Discovery of Multiple outflows in IRAS 06056+2131 *

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We report a discovery of multiple outflows in IRAS 06056+2131. The high angular resolution image (∼15″) of CO (1-0) emission reveals that the structure of outflow is very complicated. The outflow appears to be everywhere. Its configuration only show a bipolar outflow at observation of both low resolution and low signal-to-noise ratio, while two bipolar outflows can be detected when observed by both high resolution and high signal-to-noise ratio mapping. This result is significant in the understanding of the physical processes that occur at early phase of massive stars.

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The massive stars are responsible for most of the spectacular phenomena occurring in both local and galactic scales. Their formation and early evolution, however, are still poorly understood for their short evolutionary times. Molecular outflows may be the main feature of the earliest stages in massive star formation. Therefore, many researchers have investigated the phase with CO line mappings. For instance, Shepherd and Churchwell[1] and Zhang et al.[2] found that about 90% of the observed massive star-forming regions are associated with high velocity gas and outflows. Their observations, however, could not well determine the morphology and dynamics due to the poor resolution of the telescope they employed. Beuther et al.[3] found the bipolar structures only in approximately 50% in massive star-forming regions, while the observation with higher resolution antenna shows a 80% detection rate. Therefore, a moderate resolution observation is critical to isolate individual outflows and achieve the necessary degree of kinematic and morphological detail. We propose to investigate outflow features at both high resolution and high signal-to-noise ratio with the Nobeyama 45-m telescope and expect to gain new insight and clues for unsolved astrophysical problems in massive star formation.

In order to reveal outflow structures associated with massive star-forming regions on a finer scale, we made 12CO observations toward 8 IRAS sources associated with 6.7 GHz methanen masers[4] with the 45-m telescope at NRO, Japan, in April 2003. Some interesting results were found. Here we report a discovery of multiple outflows in IRAS 06056+2131.

The beam size of the telescope is ∼15″ at 115 GHz, the rest frequency of the emission line. We mapped an area of 3′×3′ around IRAS 06056+2131 using a multi-

ON-OFF position-switching technique. The BEARS (25 beams) was used. Because of its large beam separation (41.1′′), we interpolated two points to reduce grid spacing to ∼14′′, slightly less than the resolution of the telescope at the CO J = 1 − 0 frequency. The mapping integration time for each point was 6 minutes, which led to an rms ∼0.2K (T_A^*) at a velocity resolution of ∼0.1 km s⁻¹. During data reduction, the data were smoothed to a resolution of ∼1 km s⁻¹ to improve the signal-to-noise ratio. The pointing accuracy was better than 5″ and checked by observing nearby SiO maser sources at 43 GHz every hour. The main beam efficiency was about 0.40 at the observed frequency. The data were reduced on the NEOSTAR reduction package.

IRAS 06056+2131 is located in a complex of molecular clouds with a FIR-infrared luminosity of 2 × 10⁵ L☉, at distance of about 1.5 kpc.[5] Snell et al.[6] also detected a CO bipolar outflow, which is in the NE–SW direction, and peaks of blue and red wings are spatially separated. Observation with the low signal-to-noise ratio shows wing extent below 20 km s⁻¹, whereas high signal-to-noise ratio reveals a velocity spread over 34 km s⁻¹.[3] Due to both the poor resolution (∼45″) and the signal-to-noise ratio, these observations could not clearly determine the morphology and dynamics of the outflows in this region.

Figure 1 presents the IRAS 06056+2131 CO blue (thick lines) and red wing emission (thin lines). From this picture one can see that outflows almost take place everywhere, and roughly form two bipolar outflows, one (outflow 1) on the upper-left with a low collimation factor and another (outflow 2) on the right with a collimation factor of ∼2. The size of these two out-

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flows is about 0.8 and 1.3 pc, respectively. Therefore, the resolution ($15'' \approx 0.1$ pc) can reveal their structure clearly. As a comparison, Snell et al.\cite{Snell1988} only found a bipolar outflow in this region. This discrepancy is probably due to our observations with higher spatial resolution as well as a better signal-to-noise ratio.

To estimate the outflow parameters, we use the method of Beuther et al.\cite{Beuther2002} except for CO column density $N_{\text{CO}}$, which is derived from the result of Snell et al.\cite{Snell1988} We assume that the gas is in local thermodynamic equilibrium, at a gas temperature of 30 K, and a CO to H$_2$ abundance ratio of $10^{-4}$. The physical properties of the outflows are summarized in Table 1.

It is interesting from Fig. 1 that the blue-shifted emission is stronger than the red one in outflow 1, while in contrast the red-shifted lobe is dominant in outflow 2. This may indicate that both the outflows are driven by different sources. Since the mapping area is limited, the blue lobe of outflow 1 is not shown entirely. From the low resolution mapping of Snell et al.\cite{Snell1988} it should stretch beyond the map boundary to the east. The red wing of outflow 2 extends from the west to the east and connects outflow 2 to outflow 1. Therefore, outflow 1 can also be regarded as a multiple outflow since its blue wing connects the red wings of the two outflows. In order to exhibit the environment of star formation in this region, we also present the

results of other observations (see Fig. 1), such as near-infrared,\cite{NearInfrared} CS,\cite{CS} NH$_3$,\cite{NH3} H$_2$O masers,\cite{H2O} and radio emission.\cite{Radio} Near-infrared polarimetric images show two infrared nebulae in this region. They are correspondingly associated with the two outflows. The nebulae near outflow 2 is associated with a cluster of stars. The IRAS 06056+2131 is located near the centre of outflow 2. Outflow 2 is also associated with a water source, a ammonia and a CS emission peaks, and 3.6-cm radio continuum emission. These indicate that there are at least a massive star and a cluster of low- and intermediate-mass stars associated with the outflows. Due to its large momentum in the outflows, outflow 2 is most possibly driven by the massive star with radio continuum emission. Outflow 1 is associated with an infrared nebulae and a CS emission peak. This outflow may be driven by stars associated with nearby infrared nebulae. A detailed analysis of outflow properties will be presented elsewhere.

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Table 1. Parameters of the outflows. The first column presents the outflow name. The next two columns list the H$_2$ column densities $N_b$ and $N_r$ in both the blue and red outflow lobes. Columns 4-6 are the blue lobe masses $M_b$, red lobe $M_r$, and the total mass $M_{\text{out}}$, respectively. Columns 7 and 8 give the momentum $p$, and the energy $E$. The last five columns are the maximum radius $R$, the characteristic time scale $t$, the mass entrainment rate of the molecular outflow, $M_{\text{out}}$, the mechanical force $F_m$, and the mechanical luminosity $L_m$.

<table>
<thead>
<tr>
<th>Source name</th>
<th>$N_b$ (10$^{19}$ cm$^{-2}$)</th>
<th>$N_r$ (10$^{19}$ cm$^{-2}$)</th>
<th>$M_b$  ($M_\odot$)</th>
<th>$M_r$  ($M_\odot$)</th>
<th>$M_{\text{out}}$  ($M_\odot$)</th>
<th>$p$  (M$_\odot$ km s$^{-1}$)</th>
<th>$E$  (erg)</th>
<th>$R_{\text{max}}$  (pc)</th>
<th>$t$  (yr)</th>
<th>$M_{\text{out}}$  ($M_\odot$/yr)</th>
<th>$F_m$  (M$_\odot$ km s$^{-1}$/yr)</th>
<th>$L_m$  ($L_\odot$)</th>
</tr>
</thead>
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<tr>
<td>Outflow 1</td>
<td>8.6 6.3 \times 10^{19}</td>
<td>0.7</td>
<td>0.6</td>
<td>1.3</td>
<td>12.7</td>
<td>1.5 \times 10^{45}</td>
<td>0.8</td>
<td>1.9 \times 10^{4}</td>
<td>3.4 \times 10^{-5}</td>
<td>3.4 \times 10^{-4}</td>
<td>0.28</td>
<td></td>
</tr>
<tr>
<td>Outflow 2</td>
<td>4.0 8.0 \times 10^{19}</td>
<td>2.9</td>
<td>1.4</td>
<td>1.7</td>
<td>16.9</td>
<td>1.7 \times 10^{45}</td>
<td>1.3</td>
<td>3.5 \times 10^{4}</td>
<td>2.4 \times 10^{-5}</td>
<td>2.4 \times 10^{-4}</td>
<td>0.2</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 1. Contour map of outflows, which consists of two bipolar outflows. Redshifted emission contours range from 7.5 to 12.5 km s$^{-1}$ (thin lines), while blueshifted emission contours range from $-7$ to $-2$ km s$^{-1}$ (thick lines). Contour levels are 1, 2, 3, 4, 5, 6, 7, 8, 9, and 10 $\times$ 1.30 K x km s$^{-1}$. The star denotes the IRAS 06056+2131 position. The circles denote the infrared nebulae, the pentagons represent the CS emission peaks, the diamond is the ammonia emission peak, the rectangle is the water maser, and the ellipse is the radio continuum source.

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