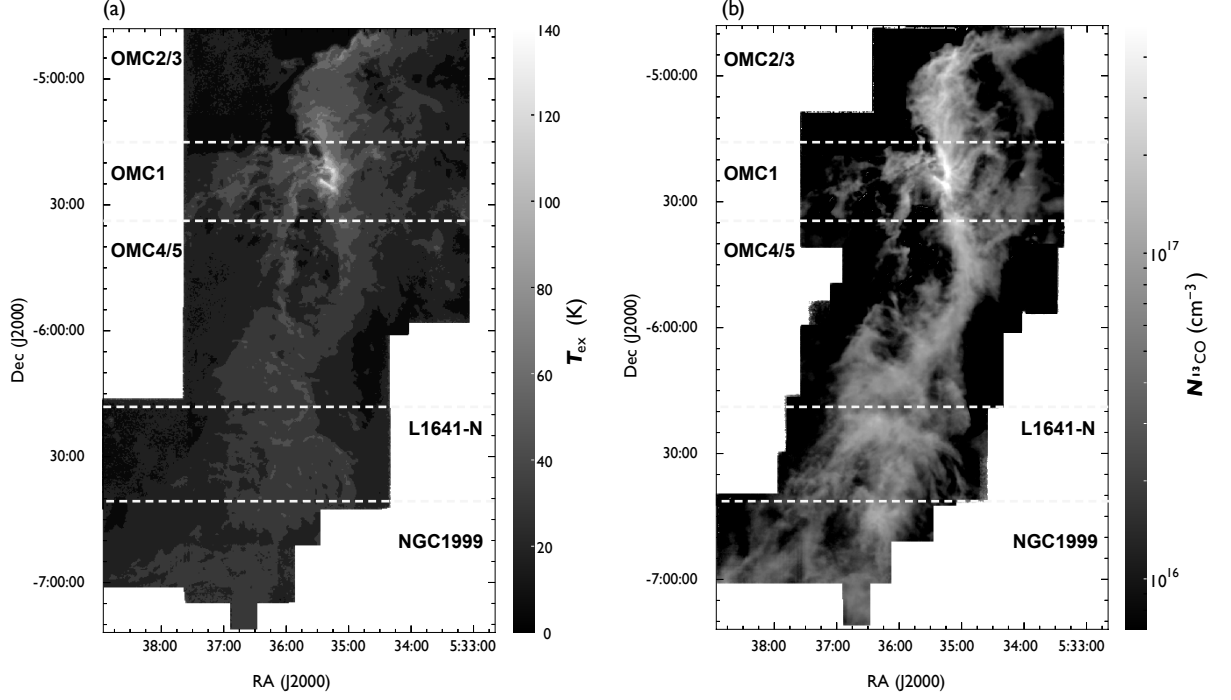


Figure 4.23. Maps of the excitation temperature from ^{12}CO ($J = 1-0$) peak intensity (a) and the column density of ^{13}CO ($J = 1-0$) (b).

Table 4.7: Cloud parameters of Orion A

subregion	M_{cl} $10^3 M_{\odot}$	$^{13}\text{CO } \sigma_v$ km s^{-1}	$\mathcal{E}_{\text{turb}}$ 10^{46} erg
OMC 2/3	5.8	0.9	13.0
OMC 4/5	9.6	1.3	31.2
L1641-N	5.0	1.5	21.0
NGC 1999	4.5	1.2	13.6
OMC 1	7.1	1.7	28.2
Total	32.0		107.0

Chapter 5

Discussion

Using the physical parameters of the outflows estimated in Chapter 4, I discuss the two issues in this Chapter. In section 5.1, I investigate the relationship between the physical properties of the outflows and of the driving sources. In section 5.2, I discuss the outflows and other protostellar feedback into the parent molecular cloud. It should be noted that all the outflow properties in the following section including that of quoted previous studies are corrected for the inclination angle to be 57.3° , which is the average value for the case of random inclination angles.

5.1 Outflow statistics

In Orion A and B, many surveys have been conducted to identify the YSOs and to clarify their physical properties. Furlan et al. (2016, hereafter F2016) compiled the SEDs for the protostars detected by M2012 based on wide-range wavelength observations from $1.2 \mu\text{m}$ to $870 \mu\text{m}$ using the Photodetecting Array Camera and Spectrometer (PACS) on the *Herschel Space Observatory* and the Atacama Pathfinder Experiment (APEX) in addition to 2MASS and Spitzer used in M2012. The SEDs provided them with the bolometric luminosity L_{bol} , bolometric temperature T_{bol} , and the spectral index between $4.5 \mu\text{m}$ and $24 \mu\text{m}$ $\alpha_{4.5-24}$. They separate the targets into four YSO categories based on $\alpha_{4.5-24}$ and/or T_{bol} : Class 0 protostars have $\alpha_{4.5-24} > 0.3$ and $T_{\text{bol}} < 70$ K, Class I protostars have $\alpha_{4.5-24} > 0.3$ and $T_{\text{bol}} > 70$ K, Flat-Spectrum (FS) sources have $-0.3 < \alpha_{4.5-24} < 0.3$, and Class II PMS stars have $\alpha_{4.5-24} < -0.3$. Out of our 178 outflow driving sources (see section 3.1 and Table 4.1), 133 are re-categorized by F2016, of which 34 are Class 0, 46 are Class I, 43 are FS, 2 are Class II, and 8 are the others (Likely extragalactic contamination or Unknown nature). All of the YSOs whose outflows are detected in this survey are Class 0, Class I, and FS, and I mention below these three protostar categories and outflows.

5.1.1 Protostar classification and detection rate of outflows

I investigate the relationship between the detection rate of the outflows and YSO classifications of the outflow driving sources. Table 5.1 and Figure 5.1 show the detection rates for each protostar

category. The detection rates are decreasing along with the evolution of protostars from Class 0 to FS. This result strongly suggests that the outflows appear more frequently in the earlier stages of star formation. This result is consistent with the simulation of Machida et al. (2007 and 2008) that the outflows are driven by the first core which appear in the first phase of the gravitational contraction.

In this survey, total 29% of Class 0 and Class I protostars are accompanied with outflows. This value is not as high as those of the previous outflow surveys toward the low-mass star forming regions (e.g., Arce et al. 2011 and Li et al 2015) and high-mass star forming regions (Zhang et al. 2001). This is probably due to that a part of the Orion A, even other than the center of the OMC 1 region, shows the high-velocity ^{12}CO ($J = 1-0$) emissions that are difficult to distinguish from molecular outflows. Also, there may be multiple outflows that cannot be identified at the low spatial resolution. It should be necessary to follow up observations using interferometry with high-angular resolution or observations with high-excitation lines of ^{12}CO and isotopologues. On the other hand, few outflows could not be detected due to insufficient data sensitivity and they had little effect on the detection rate (details are described in Appendix B).

Table 5.1: Detection rate of each protostar category

Category	Number of candidate	Number of candidate	Detection rate
Class 0	34	16	47%
Class I	46	13	28%
FS	43	7	16%
Total	123	36	29%

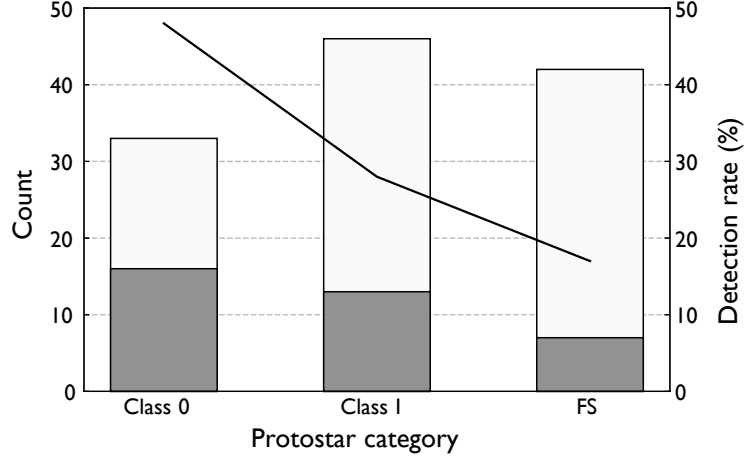


Figure 5.1. Histogram of the number of outflow driving source candidates (white) and detected outflows (gray) overlaid on the detection rate of the outflows (solid line) in each protostar category. Left and right vertical axis represent the number of protostars and the detection rate of the outflows, respectively.

I also investigate a relationship between other parameters of the protostars and the detection rates of the outflows. In Figure 5.2, left and right panels show the histograms of the spectral index between $4.5 \mu\text{m}$ and $24 \mu\text{m}$ $\alpha_{4.5-24}$, and the bolometric temperature T_{bol} , respectively. In both panels, white and gray bins represent all the protostars and protostars with the outflows, respectively, and solid lines show the detection rate in each bin. In the left panel, the detection rate decreases as $\alpha_{4.5-24}$ decreases. on the other hand, In the right panel, on the other hand, the detection rate decreases as T_{bol} increases. Since both $\alpha_{4.5-24}$ and T_{bol} are considered to shift from left to right in the graph as a protostar evolves, the both panels in Figure 5.2 show that more outflows present around younger phases of protostars, as shown in Figure 5.1.

Figure 5.3 shows the histogram of the bolometric luminosities. The white and gray bins represent all the protostars and protostars with the outflows, respectively, and solid lines show the detection rate in each bin. It can be seen that the detection rate increases rapidly as L_{bol} increases. According to F2016, the distribution of L_{bol} does not depend on the protostar evolution. Further more, as shown in Section 5.1.2, the scale of the outflows such as mass and momentum are larger as L_{bol} is larger. Taking this into account, Figure 5.3 shows that the outflow with larger scale is easier to detect. Conversely, it suggests the possibility of not detecting a low-mass outflow with a smaller L_{bol} .

5.1.2 Protostar luminosity and outflow property

The outflow mass is the fundamental parameter, and the relationship between the outflow mass and luminosity of the driving source is essential to investigate the general signature of the outflows. Figure 5.4 plots the outflow mass versus bolometric luminosity of the driving sources in log-log

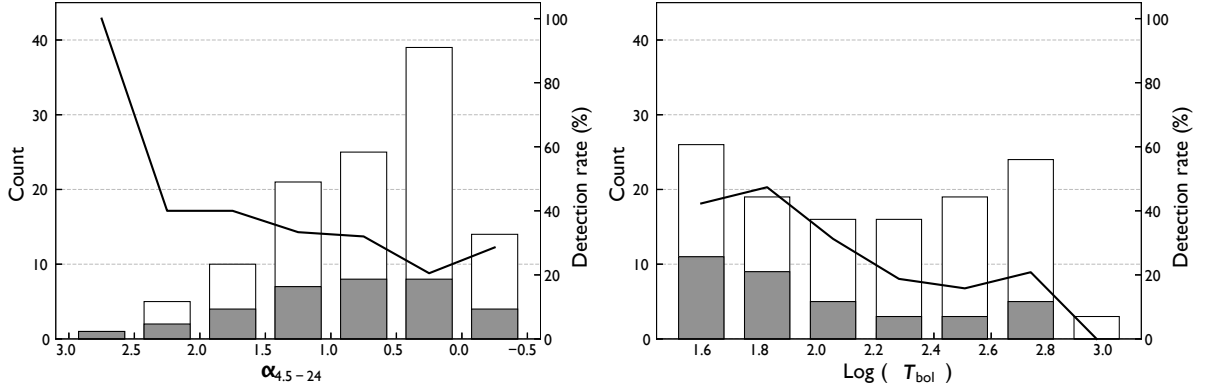


Figure 5.2. Histogram of the spectral index α (left) and bolometric temperature (right) for all the protostars (white) and the protostar driving the outflows (gray) overlaid on the detection rate of the outflows (solid line).

scale. The black, gray, and white circles represent our survey, previous survey results from Zhang et al. (2005) as high-mass star forming regions (HMSFR) and Li et al. (2015) as low-mass star forming region of Taurus, respectively. Our outflow sample in Orion A is located between these two regions. The outflow mass increases with the luminosity of driving source as a power-law. A least square fit in log-log scale shown in Figure 5.4 is $\log M_{\text{flow}} = 0.47 \times \log L_{\text{bol}} - 0.92$ with the correlation coefficient $r = 0.86$.

This power-law correlation is also seen between other outflow properties and luminosities, and some examples are shown below. Figures 5.5 shows the mass outflow rate and outflow force versus the bolometric luminosity of the driving sources. The least square fits in log-log scale shown in the dashed lines in left and right panels are $\log \dot{M}_{\text{flow}} = 0.49 \times \log L_{\text{bol}} - 5.58$ with the correlation coefficient $r = 0.83$ and $\log \dot{P}_{\text{flow}} = 0.46 \times \log L_{\text{bol}} - 4.54$ with the correlation coefficient $r = 0.69$, respectively. This nature of the outflows has been reported by many studies (e.g., Bally and Lada 1983, Wu et al. 2004, and Takahashi et al. 2008), giving us the essential clue to the origin of the outflows. The relationships that the mass, momentum and energy of the outflows depend on the luminosity of their driving sources suggest that the power of the outflows actually originate from their central YSOs and the driving mechanism of all the outflows is similar.

5.1.3 Protostar evolution and outflow property

This section examine whether the physical parameters of the outflows depend on the evolution of the driving protostars. It is important to consider the evolutionary effect of the outflow parameters. Figure 5.6 plots the outflow mass and force versus the bolometric luminosity for Class 0, Class I, and flat spectrum protostars in our sample. The dashed and solid lines show the results of the fittings for each protostar category. No significant difference can be found in distribution of outflow parameters among these three classes. The results of the fittings show that the outflow mass and

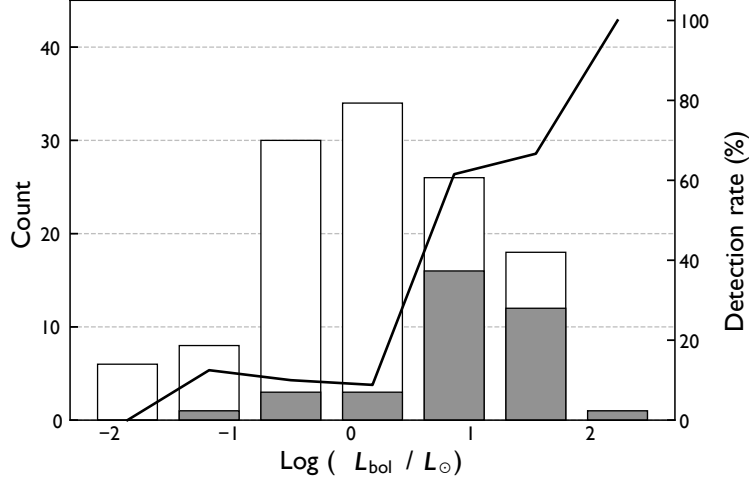


Figure 5.3. Histogram of the bolometric luminosity for all the protostars (white) and the protostar driving the outflows (gray) overlaid on the detection rate of the outflows (solid line).

force of Class 0 protostars are only 50% higher than these of the Class I and FS protostars of similar luminosities, suggesting that the power of the outflows does not depend on the evolution of the protostars. Takahashi et al. (2008) also investigated whether any trend between Class 0 and I was obtained in the OMC 2/3 region, but was unable to identify because of the small sample. I increase the number of sample sources to 3.6 times that of Takahashi et al. (2008) and confirm no difference of outflow parameters between early and later phase of protostars.

I also confirm that there is no or weak correlation between physical parameters of the outflows and protostar evolution using another parameters of the protostars. Figure 5.7 shows the distributions of M_{flow} vs. α (left) and M_{flow} vs. T_{bol} (right). Figure 5.8 shows the distributions of $\dot{P}_{\text{flow}}$ vs. α (left) and $\dot{P}_{\text{flow}}$ vs. T_{bol} (right). All four panels in Figures 5.7 and 5.8 represent no significant differences between Class 0 and I + FS protostars.

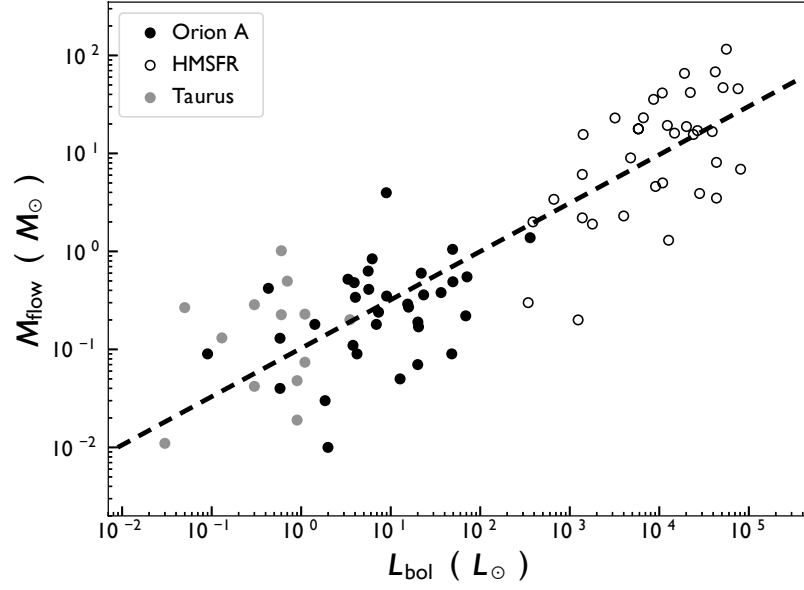


Figure 5.4. The CO outflow mass plotted as a function of the luminosity of the driving sources. The black, white, and gray circles represent the result of this survey, high-mass star forming regions conducted by Zhnag et al. (2005), and Taurus conducted by Li et al. (2015). Dashed line and equation show the result of a least square liner fitting in log-log scale.

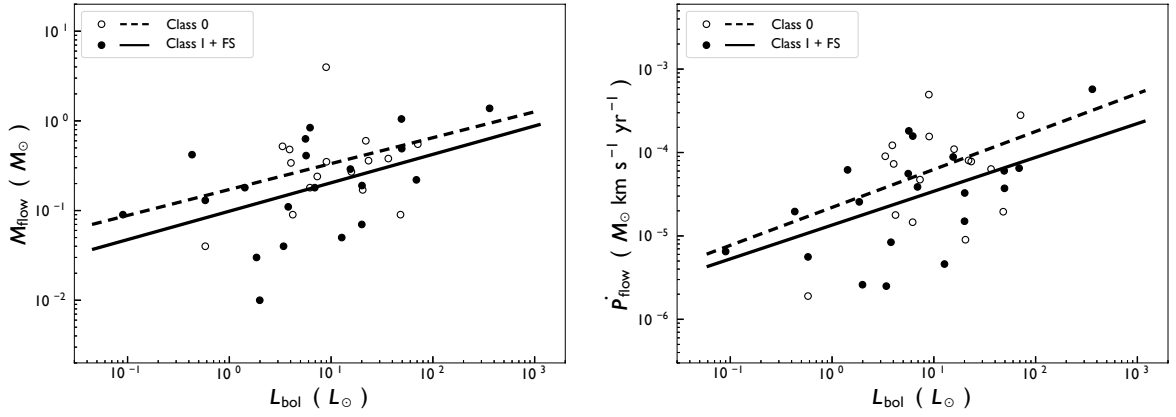


Figure 5.6. Outflow mass (left) and force (right) in OrionA plotted as a function of the luminosity of driving sources. In both panels, the open and filled circles represent the protostar classification of Class 0 and Class I + FS, respectively, and the dashed and solid lines show the results of fittings in each category.

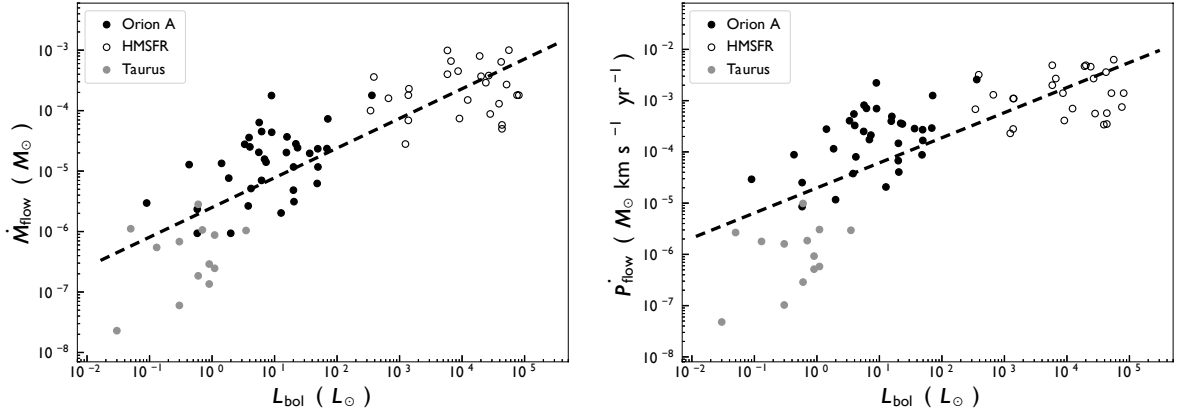


Figure 5.5. The mass outflow rate (left) and force (right) plotted as a function of the luminosity of the driving sources. The symbols are the same as in Figure 5.4. Dashed lines and equations show the result of a least square linear fitting in log-log scale.

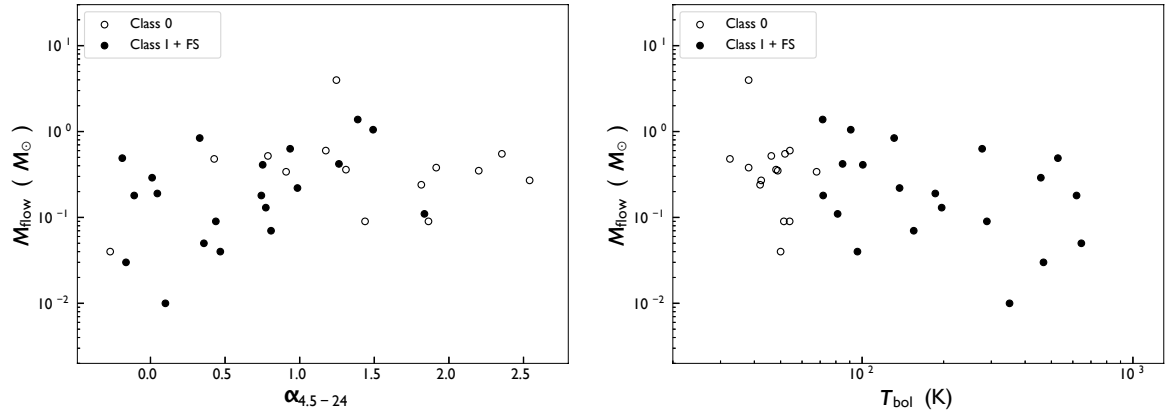


Figure 5.7. The outflow mass plotted as a function of the spectral index (left) and bolometric temperature (right). The symbols are the same as in Figure 5.6.

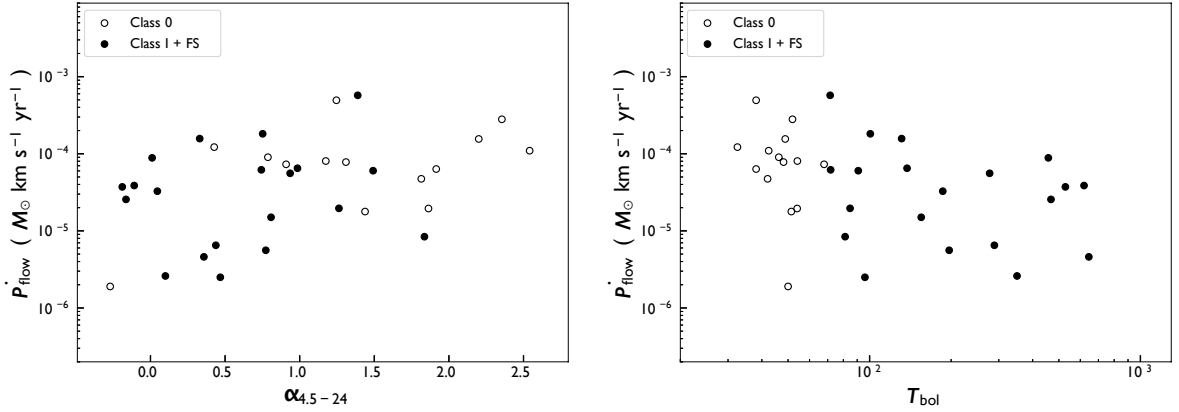


Figure 5.8. The outflow force plotted as a function of the spectral index (left) and bolometric temperature (right). The symbols are the same as in Figure 5.6.

5.2 Stellar feedback in Orion A

With our sample of the outflows of Orion A, I estimate the dynamical effect of the molecular outflow feedback and other stellar feedback on the molecular clouds. More specifically, I investigate whether the outflows and shells have sufficient energy and momentum to drive the parent cloud turbulence.

5.2.1 Protostellar molecular outflows

Table 5.2 compares the kinetic energy of the cloud turbulence with the energy ejected by the outflows in Orion A, Taurus, and Perseus. The total energy of the outflows is $1.6 \times 10^2 M_{\odot} \text{ km s}^{-1}$ and is only $\sim 1.9\%$ of the turbulent energy of the cloud, excluding OMC 1. This is similar to the situation in Taurus reported by Li et al. (2015). In the Taurus molecular clouds, the energy of all outflows detected by Li et al. (2015) is $\sim 1.2\%$ of the turbulent energy of the cloud.

I also compare the momentum of the outflows with that of the cloud turbulence, $\mathcal{P}_{\text{turb}} = (2M_{\text{cl}}\mathcal{E}_{\text{turb}})^{1/2}$, and the results are listed in Table 5.2. The total momentum of the outflows is $1.6 \times 10^2 M_{\odot} \text{ km s}^{-1}$ and is $\sim 0.4\%$ of the cloud turbulence.

5.2.2 Expanding molecular shells

Besides molecular outflows, molecular shells may be another driver of turbulence in parent molecular clouds (Churchwell et al. 2006). Molecular shells show expanding spherical structures of molecular gas and are driven by spherical stellar winds from PMS stars (e.g., see Arce et al. 2011 and Offner & Arce 2015). Molecular shells have been found in several molecular clouds such as Perseus (Arce et al. 2011) and Taurus (Li et al. 2015).

In Orion A, Feddersen et al. (2018) identified 42 molecular shells (see Figure 5.9) and estimated that the total energy and momentum of the shells, excluding OMC 1, were 16.5×10^{46} erg and $6.7 \times 10^3 M_\odot \text{ km s}^{-1}$, respectively. These values are equivalent to 21% and 15% of the turbulent energy and momentum. Similar trends are seen in Taurus and Perseus, with 28% and 48% for the energy, and 16% and 20% for the momentum, respectively. As shown in Table 5.2, the energy and momentum of the shells are about an order of magnitude larger than that of the outflows in these molecular clouds, but only less than a few percent of the molecular cloud turbulence.

Table 5.2: Energy and momentum of outflows, shells and cloud turbulence

Region	M_{cl} $10^3 M_\odot$	$\mathcal{E}_{\text{turb}}$	$\mathcal{E}_{\text{flow}}$	$\mathcal{E}_{\text{shell}}$	$\mathcal{P}_{\text{turb}}$	$\mathcal{P}_{\text{flow}}$	$\mathcal{P}_{\text{shell}}$	Reference
		10^{46} erg			$10^3 M_\odot \text{ km s}^{-1}$			
Orion A ^{*1}	25	79	1.5	16.5	44	0.16	6.7	1, 2
Taurus	15	32	0.4	9.2	22	0.08	3.8	3
Perseus	7	16	2.0	7.6	11	0.52	2.2	4, 5

¹ Excluding OMC 1.

Reference—1 This work; 2 Feddersen et al. (2018); 3 Li et al. (2015); 4 Arce et al. (2010); 5 Arce et al. (2011).

5.2.3 Protostellar Feedback vs. cloud turbulent

I also investigate whether the outflows and shells have sufficient energy and momentum to maintain the turbulence in the cloud. I estimate the turbulent dissipation rate as

$$\dot{\mathcal{E}}_{\text{turb}} = 0.5 \frac{\mathcal{E}_{\text{turb}}}{t_{\text{diss}}}, \quad (5.1)$$

where the factor of 0.5 is derived from Mac Low (equation 8; 1999), and t_{diss} is the turbulent dissipation time which is estimated by the following method. With the cloud size R_{cl} , the dissipation time of turbulence is given by

$$t_{\text{diss}} = \frac{R_{\text{cl}}}{\bar{\sigma}_v}, \quad (5.2)$$

where $\bar{\sigma}_v$ is the ^{13}CO averaged one-dimensional velocity dispersion at each subregion (McKee & Ostriker 2007). For R_{cl} , the half thicknesses of the filaments are estimated to be 1.0, 1.3, 1.2, 1.4, and 1.4 pc for OMC 2/3, OMC 1, OMC 4/5, L1641-N, and NGC 1999 subregions, respectively, from the 5σ contour in the integrated intensity map of the ^{12}CO . Accordingly, equation 5.2 gives us $t_{\text{diss}} = 1.1, 0.7, 0.9, 0.8$, and 1.1×10^6 yr, respectively, and the turbulent dissipation rates are then estimated to be $\dot{\mathcal{E}}_{\text{turb}} = 1.9, 6.4, 5.5, 4.2$, and 2.0×10^{33} erg s $^{-1}$, respectively. Table 5.3 compares the dissipation rate of the cloud turbulence to the luminosity of the outflows in each subregion. Excluding OMC 1, the total luminosity of the outflows is approximately 235% of the total dissipation rate of the cloud turbulence. The momentum dissipation rate of the cloud is described as

$$\dot{\mathcal{P}}_{\text{turb}} = 0.6 \frac{\mathcal{P}_{\text{turb}}}{t_{\text{diss}}}, \quad (5.3)$$

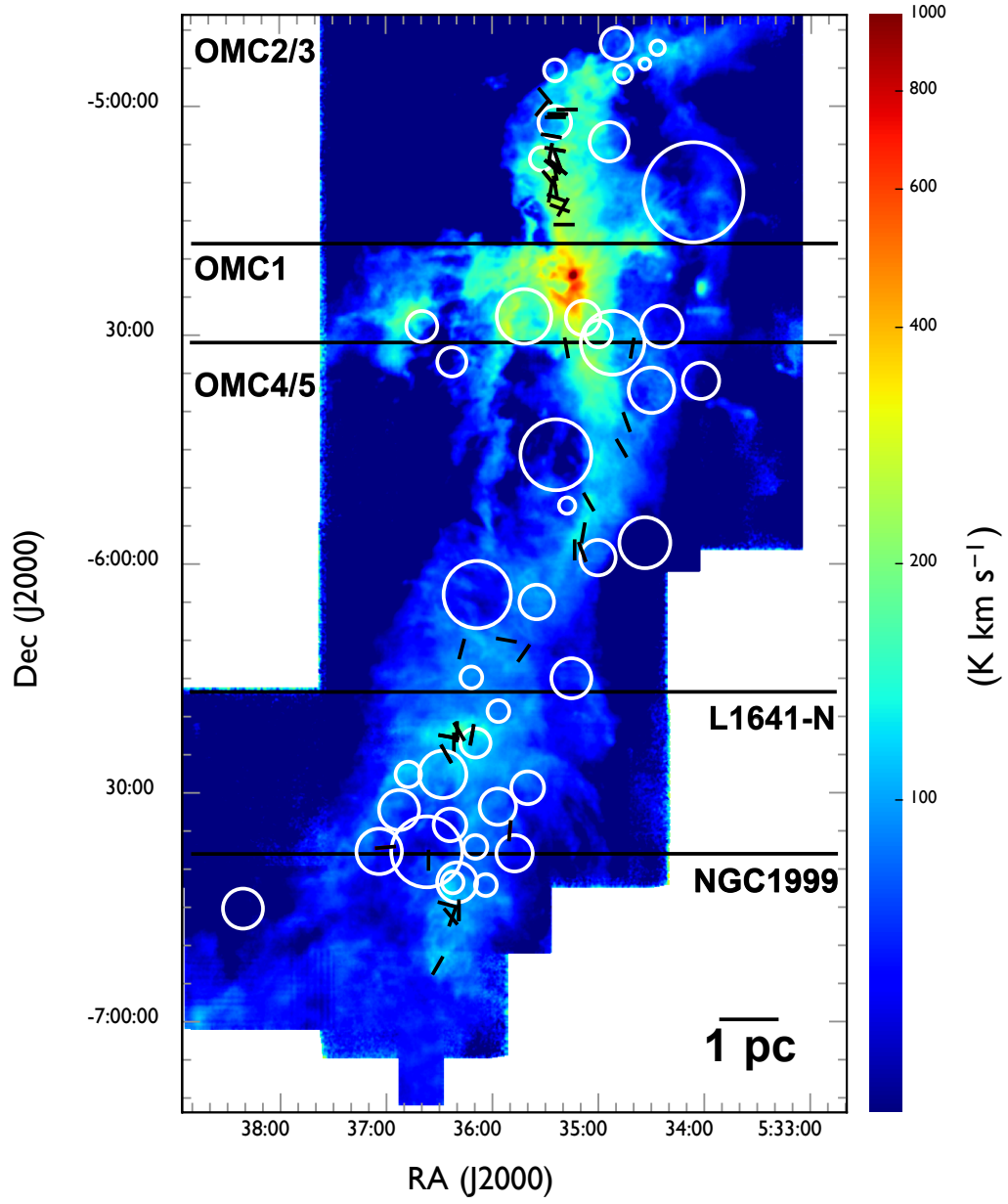


Figure 5.9. Outflows and shells overlaid on the ^{12}CO ($J = 1-0$) total integrated intensity map which is the same as in Figure 3. The Black lines show the location and orientation of outflows and the white circles show the location and radius of shells from Feddersen et al. (2018).

where the factor of 0.6 is derived from Mac Low (equation 8; 1999). According to this formula, I estimated the momentum dissipation rate of each subregion and compared them with each outflow force. The results are listed in Table 5.3. Excluding OMC 1, the total outflow force is approximately 36% of the momentum dissipation rate of the cloud turbulence.

Note that the Orion cloud complex is assumed to be located on the edge of a large-scale expanding bubble called “the Orion-Eridanus bubble” (e.g., see Wilson et al. 2005 and Pon et al. 2014), and its contributions to the cloud kinematics, including turbulence, may also have to be considered. However, in this thesis, I omit these large-scale effects, and I simply estimate t_{diss} from the cloud crossing time using the speed of sound.

According to Feddersen et al. (2018), the total energy and force of the shells, excluding OMC 1, are $36.7 \times 10^{33} \text{ erg s}^{-1}$ and $36.3 \times 10^{-3} M_{\odot} \text{ km s}^{-1} \text{ yr}^{-1}$, respectively. Those values are comparable with the energy and force of the outflows.

The total luminosity and force of the outflows and shells are respectively 5.1 and 1.6 times larger than those of the cloud turbulence. This means that 20% and 60% of the energy and momentum, respectively, must be converted into cloud turbulence to compensate for their dissipations. These values seem high, but the conversion efficiencies are highly uncertain, and whether the outflows and shells can drive the molecular cloud turbulence still remains an open question. If the conversion efficiencies are smaller than these values, the outflows and shells in Orion A cannot maintain the cloud turbulence, and other agents such as a large-scale HI bubble, may be responsible for maintaining the turbulence. However even in such a case, the outflows may play an important role in dispersing dense cores at smaller scales. As seen in Figure 5, the outflows are preferentially distributed in the ridge of the molecular clouds, suggesting that the outflows including high velocity jets may have a significant impact on the turbulent gas motions in the densest but small portion of molecular clouds.

Table 5.3: Energy, momentum, and ejection rate of outflows, shells and cloud turbulence

Subregion	$\dot{\mathcal{E}}_{\text{turb}}$	$\dot{\mathcal{E}}_{\text{flow}}^{*1}$	$\dot{\mathcal{E}}_{\text{shell}}^{*2}$	$\frac{\dot{\mathcal{E}}_{\text{flow}} + \dot{\mathcal{E}}_{\text{shell}}}{\dot{\mathcal{E}}_{\text{turb}}}$	$\dot{\mathcal{P}}_{\text{turb}}$	$\dot{\mathcal{P}}_{\text{flow}}^{*1}$	$\dot{\mathcal{P}}_{\text{shell}}^{*2}$	$\frac{\dot{\mathcal{P}}_{\text{flow}} + \dot{\mathcal{P}}_{\text{shell}}}{\dot{\mathcal{P}}_{\text{turb}}}$
	$10^{33} \text{ erg s}^{-1}$				$10^{-3} M_{\odot} \text{ km s}^{-1} \text{ yr}^{-1}$			
OMC 2/3	1.9	17.4	4.0	11.3	4.7	6.1	6.0	2.6
OMC 4/5	5.5	4.3	26.8	5.7	11.6	1.2	22.1	2.0
L1641-N	4.2	5.0	3.5	2.0	7.7	1.4	4.5	0.8
NGC 1999	2.0	5.3	2.6	4.0	4.3	1.5	3.7	1.2
Subtotal	13.6	32.0	36.9	5.1	28.3	10.2	36.3	1.6
OMC 1	6.4	4000 ^{*3}	7.2	626	12.2	566 ^{*3}	8.6	55

¹ Feddersen et al. (2018).

² These values are from Snell et al. (1984) ^{12}CO ($J = 1-0$), Kwan & Scoville (1976) ^{12}CO ($J = 1-0$), and Zapata et al. (2005) ^{12}CO ($J = 2-1$). In OMC 1, the massive velocity outflows ($\sim 100 \text{ km s}^{-1}$) in Orion KL account for a large fraction of their energy and momentum. The outflows in OMC 1 have sufficient energy and momentum to maintain cloud turbulence in OMC 1.

Chapter 6

Summary

I conducted mapping observations of the main 2 deg² regions of Orion A by ¹²CO ($J = 1-0$) and ¹³CO ($J = 1-0$) using the Nobeyama 45-m telescope to investigate the outflow properties and the outflow feedback into the parent molecular clouds. The main results of this study are as follows:

1. Based on a systematic procedure, I identified 44 ¹²CO outflows associated with the *Spitzer* YSOs in Orion A, and of these, 17 are new detections. Notably, I identified 11 outflows in the OMC 4/5 region which no outflows were previously detected in.
2. The detection rate of outflows in each YSO classification is clearly reduced with evolution of the YSOs and this result suggest that the outflows appear more frequently in the early stages of star formation.
3. The ratio of brightness temperature of the ¹²CO to ¹³CO lines suggests that the optical depth of the ¹²CO is ~ 5 in the detected outflows.
4. I estimated the kinematic properties of the detected outflows. The momentum and energy of each outflow range from $4.0 \times 10^{-2} M_{\odot} \text{ km s}^{-1}$ to $1.7 \times 10 M_{\odot} \text{ km s}^{-1}$ and $1.9 \times 10^{42} \text{ erg}$ to $7.8 \times 10^{44} \text{ erg}$, respectively. The total momentum and energy of the outflows are $1.6 \times 10^2 M_{\odot} \text{ km s}^{-1}$ and $1.5 \times 10^{46} \text{ erg}$, respectively.
5. The physical parameters of the outflows are increases with the luminosities of their driving sources as a power-law and no significant differences are obtained between the outflow parameters and protostar evolution.
6. I compared the force and luminosity of the outflows and shells with the momentum and energy dissipation rate of the cloud turbulence. The total force and luminosity of the outflows are 36% and 235% of those of the cloud turbulence. The total force and luminosity of the shells in Orion A are estimated to be 128% and 271% of those of the cloud turbulence. The total force and luminosity of the outflows and shells in Orion A are 1.6 and 5.1 times larger than the momentum and energy dissipation rates of the cloud turbulence. The cloud turbulence

cannot be sustained by the outflows and shells unless the efficiencies of energy and momentum conversion are as high as 20% and 60%, respectively.

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Appendix A

Previously known outflows

In the Appendix, I show the integrated images and P–V diagrams of the known outflows.

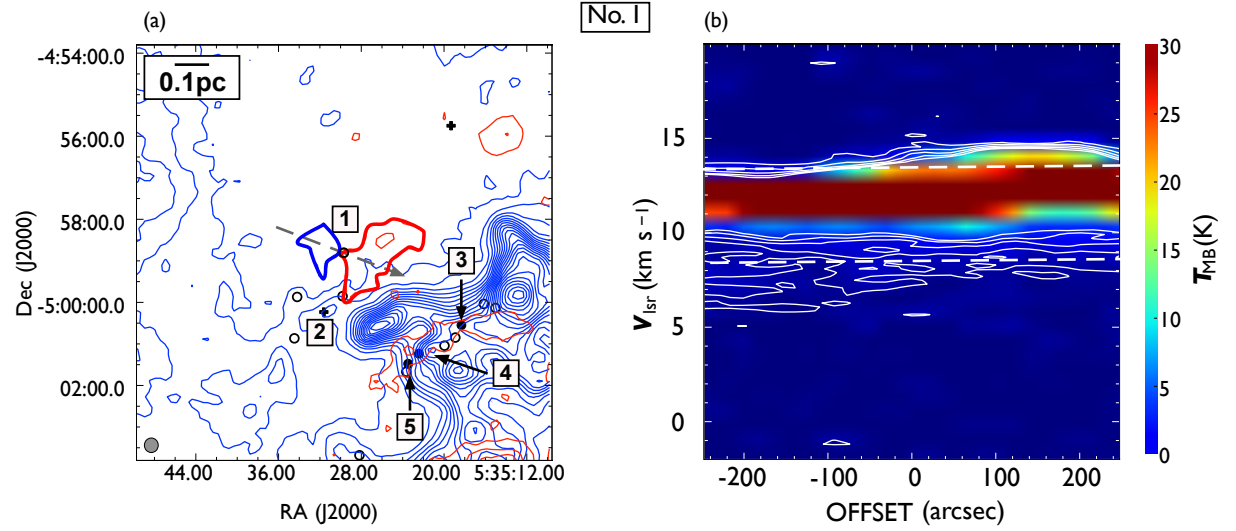


Figure A.1. The same as in Figure 4.3 but for outflow No. 1. In panel (a), the blue- and red-shifted integrated intensity velocity ranges are 0.0 km s^{-1} to 8.2 km s^{-1} and 13.2 km s^{-1} to 20.2 km s^{-1} , respectively.

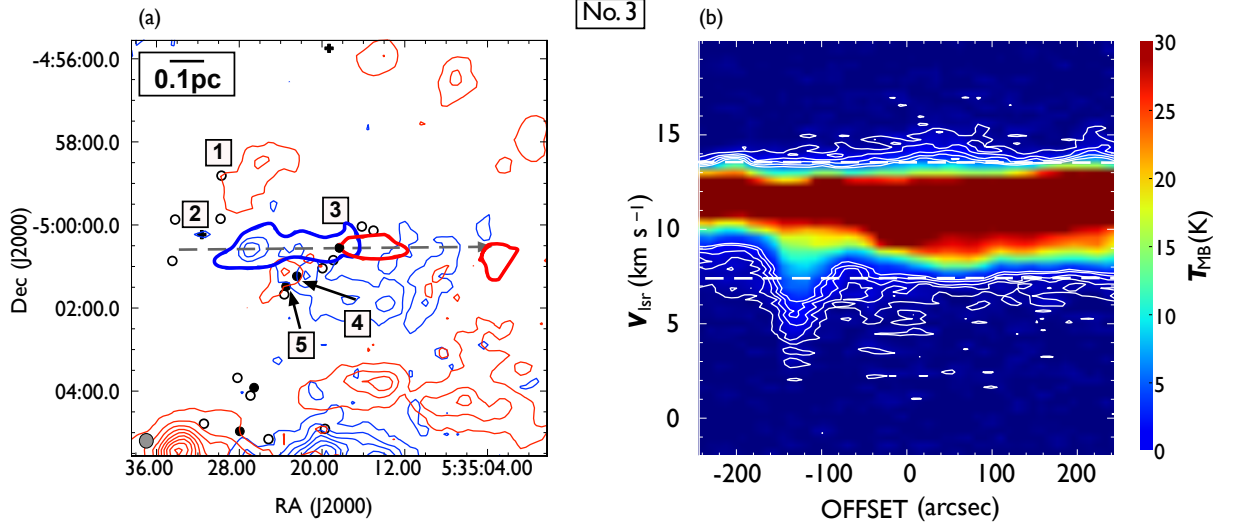


Figure A.2. The same as in Figure 4.3 but for outflow No. 3. In panel (a), the blue- and red-shifted integrated intensity velocity ranges are 0.0 km s^{-1} to 7.4 km s^{-1} and 13.6 km s^{-1} to 20.2 km s^{-1} , respectively.

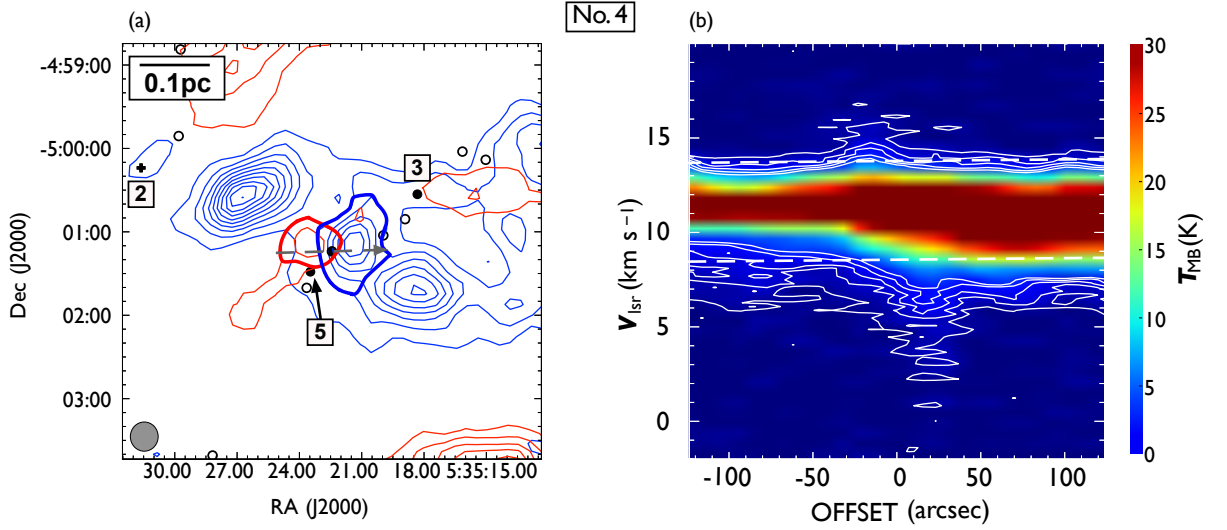


Figure A.3. The same as in Figure 4.3 but for outflow No. 4. In panel (a), the blue- and red-shifted integrated intensity velocity ranges are 0.0 km s^{-1} to 8.2 km s^{-1} and 13.8 km s^{-1} to 20.2 km s^{-1} , respectively.

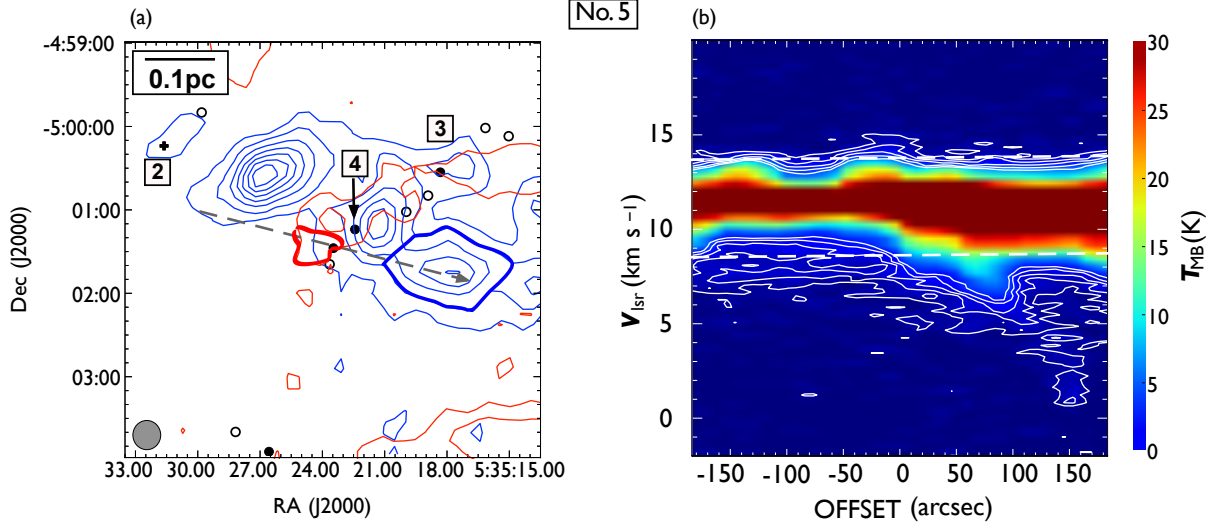


Figure A.4. The same as in Figure 4.3 but for outflow No. 5. In panel (a), the blue- and red-shifted integrated intensity velocity ranges are 0.0 km s^{-1} to 8.6 km s^{-1} and 14.0 km s^{-1} to 20.2 km s^{-1} , respectively.

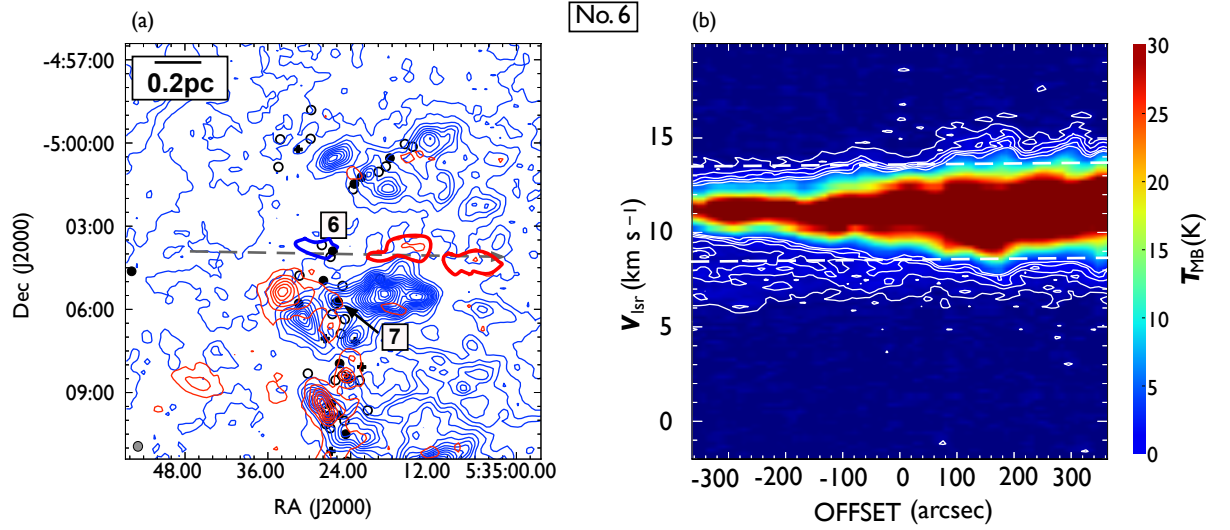


Figure A.5. The same as in Figure 4.3 but for outflow No. 6. In panel (a), the blue- and red-shifted integrated intensity velocity ranges are 0.0 km s^{-1} to 8.5 km s^{-1} and 13.5 km s^{-1} to 20.2 km s^{-1} , respectively.

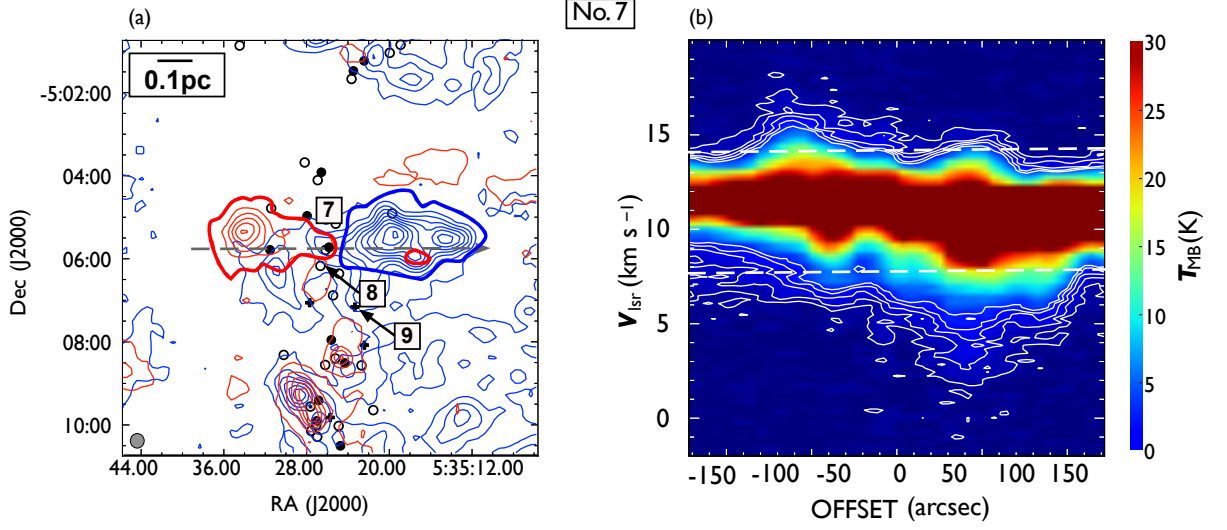


Figure A.6. The same as in Figure 4.3 but for outflow No. 7. In panel (a), the blue- and red-shifted integrated intensity velocity ranges are 0.0 km s^{-1} to 7.8 km s^{-1} and 14.1 km s^{-1} to 20.2 km s^{-1} , respectively.

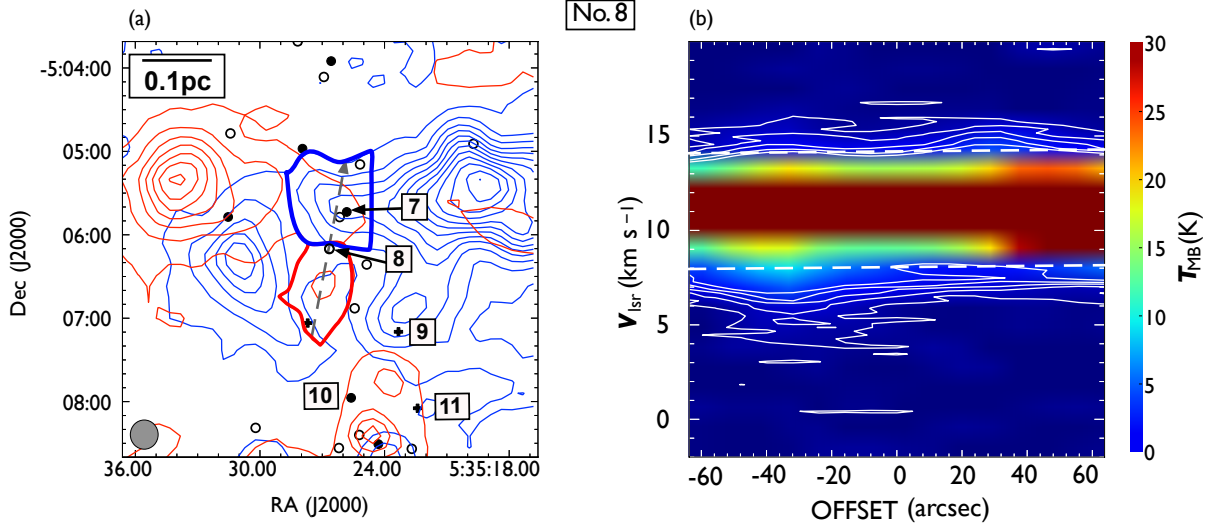


Figure A.7. The same as in Figure 4.3 but for outflow No. 8. In panel (a), the blue- and red-shifted integrated intensity velocity ranges are 0.0 km s^{-1} to 8.1 km s^{-1} and 14.1 km s^{-1} to 20.2 km s^{-1} , respectively.

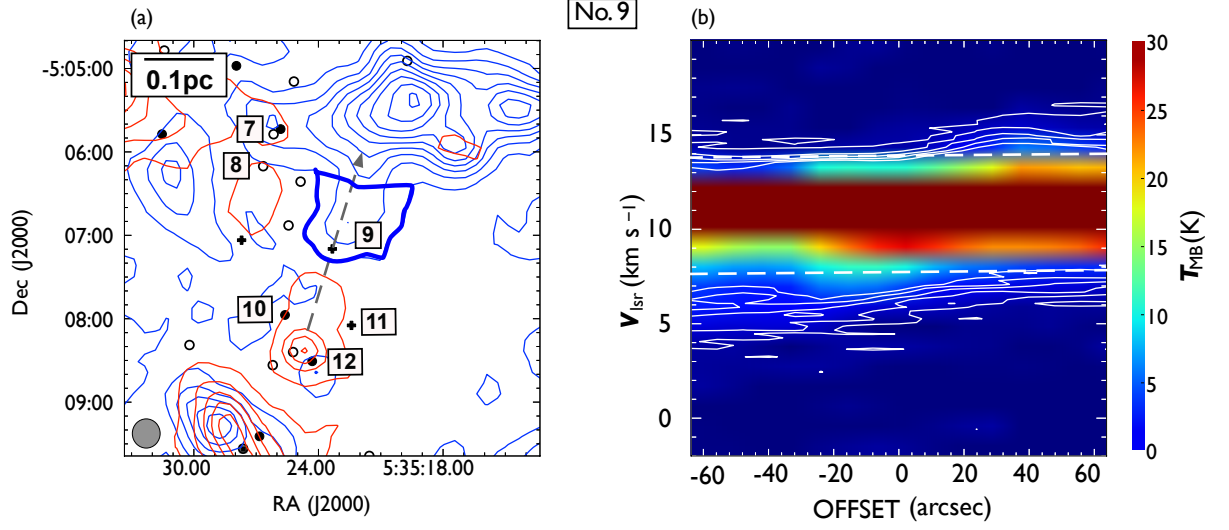


Figure A.8. The same as in Figure 4.3 but for outflow No. 9. In panel (a), the blue- and red-shifted integrated intensity velocity ranges are 0.0 km s^{-1} to 7.6 km s^{-1} and 13.8 km s^{-1} to 20.2 km s^{-1} , respectively.

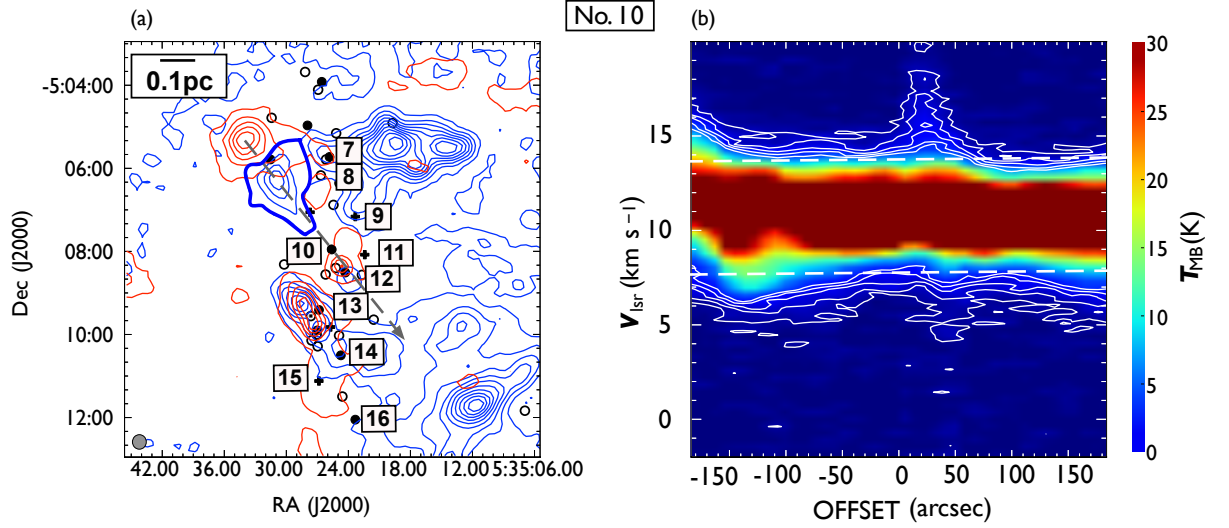


Figure A.9. The same as in Figure 4.3 but for outflow No. 10. In panel (a), the blue- and red-shifted integrated intensity velocity ranges are 0.0 km s^{-1} to 7.8 km s^{-1} and 13.7 km s^{-1} to 20.2 km s^{-1} , respectively.

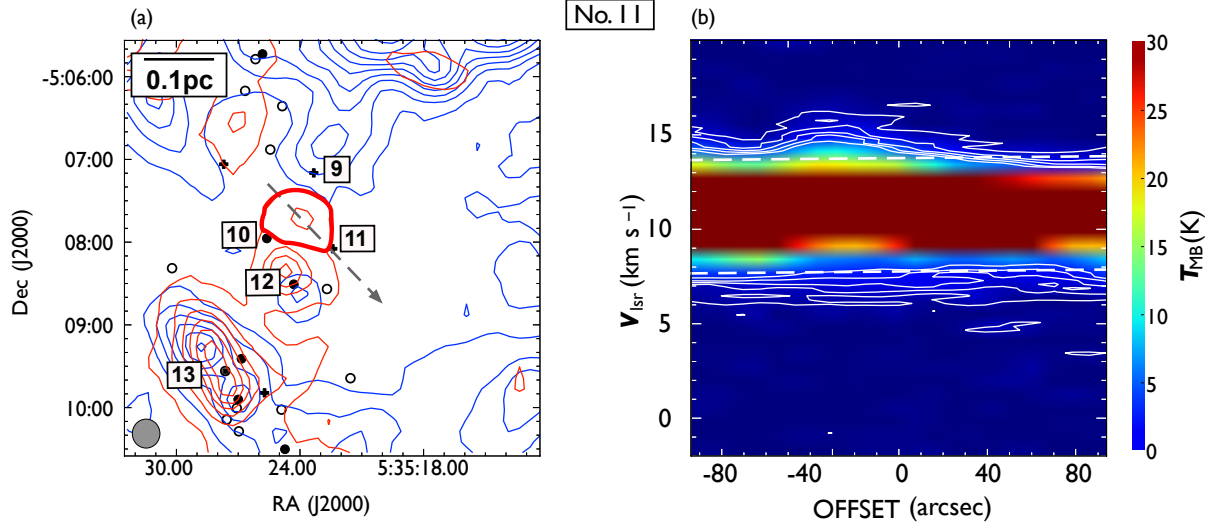


Figure A.10. The same as in Figure 4.3 but for outflow No. 11. In panel (a), the blue- and red-shifted integrated intensity velocity ranges are 0.0 km s^{-1} to 7.7 km s^{-1} and 13.8 km s^{-1} to 20.2 km s^{-1} , respectively.

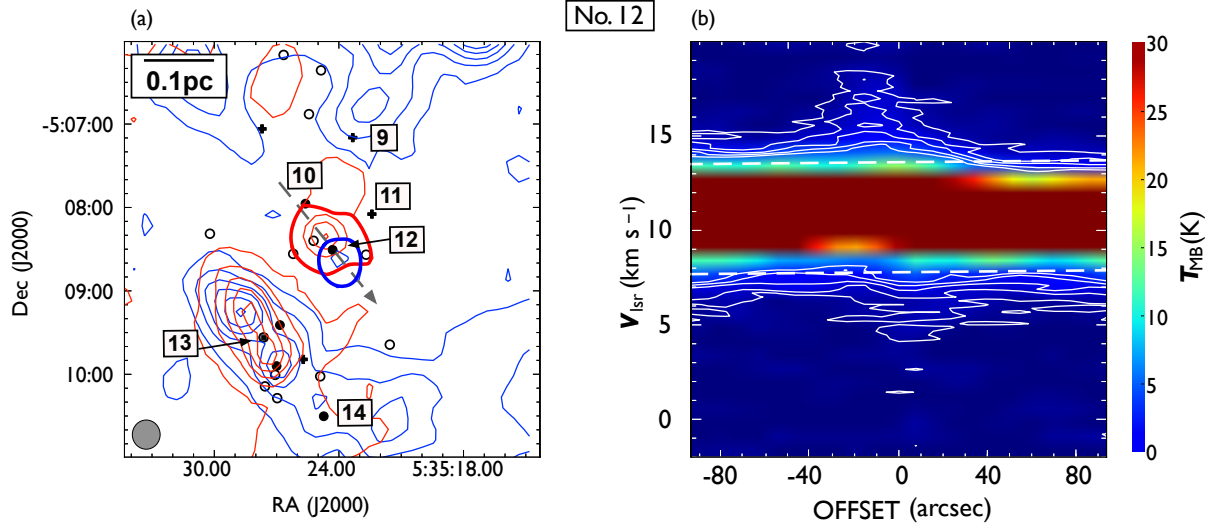


Figure A.11. The same as in Figure 4.3 but for outflow No. 12. In panel (a), the blue- and red-shifted integrated intensity velocity ranges are 0.0 km s^{-1} to 7.8 km s^{-1} and 13.5 km s^{-1} to 20.2 km s^{-1} , respectively.

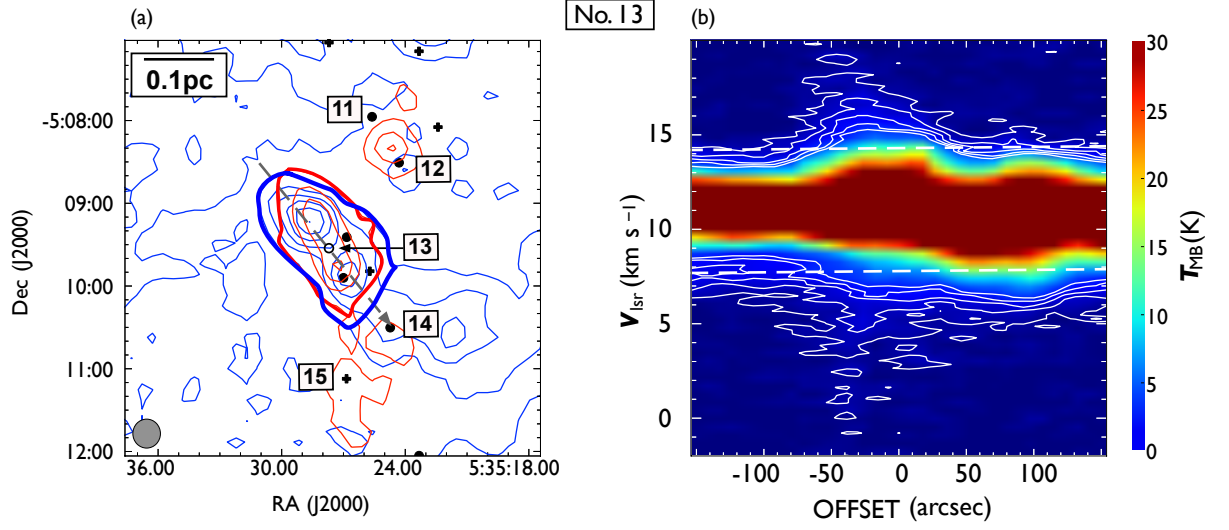


Figure A.12. The same as Figure 4.3, but for outflow No. 13. In panel (a), the blue- and red-shifted integrated intensity velocity ranges are 0.0 km s^{-1} to 7.7 km s^{-1} and 14.2 km s^{-1} to 20.2 km s^{-1} , respectively.

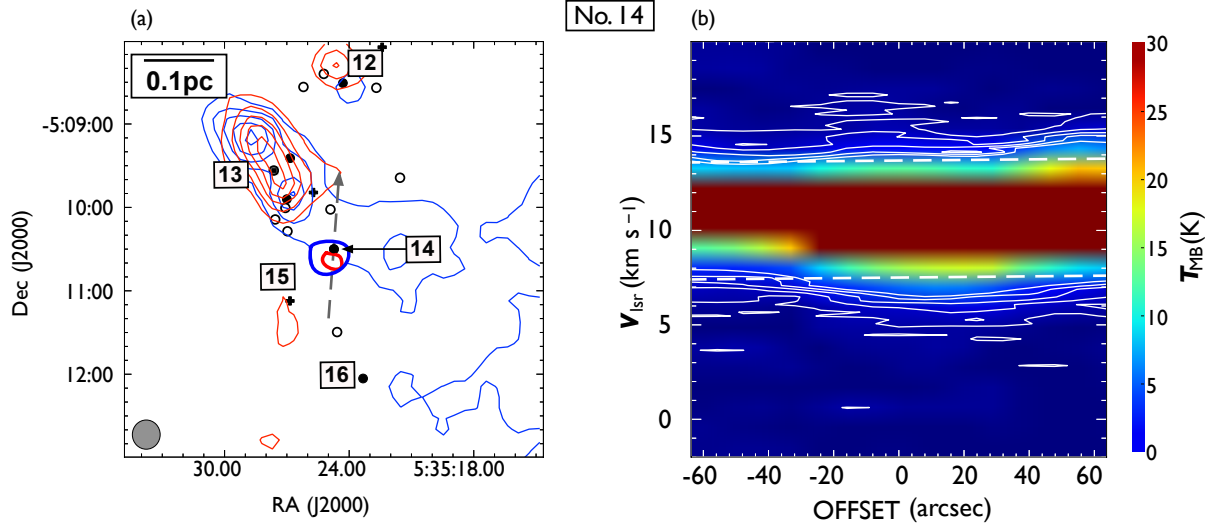


Figure A.13. The same as in Figure 4.3 but for outflow No. 14. In panel (a), the blue- and red-shifted integrated intensity velocity ranges are 0.0 km s^{-1} to 7.3 km s^{-1} and 13.6 km s^{-1} to 20.2 km s^{-1} , respectively.

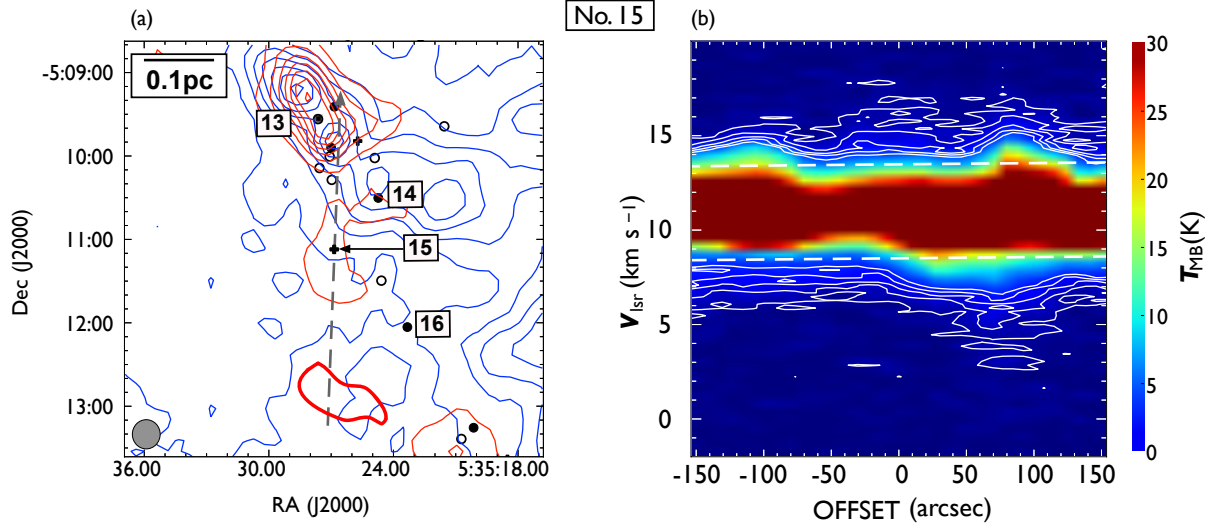


Figure A.14. The same as in Figure 4.3 but for outflow No. 15. In panel (a), the blue- and red-shifted integrated intensity velocity ranges are 0.0 km s^{-1} to 8.4 km s^{-1} and 13.3 km s^{-1} to 20.2 km s^{-1} , respectively. The red-shifted emission south of the central source is considered to be part of outflow No. 16.

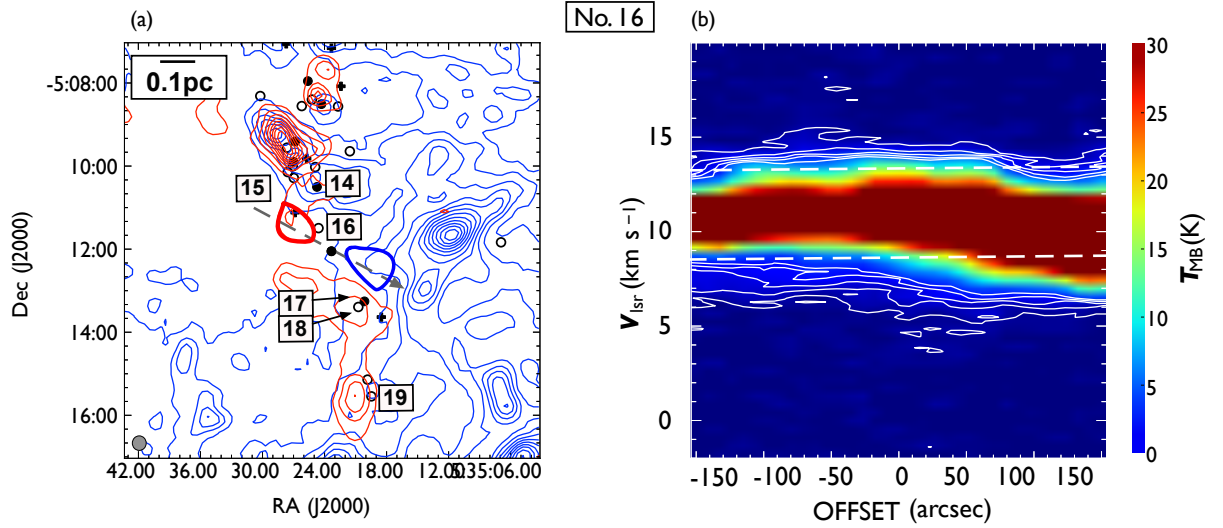


Figure A.15. The same as in Figure 4.3 but for outflow No. 16. In panel (a), the blue- and red-shifted integrated intensity velocity ranges are 0.0 km s^{-1} to 8.3 km s^{-1} and 13.2 km s^{-1} to 20.2 km s^{-1} , respectively.

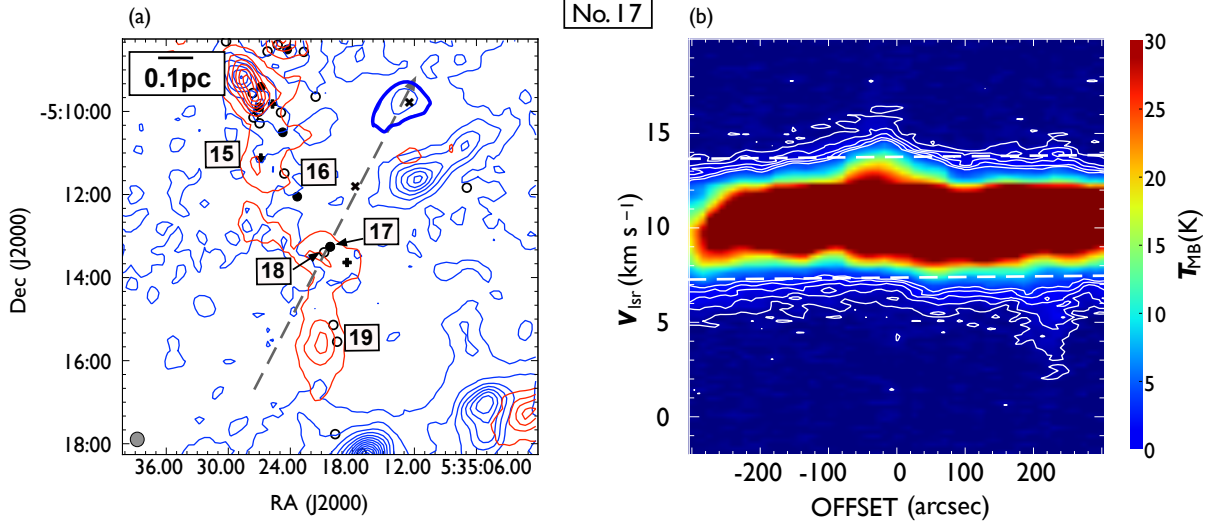


Figure A.16. The same as in Figure 4.3 but for outflow No. 17. In panel (a), the blue- and red-shifted integrated intensity velocity ranges are 0.0 km s^{-1} to 7.2 km s^{-1} and 13.6 km s^{-1} to 20.2 km s^{-1} , respectively. The black cross represents the location of the emission peak of H₂ jets detected by Davis et al. (2009). The position angle of outflows represented by the arrow in panel (a) and that of the H₂ jet described by Davis et al. (2009) are in agreement.

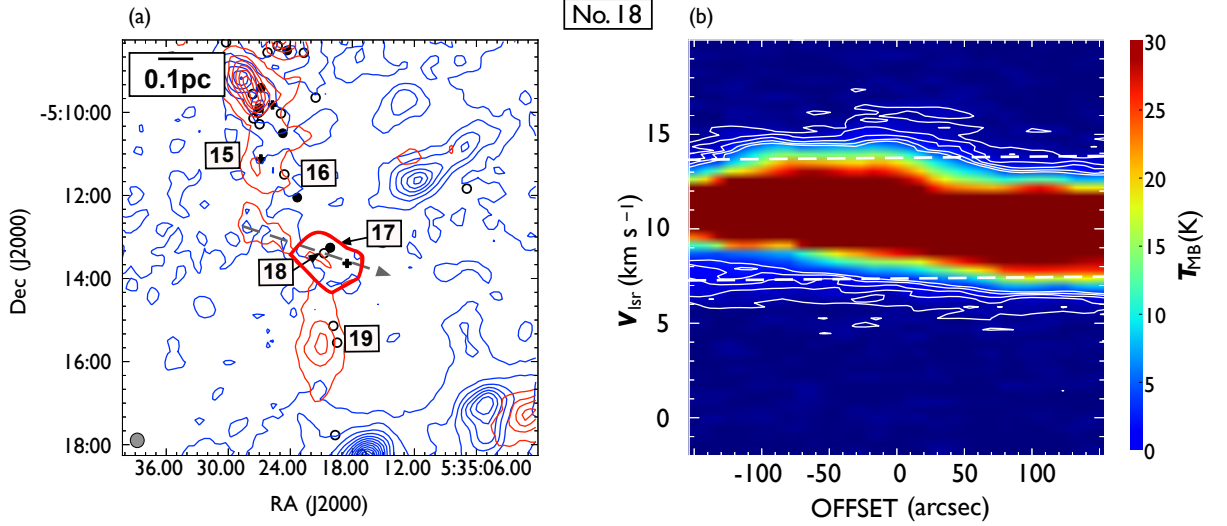


Figure A.17. The same as in Figure 4.3 but for outflow No. 18. In panel (a), the blue- and red-shifted integrated intensity velocity ranges are 0.0 km s^{-1} to 7.2 km s^{-1} and 13.6 km s^{-1} to 20.2 km s^{-1} , respectively.

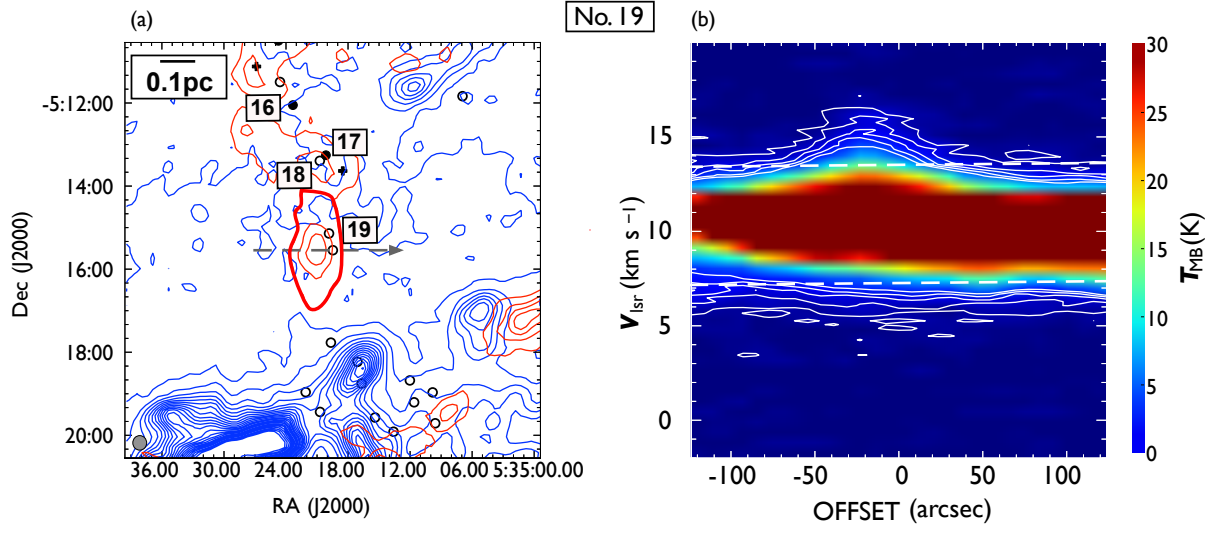


Figure A.18. The same as in Figure 4.3 but for outflow No. 19. In panel (a), the blue- and red-shifted integrated intensity velocity ranges are 0.0 km s^{-1} to 7.1 km s^{-1} and 13.5 km s^{-1} to 20.2 km s^{-1} , respectively.

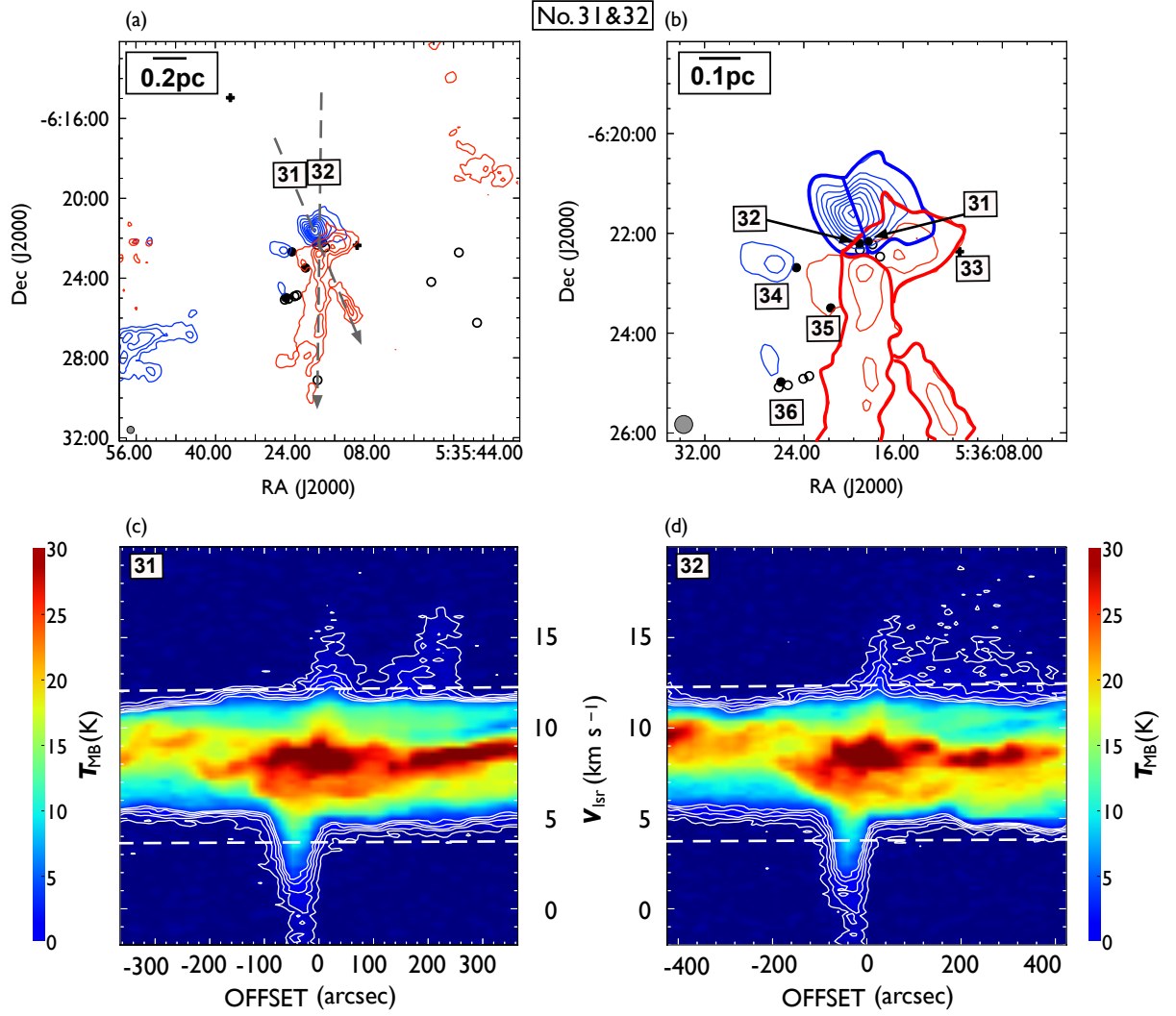


Figure A.19. The same as in Figure 4.3 but for outflow No. 31 and 32. In panel (a), the blue- and red-shifted integrated intensity velocity ranges are -1.9 km s^{-1} to 3.8 km s^{-1} and 12.3 km s^{-1} to 20.2 km s^{-1} , respectively. Panel (b) is a close up view of the center of panel (a). Panel (c) and (d) are the P-V diagrams of No. 31 and No. 32, respectively.

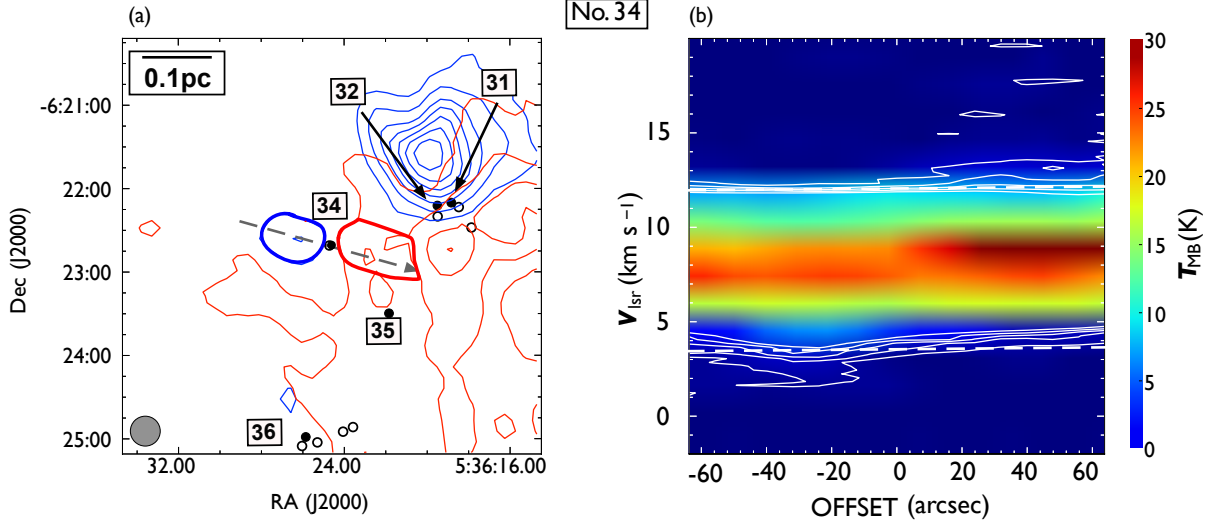


Figure A.20. The same as in Figure 4.3 but for outflow No. 34. In panel (a), the blue- and red-shifted integrated intensity velocity ranges are -1.9 km s^{-1} to 3.4 km s^{-1} and 12.0 km s^{-1} to 20.2 km s^{-1} , respectively.

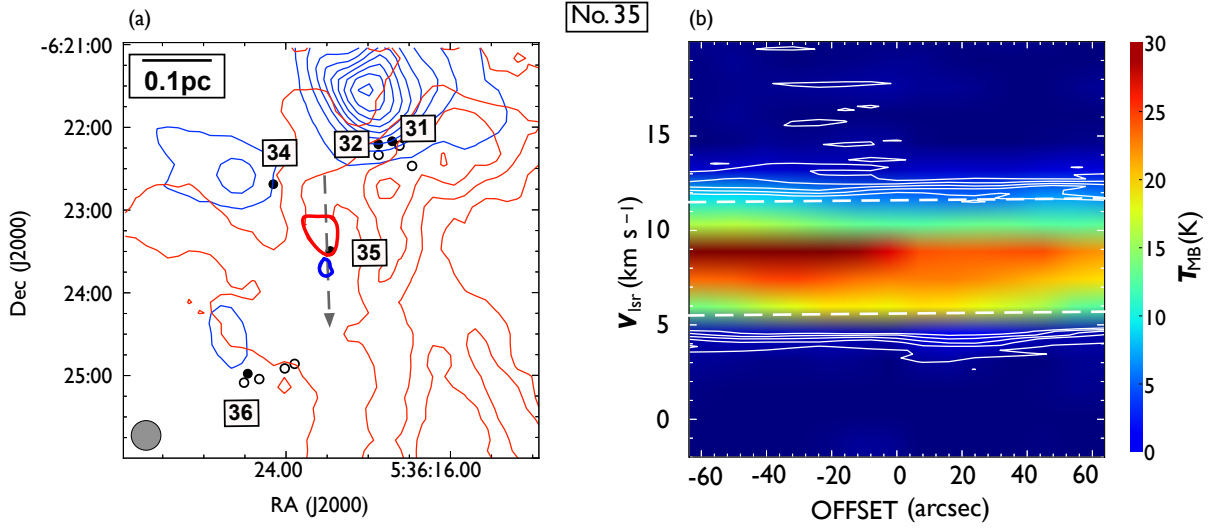


Figure A.21. The same as in figure 4.3 but for outflow No. 35. In panel (a), the blue- and red-shifted integrated intensity velocity ranges are -1.9 km s^{-1} to 5.5 km s^{-1} and 11.4 km s^{-1} to 18.0 km s^{-1} , respectively.

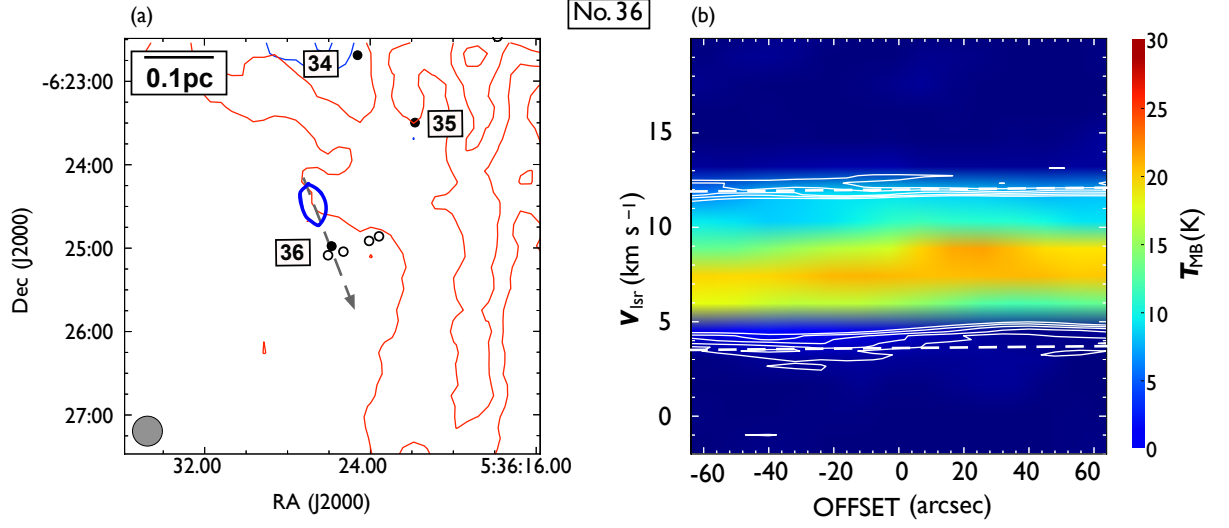


Figure A.22. The same as in Figure 4.3 but for outflow No. 36. In panel (a), the blue- and red-shifted integrated intensity velocity ranges are -1.9 km s^{-1} to 3.4 km s^{-1} and 11.9 km s^{-1} to 18.0 km s^{-1} , respectively.

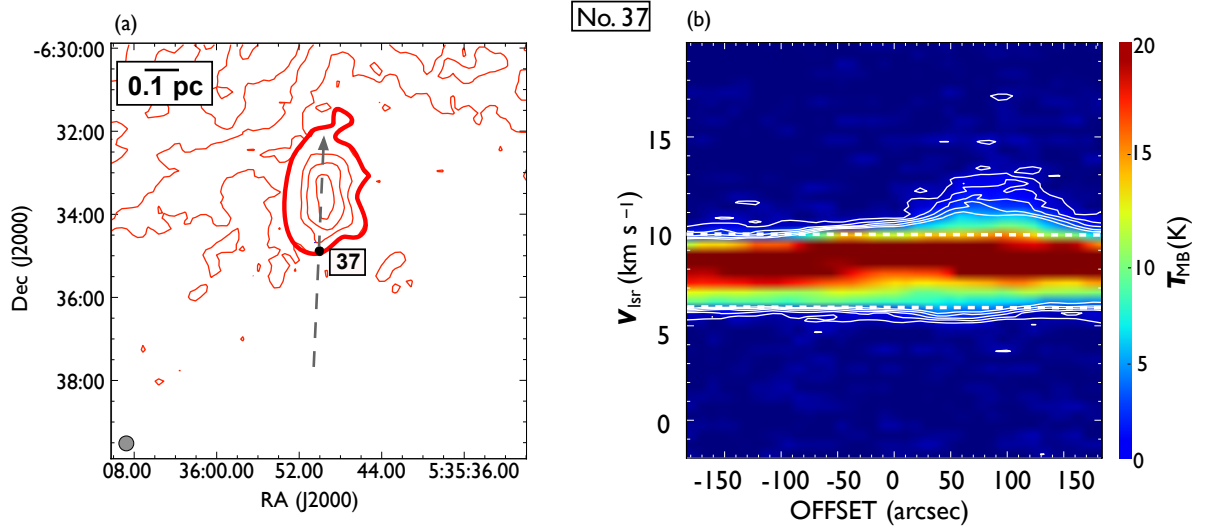


Figure A.23. The same as in Figure 4.3 but for outflow No. 39. In panel (a), the blue- and red-shifted integrated intensity velocity ranges are -1.9 km s^{-1} to 4.9 km s^{-1} and 10.4 km s^{-1} to 18.0 km s^{-1} , respectively.

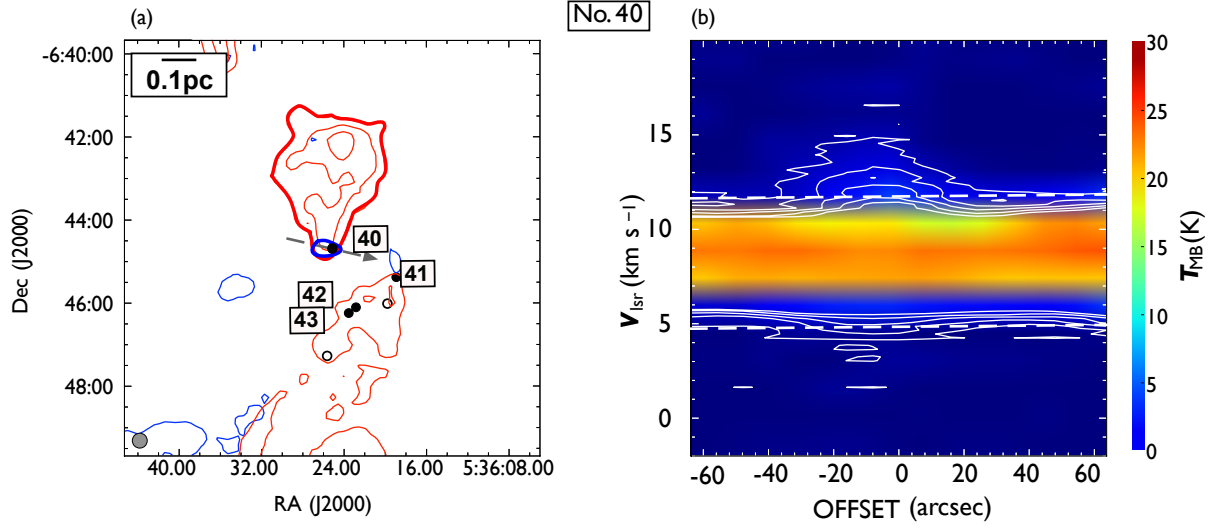


Figure A.24. The same as in Figure 4.3 but for outflow No. 40. In panel (a), the blue- and red-shifted integrated intensity velocity ranges are -1.9 km s^{-1} to 4.8 km s^{-1} and 11.6 km s^{-1} to 18.0 km s^{-1} , respectively.

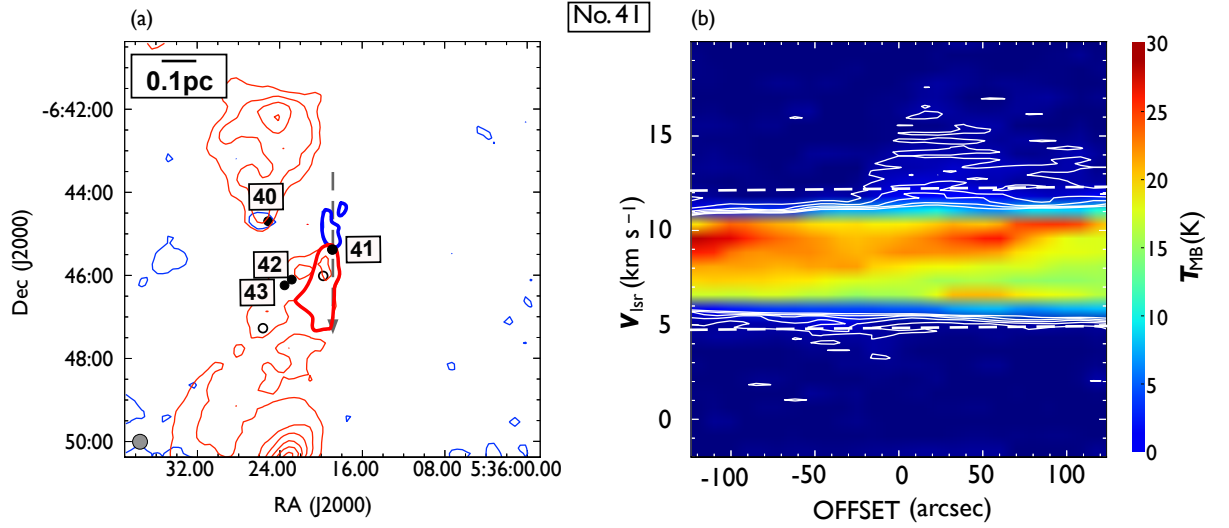


Figure A.25. The same as in Figure 4.3 but for outflow No. 41. In panel (a), the blue- and red-shifted integrated intensity velocity ranges are -1.9 km s^{-1} to 4.9 km s^{-1} and 12.1 km s^{-1} to 20.2 km s^{-1} , respectively.

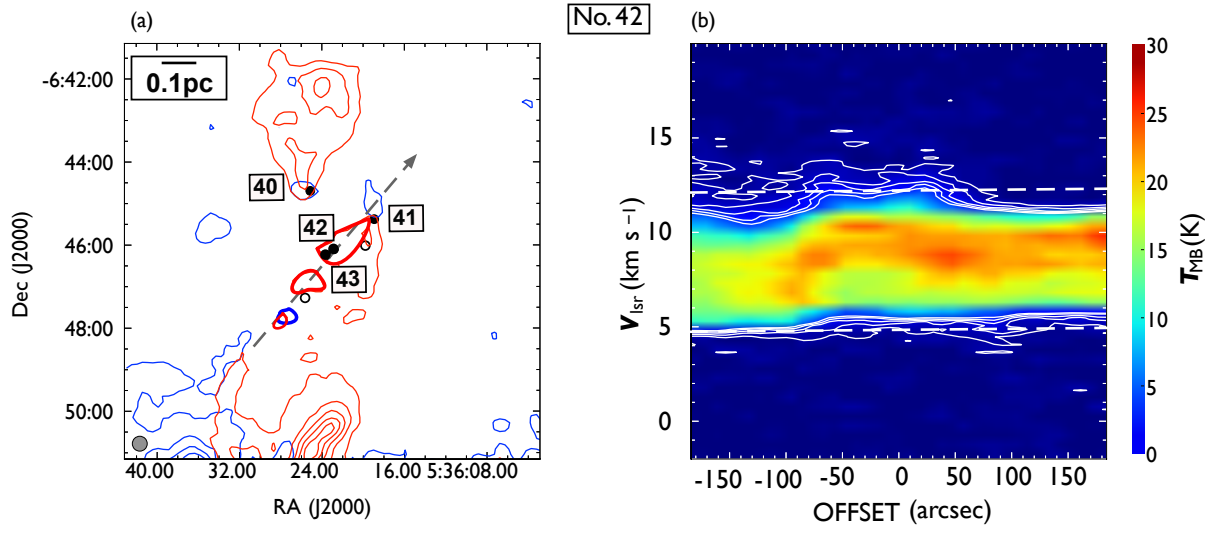


Figure A.26. The same as in Figure 4.3 but for outflow No. 42. In panel (a), the blue- and red-shifted integrated intensity velocity ranges are -1.9 km s^{-1} to 4.8 km s^{-1} and 12.1 km s^{-1} to 20.2 km s^{-1} , respectively.

Appendix B

Detection limit due to data sensitivity

In this appendix, I show that there is only a few outflow that cannot be detected due to insufficient data sensitivity. Based on equation 4.2, I estimated the detection limit due to sensitivity effects as

$$M_{\min} = \overline{n_{\text{ch}}} \times 4.33 \times 10^{13} \frac{\bar{\mu} m_{\text{H}}}{\chi^{12\text{CO}}} \left(\frac{\bar{s}}{\text{cm}^2} \right) f_{\tau} \left(\frac{\overline{T_{\text{ex}}}}{\text{K}} \right) \exp \left(\frac{5.53}{\overline{T_{\text{ex}}}} \right) \left(\frac{3 \times \sigma}{\text{K}} \right) \left(\frac{\Delta v}{\text{km s}^{-1}} \right), \quad (\text{B.1})$$

where $\overline{n_{\text{ch}}}$, $\bar{s}$, and $\overline{T_{\text{ex}}}$, are the average value of detected outflows channel count, that of size, and that of excitation temperature, respectively, and σ is the noise level per channel. Using equation B.1, I estimate the minimum mass of the outflows as $M_{\min} = 3 \times 10^{-2} M_{\odot}$. This value is equivalent to $L_{\text{bol}} = 4 \times 10^{-2} L_{\odot}$ using the relationship between the outflow mass and the protostar luminosity shown in Figure 5.4. Only seven of the sample have $L_{\text{bol}} \leq 4 \times 10^{-2} L_{\odot}$, which do not significantly affect the discussion in Chapter 5.1.