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Large-scale mapping of the IRAS 0042+5530 region in the ^{12}CO (J = 1-0) and ^{13}CO (J = 1-0) molecular lines

We present new radio observations of molecular lines in the region of high mass star formation, namely G122.0-7.1. A large-scale map of the emission observed in the ^{12}CO (J = 1-0) and ^{13}CO (J = 1-0) lines covers the area of $15'\times9'$, revealing two dense regions. The molecular bipolar outflows have been resolved in ASO1 region. It is associated with the known candidate YSO nearby IRAS 0042+5530. Also, a new dense region has been discovered in the North-Western part of the G122.0-7.1 at a distance of 5′ from IRAS 0042+5530. Its position is close to the peak of 4850 MHz emission.

ВЕЛИКОМАСШТАБНЕ КАРТОГРАФУВАННЯ ОБЛАСТІ IRAS 0042+5530 У ЛІНІЯХ МОЛЕКУЛ ^{12}CO (J = 1-0) І ^{13}CO (J = 1-0), Антюфєєв А., Торісєва М., Шульга В. — Приведено дані спостережень молекулярних ліній в області зіркоутворення G122.0-7.1, що має велику масу. Виконано картографування випромінювання ділянки $15'\times9'$ у лініях молекул ^{12}CO (J = 1-0) та ^{13}CO (J = 1-0), де виявлено дві області з підвищеною щільністю молекул. В області ASO1 поблизу ІЧ-джерела IRAS 0042+5530 виявлено біполярні потоки речовини. У північно-східній частині G122.0-7.1 на відстані 5′ від IRAS 0042+5530 виявлено невідому раніше область ASO2, положення якої збігається з положенням максимуму випромінювання на частоті 4850 МГц.

КРУПНОМАСШТАБНОЕ КАРТОГРАФИРОВАНИЕ ОБЛАСТИ IRAS 0042+5530 В ЛИНИЯХ МОЛЕКУЛ ^{12}CO (J = 1-0) И ^{13}CO (J = 1-0), Антюфеев А., Торисева М., Шульга В. — Приводятся данные наблюдений молекулярных линий в области звездообразованя G122.0-7.1, имеющей большую массу. Выполнено картографирование излучения участка $15'\times9'$ в линиях молекул ^{12}CO (J = 1-0) и ^{13}CO (J = 1-0), где обнаружены две области с повышеной плотностью молекул. В области ASO1 вблизи ИК-источника IRAS 0042+5530 обнаружены биполярные потоки вещества. В северно-восточной части G122.0-7.1 на расстоянии 5′ от IRAS 0042+5530 обнаружена неизвестная раньше область ASO2, положение которой совпадает с положением максимума излучения на частоте 4850 МГц.

INTRODUCTION

Understanding the physical processes that dominate during early stages of massive star formation and their influence on the structure and physical properties of the surrounding out of which they have been formed requires a detailed study of the physical conditions of the environment. That was successfully implemented for investigating star formation processes of low mass stars [2]. But the study of high mass stars in their evolutionary stages is complicated by the fact that they are less abundant than low mass stars, besides the clouds in which they are formed are usually at greater distances (more than 1 kpc), which limits detailed observations with the currently achievable sensitivity and spatial resolution. Interferometric measurements are needed to study the close surrounding of the embedded objects. Meanwhile single-dish observations are important for investigating the physical and kinematic properties of the molecular environments of massive protostars. While high-resolution observations give a complete picture at the first step, the resolution provided by a single telescope prove may sufficient to study the physical state of objects and to derive a rough estimate properties of the associated molecular material.

In this paper we present results of our J = 1-0 ^{12}CO, as well as J = 1-0 ^{13}CO observations towards the region of massive star formation, G122.0-7.1. We have specially selected the object for study in the outer Galaxy, rather than in the inner Galaxy because of the reduced confusion between sources which is important for observations of objects at large distances. The IRAS database provides new information on the star forming activity in our Galaxy. The G122.0-7.1 was identified as a discrete but extended source of IRAS emission that could be a massive star-forming region with a size of approximately 11′ [7]. The region contains the IRAS 0042+5530 source from the Point Source Catalog (1988). IRAS maps show that IRAS 0042+5530 has extended shape stretched from South-East to North-West. As result of this we suggest that this object can consist of two separate dense cores. This will be the basis of spectral investigations of this object in extensive area.

Neckel and Staude [13] realized UBV observation towards IRAS 0042+5530 region and found two stars of spectral type B5. An H_2O maser was found nearby [14]. The vicinities of the H II region and IRAS 0042+5530 have been observed in different molecular lines. The observations of NH_3 (1.1) and (2.2) emission lines towards IRAS point source have been carried out by Molinari et al. [10]. The object was selected as a Low-type Young Stellar Object whose evolutionary status is unknown, being among the youngest high-mass forming objects. High resolution imaging in HCO^+, ^{13}CO, CS, C^{18}O, C^{34}S and other molecular lines near the sub-mm peak [11] led to finding a small-size clump (30″) named Mol 3 with an embedded high mass protostar candidate [4]. In this paper two compact cores were found, characterized by double-peaked spectra of ^{13}CO. It was suggested that those may be due to the superposition of individual velocity components. The size of those cores is less than 10 arcmin. Using the Owens Valley Millimeter Array and Very Large Array, Molinari et al. [12] obtained interferometric maps at millimeter and centimeter wavelengths both in continuum, and a variety of lines (HCO^+ (1-0), H^{13}CO$^+$ (1-0), SiO (v = = 0, J = 2-1) and H^{13}CN (1-0) towards the Mol 3.

All previous studies suggested that the Mol 3 is a massive forming region with evidence of a high-mass protostellar candidate. However in the previous observations the object was not mapped to the full spatial extent of the bipolar emission. Thus it appeared interesting to study the structure and physical conditions of this object in detail. We mapped emissions from ^{13}CO and ^{12}CO molecules towards the whole massive star forming region G122.0-7.1 covering an area of $15' \times 9'$ and corresponding to the size of sim 33×20 pc (for an assumed distance of 7.7 kpc). The aim of our observation was to obtain a picture of the molecular environment associated with IRAS point sources, to study the bipolar outflows and to search for any massive protostars in whose vicinity sources of the outflow could be suspected.

OBSERVATIONS

The observations of ^{13}CO (J = 1-0) were started with the 14-m telescope of Metsahovi (Finland). The antenna beam size at the frequency of 115 GHz was 60″. The cooled receiver was a Schottky diode mixer giving typical noise temperatures of about 100 K (DSB), followed by an acousto-optical spectrometer of 1600 channels of 50 kHz width (0.13 km/s for the ^{12}CO (J = = 1-0) molecular rest frequency). The observations with the Metsachovi telescope were carried out both in the position switching mode and in the frequency switching mode.

The observations of ^{12}CO (J = 1-0) were continued and the mapping of the G0042.0-7.1 was completed at the 22-m telescope in Simeiz (Ukraine) in October, 2004. The HPBW of the antenna was 40″ at 115 GHz. The high-sensitivity Schottky diode mixer receiver was used, with the noise temperature of 70 K (DSB) [15, 16]. The observations were performed with a digital Fourier spectrometer [1] which gave the frequency resolution of 32 kHz (0.08 km/s for ^{12}CO (J = 1-0) molecular rest frequency). The data were calibrated by the chopper-wheel method. The intensities are expressed in units of T_A^* in the sense of Kutner and Ulich [9].

RESULTS OF THE ^{12}CO (J = 1-0) AND ^{13}CO (J = 1-0) MAPPING OF HIGH MASS FORMING REGION G122.0-7.1

An integrated intensity map of the ^{12}CO (J = 1-0) and ^{13}CO (J = 1-0) lines covering the area $15' \times 9'$ is presented in Fig. 1. As can be seen the molecular emission extends over the whole region of G122.0-7.1. The map confirms the existence of two separate dense regions. We named these ASO1 and ASO2 (Labels I and II in Fig. 1). The two maps are overlaid on the map of the 4850 MHz continuum remission [6] in which two peak positions can be identified. The similarity of the ^{12}CO (J = 1-0), ^{13}CO (J = 1-0) and 4850 MHz maps indicates that the microwave and the line emissions are formed in similar regions. The map is centered on $RA(1950) = 00^h42^m05^s$, $Dec.(1950) = 55°31$ arcmin 00″.

The spectra towards the central path of G122.0-7.1 region are shown in Fig. 2. At many positions near ASO1 center the signal-to-noise of the spectra is high enough to make it clear that many of the ^{12}CO (J = 1-0) and ^{13}CO (J = = 1-0) line profiles are not simple Gaussian. They have a clear asymmetry with shoulders. The broader emission is visible in the wings on both sides of the profiles. Several of the ^{12}CO spectra nearby ASO1 peak positions show dips. The ^{12}CO spectra with very small deviation from Gaussian profiles are seen in the small region between ASO1 and ASO2. Those spectra have narrower

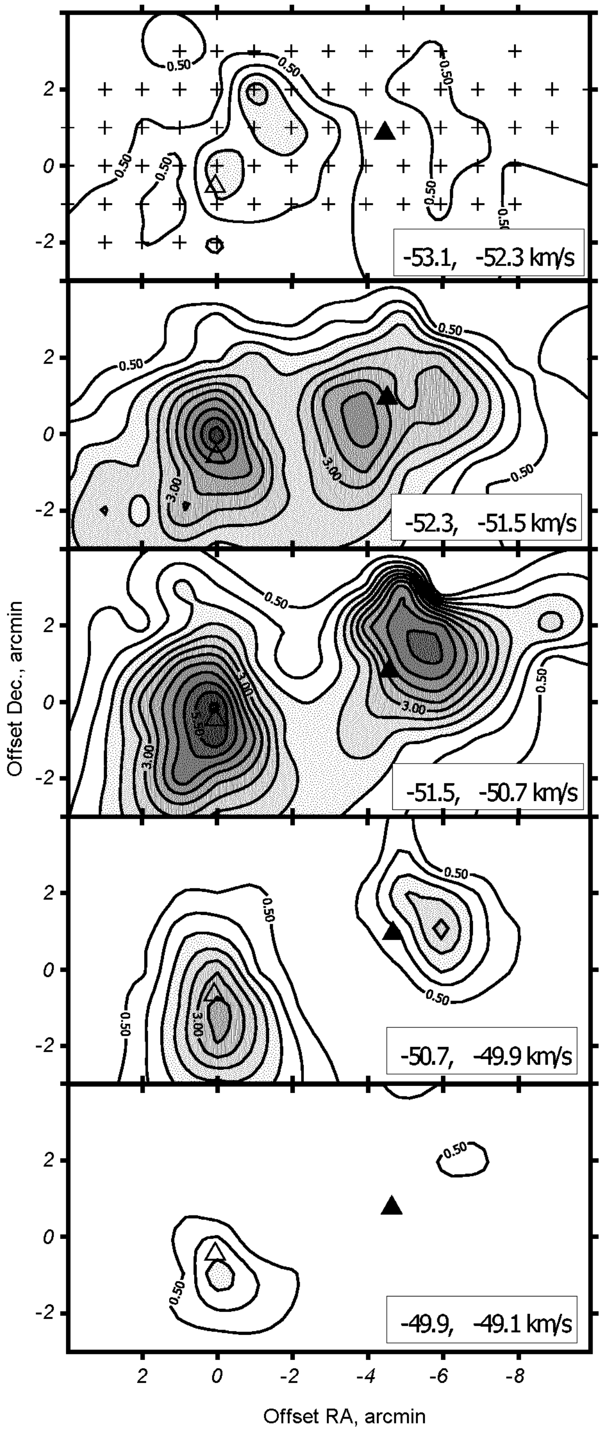

Figure 3. Maps towards G122.0-7.1 region of ^{13}CO J = 1-0 emission at different velocity ranges. The velocity ranges are shown in the right bottom corner of each map. The map is centered on $RA(1950) = 00^h\ 42^m 05^s$, $Dec.(1950) = 55°31'00''$. The Symbol Δ denotes the peak position of paper [4]. The Symbol denotes the peak position of the map of the 4850 MHz continuum remission [6]. The crosses indicate points of the map

profiles. This may be related to the fact that the region is generally quiescent. The other regions are dynamically active. The ^{12}CO line profiles in ASO2 area are symmetrical and can be well approximated by Gaussian. Its central velocity systematically changes with position.

Considering our great separation from the sources in G122.0-7.1, and the relatively large beam size covering a sizable part of the outflow area, the broadening of the line profiles tends to obscure the visibility of line wing asymmetry in the spectra. The systematic asymmetry of line profiles is evidence for bipolar motion in the ASO1 region of G122.0-7.1.

ASO1. Fig. 3 show maps of ^{13}CO molecule radiation in different velocity ranges. The map is centered on $RA(1950) = 00^h\ 42^m 05^s$, $Dec.(1950) = 55°31'00''$. The symbol DELTA denotes the peak position in paper [4]. As can be seen from Fig. 3, a variation of velocity ranges (toward increase of velocities) results in a change of peak emission coordinates. The peak shifts from the position with RA offset and declination offset [0, 0] to the position with RA offset and declination offset [0, −1] respectively. The line profiles at these positions are not Gaussian. The effects may result from the presence in ASO1 of either bipolar outflows or two separate clumps characterized by different VLSR [4].

The emission structure of the ^{12}CO molecule is more complex. None of the ^{12}CO lines is a simple Gaussian, and a broader emission is visible in the wings on both sides. Moreover, line profiles vary considerably in shape at different points of the ASO1 map. Fig. 4 shows two spectra observed in the Southern and Northern parts. The deviation of the profiles can be quantified by looking at the value of $\int Tdv$ on the blue — and red sides of the lines (where the «blue» and «red» are relative to the central velocity of -51.5 km/s). The observed deviations may be due to superposition of separate velocity components. We can recognize four velocity ranges on the profiles where the value $\int Tdv$ varies around the whole ASO1 object. Fig. 5 shows maps of the ^{12}CO molecule radiation in different velocity ranges. We try to identify different velocity components of the molecular emission as those associated with outflows. The bipolar outflows can be seen at the velocity — position plot (Fig. 6) for ^{12}CO and ^{13}CO along the outflow axis with the center at $RA(1950) = 00^h 42^m 05^s$, $Dec.(1950) = 55°31'00''$ (see the vertical section in Fig. 1).We can separate two

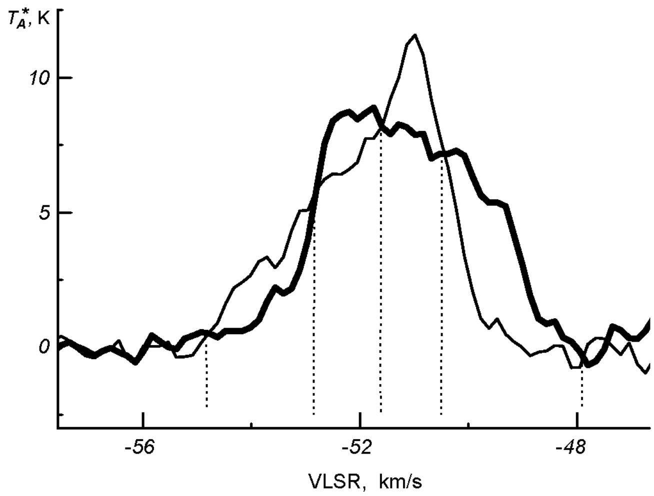

Figure 4. Comparison of the CO (J = 1-0) spectra at two points in northern (thin curve) and southern (thick curve) parts of ASO1. The vertical lines indicate the four velocity ranges where value $\int Tdv$ varies around the whole ASO1 object

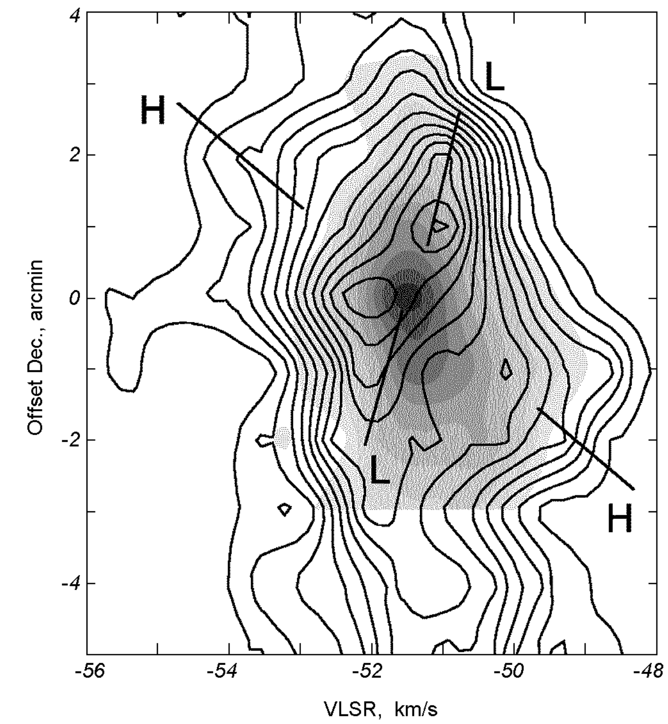

Figure 6. The position-velocity plot at the RA center of ASO1. The emission of ^{13}CO (J = 1-0) is shown by the grey background, the ^{12}CO is shown by the solid line. ^{12}CO levels are 1 to 13 K in steps of 1 K, ^{13}CO levels are 1 to 9 K in steps of 1 K

bipolar outflows originating from the common point that is coincident with the peak of the integrated emission in the line of ^{13}CO.

We have named the two components of the bipolar outflow the «high-velocity» and «low-velocity» lobes. The «low-velocity» lobe can be identified below 1.5 km/s with respect to central velocity. It is marked with «L» in Fig. 6. The «high-velocity» lobe is seen at greater than 1.5 km/s (with respect to central velocity) and has been marked in Fig. 6 as «H». Both lobes are extended from South toward North. The maximum light-of-sight velocity of the emitted substance is sim 2 km/sec relative to the central velocity in the «High-velocity» lobe and sim 1 km/sec in the «Low-velocity» lobe. The «high-velocity» lobe is well collimated and can but weakly be discerned at points off the outflow axis. The «low-velocity» lobe is less collimated and is detectable at points lying at 1′ off the axis.

The «low-velocity» lobe in the ASO1 can hardly be explained to the optical depth effect of the ^{12}CO line. Indeed, in the care of a symmetric cloud the spectra of the Southern and Northern path of the cloud should be identical. In this case, however, we can observe a systematic asymmetry of the profiles. Therefore we suppose, that the «low-velocity» lobe is the bipolar outflows.

Based of the above mentioned data the kinematic time of the «high-velocity» outflow existence can be calculated. It is sim 500 000 years. This is too long for the YSO of such mass. In our opinion, the most probable explanation of the discrepancy is the fact that the kinematic distance, used in calculations, does not correspond to the real one, which is much less.

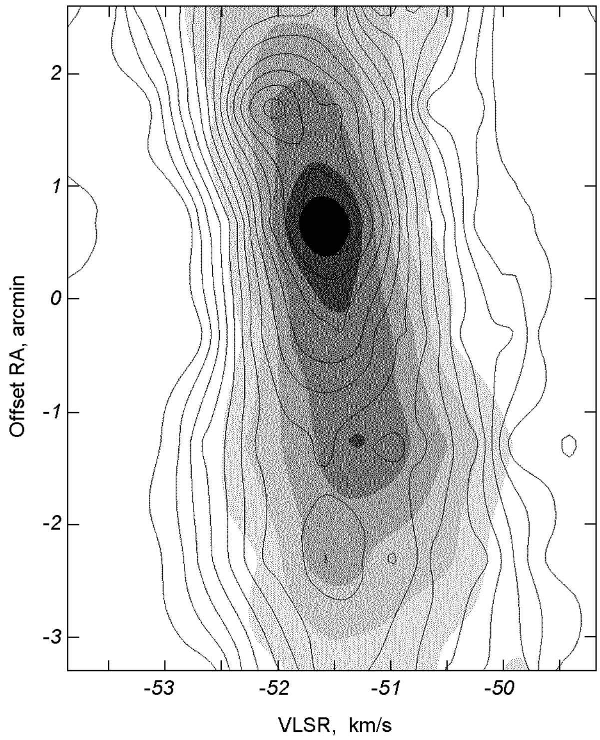

Figure 7. The position-velocity plot at the declination center of ASO2. The emission of ^{13}CO (J = 1-0) is shown by the grey background, the ^{12}CO is shown by the solid line. ^{12}CO levels are 1 to 13 K in steps of 1 K, ^{13}CO levels are 1 to 6 K in steps of 1 K

In this paper we prefer to assume that the distance to G122.1-7.1 is 7.7 kpc. In fact, the distance to that object is only poorly known. The kinematic distance was estimated from the NH_3 line velocity in [4, 10], using the analytical fit of Brand and Blitz [3] for the Galactic rotation curve. On the other hand, the distance found from HCO^+ line velocity is 5 kpc [12]. Codella and Fally [5] computed the kinematic distance for the maser near IRAS 00420+5530 as 4.3 kpc. Neckel and Staude [13] derived a photometric distance to the stars in the H II object of 1.7 kpc. But Brand et al. [4] noted that their photometric distance was uncertain, and using the kinematic distance would be more correct. This means that careful investigations are necessary to solve the problem.

ASO2. The ^{12}CO and ^{13}CO line profiles in ASO2 are symmetrical and well approximated by Gaussian curve. The line widths are less than in ASO1, but larger that in the small region between ASO1 and ASO2. There are not wings in this profiles. Central velocity of line profiles, obtained by approximation of Gaussian curve, uniformly displaces with change position from West to East. The center of this velocity gradient contains the maximum of continual emission at the 4850 MHz. We suppose this point to be a center of object ASO2. It coordinates $RA(1950) = 00^h\ 41^m 34^s$, $Dec.(1950) = 55°31$ arcmin $55''$. Fig. 7 shows ^{12}CO and ^{13}CO spatial-velocity plot along the direction of a maximum velocity gradient with center at the peak of 4850 MHz emission (see the horizontal section in Fig. 1). The above features of line profiles and analysis of spatial-velocity plot allow us to suppose, that the reason of systematical velocity variations with point of observation is the rotation motion of the gas around the peak of continual emission at the 4850 MHz.

Mass and energy characteristics of bipolar flows. We used the method, suggested by Garden et al. [8] for estimating general energetic parameters of the outflow in the ASO1 region and core of ASO2. This method based on the LTE model uses ^{12}CO and ^{13}CO observation data to obtain mean optical depth, mass, impulse and energy in the chosen velocity range.

For ASO1 object parameters have been calculated for «High-velocity» lobe. We identified the «red» and the «blue» component by integrating $\int T dv$ over the appropriate velocity intervals. The excitation temperature was estimated from observations of optically thick ^{12}CO lines and we assumed the excitation temperature equal to peak brightness temperature of central of ASO1 ^{12}CO line profile ($T_{ex} \approx 20$ K). The observed projected area was determined using all emissions above the FWHM level of the integrated ^{12}CO emission. The mass estimates are lower limits because only high-velocity path of the outflow taken into account.

Mass of the core of ASO2 object have been calculated. The excitation temperature was estimated from observations of optically thick ^{12}CO lines and we assumed the excitation temperature equal to peak brightness temperature of central of ASO2 ^{12}CO line profile ($T_{ex} \approx 20$ K). Mass of the ASO2 was determined using all emissions above the FWHM level of the integrated ^{13}CO emission.

The results of these calculations are presented in Table.

Mass, momentum and kinetic energy

Parameter	ASO1 Blue	ASO1 Red	ASO2 Core
Velocity range km/s	−54...−53	−49.5...−48	
Mean Tau (^{12}CO)	12	21	
Mass, $M_{\odot}$ (^{12}CO)	475	464	
P, $M_{\odot}\cdot$km/s)	950	1277	
E, erg	$2\cdot10^{46}$	$3.5\cdot10^{46}$	
Mean Tau (^{13}CO)			0.45
Mass, $M_{\odot}$ (^{13}CO)			21000

CONCLUSIONS

We observed two regions of massive star formation in G122.0-7.1 in the J = 1-0 ^{12}CO and ^{13}CO lines and mapped an area of $15' \times 9'$. We revealed two dense regions that have been designated here as ASO1 and ASO2. The ^{12}CO and ^{13}CO line profiles are asymmetrical in ASO1 region with blue-shifted and red-shifted wings. The ASO2 is a rather compact region and ASO1 is more extended. Positions of the peak molecular emission correlate with maximum luminosity at 4850 MHz. A number of narrow and symmetric line profiles are detectable in some positions between ASO1 and ASO2 regions. This suggests that the formation of the ^{12}CO and ^{13}CO emission at the positions takes place in a relatively quiescent gas. The ASO1 region was studied in various molecular lines, but in a small area around the IRAS source 0042+5530 only. We assumed that the asymmetry of line profiles in ASO1 is associated with the outflows. We separate two bipolar outflows in ^{12}CO line originating from the common point that is coincident with the peak of the integrated emission in the line of ^{13}CO. Estimated masses of ASO1 and ASO2 indicate that these objects are the high-mass star forming regions.

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