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BIPOLAR OUTFLOW IN B335[1]

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ABSTRACT

We have mapped the high-velocity ^{12}CO (J = 1–0) emission in B335 with a high angular resolution of 16″. The high-velocity emission shows distinct bipolar pattern centered at IRAS 19345+0727, toward which we have detected a strong high-velocity ^{12}CO emission. The bipolar lobes delineate remarkable collimation toward the *IRAS* source, indicating that the flow is focused within 0.02 pc of the driving source. Each lobe is accompanied by significant wing emission with the *opposite* velocity shift, which clearly shows the association with IRAS 19345+0727. This feature is well explained as a bipolar flow the axis of which is nearly perpendicular to the line of sight. There is no evidence of another evolved bipolar flow which does not associate with any dense core as previously suggested. This leads us to suggest that B335 is a site of very recent star formation, containing a single bipolar flow with an age of ∼3 × 10^4 yr.

Subject headings: infrared: sources — interstellar: molecules — stars: formation — stars: winds

I. INTRODUCTION

B335 is an elliptical dark cloud with an optical size of 3′ × 4′ and is located at 250 pc from the Sun according to Tomita, Saito, and Ohtani (1979). This cloud is a site of low-mass star formation as indicated by the high-velocity ^{12}CO emission (Frerking and Langer 1982; Goldsmith *et al.* 1984; Langer, Frerking, and Wilson 1986), a dense molecular cloud core (e.g., Menten *et al.* 1984; Hasegawa *et al.* 1986; Kameya *et al.* 1987; Walmsley and Menten 1987), and a far-infrared source (Keene *et al.* 1983; *IRAS Explanatory Supplement* 1984; Gee *et al.* 1985). At the distance of 250 pc, the luminosity of this far-infrared source reported by Keene *et al.* corresponds to ∼2.7 $L_\odot$. The source is visible only in the far-infrared and submillimeter wavelength regions, and was suggested to be a probable candidate for the solar-type protostar (Keene *et al.* 1983; Gee *et al.* 1985).

^{12}CO wing emission in B335 was discovered by Frerking and Langer (1982). Goldsmith *et al.* (1984) mapped this region with 48″ beam every 1′, showing that the ^{12}CO wings delineate detached redshifted and blueshifted lobes, and that there is a hole of high-velocity emission toward the infrared source. They suggested that the two lobes represent a bipolar outflow, and that the hole is a cavity evacuated by the stellar wind from the central source. In order to reveal more detailed distribution of the high-velocity ^{12}CO emission, we mapped 8′ × 4′ (EW–NS) region centered at the far-infrared source in 1986 April, using a 16″ beam of the 45 m radio telescope. After we completed this mapping, another observation by Langer, Frerking, and Wilson (1986) was published. Their observation covers a larger area than the observations of Frerking and Langer (1982), Goldsmith *et al.* (1984), and ours, and shows more extended distribution of the high-velocity ^{12}CO emission. Namely, there is a redshifted component in the central region of the blue lobe, and another isolated blueshifted component on the east of the originally suggested bipolar flow. The authors interpreted these results as the presence of two bipolar outflows overlapping each other; one of the outflows, located well outside of the dense core, was suggested to be an aged one. They contended that B335 is an evolved cloud which has undergone multiple star formation instead of a young cloud beginning star formation as previously suggested.

In this *Letter*, we present observational results on the detailed distribution of the high-velocity ^{12}CO (J = 1–0) emission in angular resolution of 16″, a factor of 3 higher than the resolution of Goldsmith *et al.* (1984) and a factor of 6 higher than that of Langer, Frerking, and Wilson (1986). The present data provide us a completely different view from that of Langer, Frerking, and Wilson (1986). Our results will lead us to a better understanding of the driving source of the high-velocity emission and will provide us with valuable information on star formation in B335.

II. OBSERVATIONS

Observations of the ^{12}CO (J = 1–0) emission were made in 1986 April using the 45 m telescope of Nobeyama Radio Observatory. The telescope had a beam size of 16″ with a main beam efficiency of 0.45 at 115 GHz. The receiver frontend was a single-sideband cooled Schottky mixer, providing the typical system noise temperature of 800–950 K including the atmospheric noise and antenna ohmic loss. Spectra were taken with an acousto-optical spectrometer having a frequency resolution of 37 kHz and a band width of 40 MHz. The frequency resolution corresponds to 0.1 km s^{-1} at 115 GHz. The pointing accuracy was checked by observing the SiO maser in R Aql at 43 GHz and was better than 5″. Spectra were taken every 20″ spacing in an area of 8′ (E–W) × 4′ (N–S). The intensity scale was estimated by correcting the antenna temperature for the atmospheric extinction and for the main beam efficiency. The peak brightness temperature of ^{12}CO line was ∼8.5 K at the reference center, $\alpha = 19^h34^m34^s$, and $\delta = +7°27'00''$ (1950). Typical rms noise fluctuation averaged over five channels, corresponding to a velocity resolution of 0.27 km s^{-1}, was ∼0.4 K.

III. RESULTS AND DISCUSSION

a) The High-Velocity ^{12}CO *Emission*

Figure 1 (Plate L3) shows the distribution of the high-velocity ^{12}CO (J = 1–0) emission and the ambient gas super-

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[1] This work was carried out under the common use observation program at the Nobeyama Radio Observatory (NRO). NRO, a branch of the Tokyo Astronomical Observatory, University of Tokyo, is a cosmic radio observing facility open for outside users.

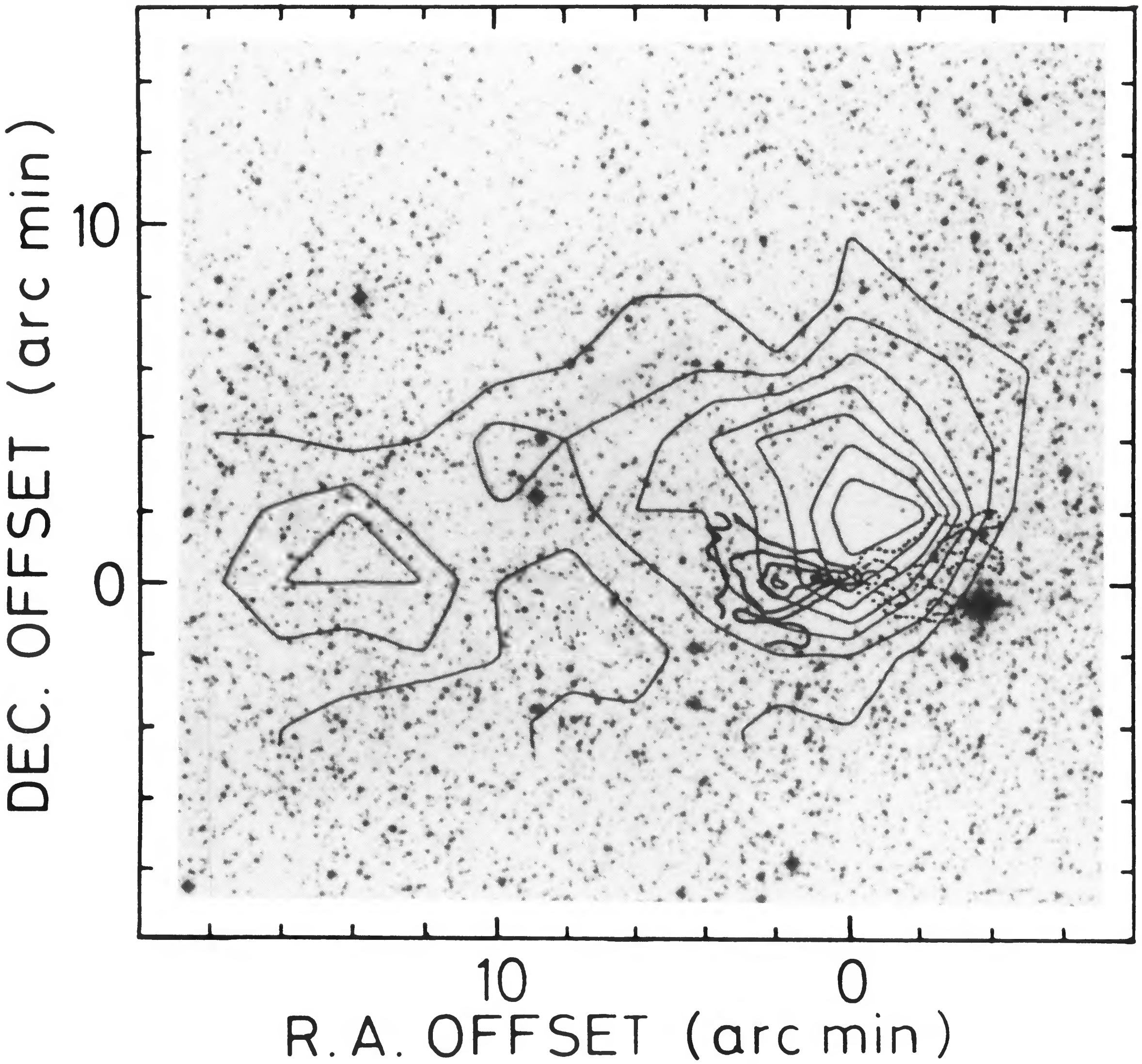

FIG. 1.—A map of ^{13}CO (J = 1–0) integrated intensity obtained with the 4 m radio telescope at Nagoya University (N. Hirano *et al.* 1988, in preparation), superposed on the POSS blue print. Contours are every 0.2 K km s^{-1} with the lowest contour at 0.2 K km s^{-1}. The spatial distribution of the blueshifted and the redshifted high-velocity emission of ^{12}CO (J = 1–0) obtained with 45 m telescope is indicated by solid and dotted curves, respectively. The bipolar outflow is located near the SW edge of the ^{13}CO cloud, suggesting that the western red lobe is less affected by the ambient gas and has kept the shell structure.

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posed on the POSS blue print. The ambient cloud was observed with the 4 m radio telescope at Nagoya University in the ^{13}CO ($J = 1$–0) emission (N. Hirano *et al.* 1988, in preparation). Our ^{13}CO map shows good agreement with that of Langer, Frerking, and Wilson (1986). The peak velocity of the ^{13}CO emission is $V_{\rm LSR} = 8.3$ km s^{-1} with no spatial variation greater than ~0.1 km s^{-1} over the mapped region. The outflow in B335 is located near the SW edge of the ^{13}CO cloud.

Figure 2 shows the distribution of the high-velocity ^{12}CO emission at four velocity intervals: (*a*) 3.0–7.5 km s^{-1}, (*b*) 9.5–14.0 km s^{-1}, (*c*) 7.3–7.8 km s^{-1}, and (*d*) 8.8–9.3 km s^{-1}. The upper two panels, Figures 2*a* and 2*b*, show that the high-velocity emission has a clear bipolar pattern centered at the far-infrared source, IRAS 19345+0727. The red and blue lobes delineate fan shapes with a constant opening angle of ~45°. The shape of the red lobe is hollow cone–like, suggesting that the flow has a shell structure as that seen in L1551 (Snell and Schloerb 1985; Uchida *et al.* 1987), whereas the hollow cone shape is less evident in the blue lobe.

We have detected strong and compact high-velocity ^{12}CO emission within ~1′ of the *IRAS* source, the N–S extent of which is not yet resolved with the present beam. At the position of the *IRAS* source, the CS ($J = 2$–1) wing was also detected by Kameya *et al.* (1987) with 17″ beam. These results disagree with the previous ^{12}CO ($J = 1$–0) map that shows no high-velocity emission toward the infrared source (Goldsmith *et al.* 1984). This disagreement is probably due to the dilution effect in the 48″ beam. The present ^{12}CO maps strongly suggest that the outflow is currently fairly active, and that the collimation of the ^{12}CO outflow is taking place at a very small distance from the central source, <0.02 pc ($=6 \times 10^{16}$ cm).

Another characteristic of the ^{12}CO emission is that each of the ^{12}CO lobes is accompanied by ^{12}CO wings with the opposite velocity shifts; i.e., the red lobe is accompanied by weak blueshifted wings (hereafter refered to as *minor blue lobe*), and the blue lobe by redshifted wings (*minor red lobe*). These minor lobes are seen in the lower two panels of Figure 2, which shows the distribution of the lower velocity ^{12}CO wings with velocity shifts of 0.5–1 km s^{-1}. Figure 2*d* (8.8–9.3 km s^{-1}) indicates a fan-shaped redshifted feature on the east of the *IRAS* source. This is the minor red lobe toward the *major* blue lobe. Similarly, we can see the minor blue lobe in Figure 2*c* (7.3–7.8 km s^{-1}), which is less evident in Figure 2*a* (3.0–7.5 km s^{-1}). We consider that these four lobes are all driven by a common infrared source, IRAS 19345+0727, since the distribution of the four lobes indicates clear association with the *IRAS* source.

Langer, Frerking, and Wilson (1986) interpreted the minor red lobe as part of a second bipolar flow centered at ~7′ east of the *IRAS* source. The present high-resolution data, however, show that the minor red lobe has the fan-shaped collimation toward the infrared source; this lobe is most likely to be driven

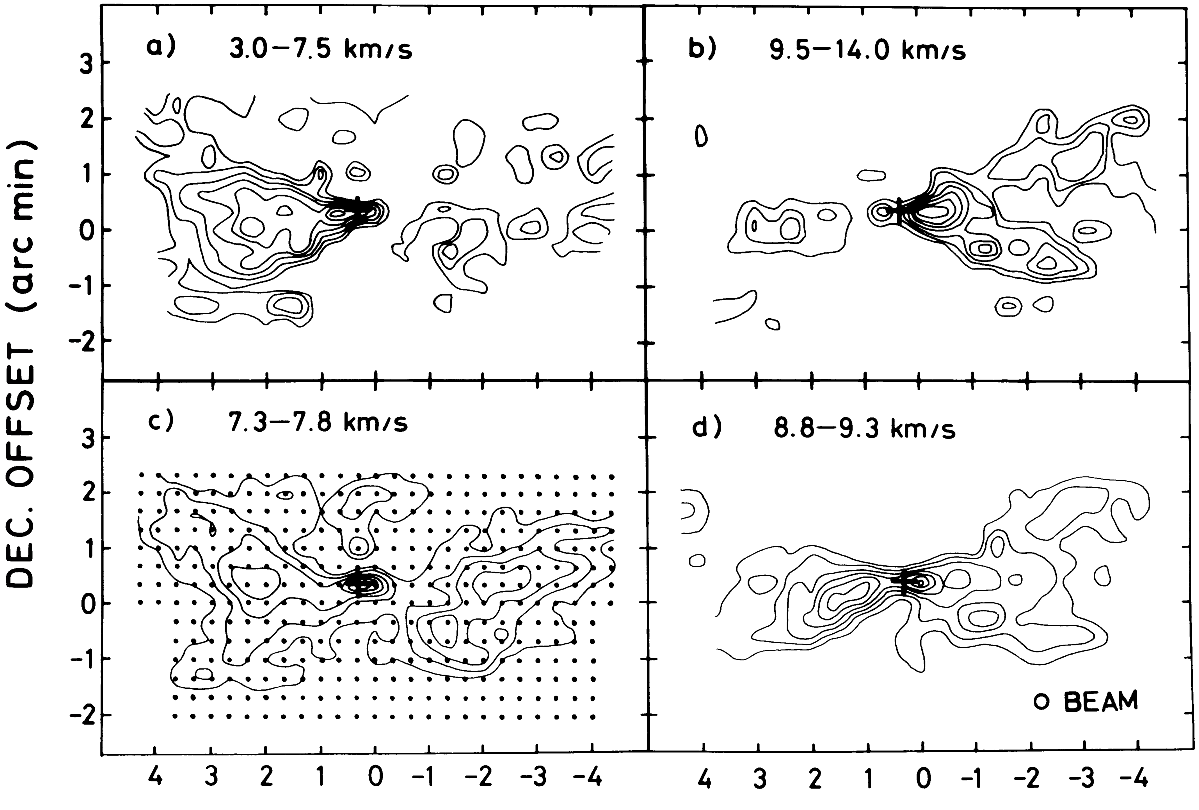

FIG. 2.—Integrated intensity maps of ^{12}CO ($J = 1$–0) emission at four velocity intervals: (*a*) 3.0–7.5 km s^{-1}; (*b*) 9.5–14.0 km s^{-1}; (*c*) 7.3–7.8 km s^{-1}; and (*d*) 8.8–9.3 km s^{-1}. The velocity intervals of upper two panels, (*a*) and (*b*), are the same as those of Fig. 2 of Goldsmith *et al.* (1984). The lowest contours are 0.9 K km s^{-1} for (*a*) and (*b*), and 0.45 K km s^{-1} for (*c*) and (*d*). The contour spacings are 0.6 K km s^{-1} for (*a*) and (*b*), and 0.3 K km s^{-1} for (*c*) and (*d*). The beam size and the observed points are indicated in (*d*) and (*c*), respectively. The position of IRAS 19345+0727 is shown by a plus sign in each panel.

by the same *IRAS* source and is not a contamination due to another evolved bipolar flow which has no apparent driving source.

b) *Model*

The coexistence of the redshifted and blueshifted emission in both lobes is well interpreted in terms of a biconical outflow whose axis is nearly perpendicular to the line of sight. This model consists of two circular cones having a common apex and a common symmetry axis and is characterized by two angles; an opening angle of the cone θ, and the inclination angle of the axis to the plane of the sky i. If $i < \theta/2$, the model predicts that each of the lobes is accompanied by a lower velocity lobe with the opposite velocity shift, as is just observed in B335. In the following, we shall determine the geometrical parameters of the conical outflow. We assumed for simplicity that the flowing gas is homogeneous and confined within a thin shell of biconical shape. We obtain tangent of the inclination angle i by

$$\tan i = \tan(\theta/2) \cdot \cos[\pi \cdot M_{\rm minor}/(M_{\rm major} + M_{\rm minor})] , \quad (1)$$

where $M_{\rm major}$ and $M_{\rm minor}$ are the masses of the major lobes and the minor lobes, respectively. These masses are estimated as follows. The column density of the ^{12}CO high velocity gas is calculated assuming LTE by

$$N_{\rm CO} = \frac{4.2 \times 10^{13} T_{\rm ex} \tau \int T_R(v)\,dv}{\exp(-5.5/T_{\rm ex}) \cdot [1 - \exp(\tau)]} \; ({\rm cm}^{-2}) , \quad (2)$$

where $T_{\rm ex}$ is the ^{12}CO excitation temperature, $T_R(v)$ is the ^{12}CO brightness temperature, τ is the averaged optical depth of the ^{12}CO line wings, and v is the relative velocity shift from the line center. We assumed the excitation temperature to be 10 K, equal to that of the ambient quiescent CO gas. We adopted an averaged optical depth of ~ 3.9 derived from ^{13}CO data by Goldsmith *et al.* (1984), because we could not obtain ^{13}CO data in our observing run. We assumed H$_2$/^{12}CO abundance ratio to be $\sim 1 \times 10^4$. This value agrees with the H$_2$/^{13}CO abundance ratio derived by Dickman (1978) within a factor of 2 for the terrestrial ^{12}CO/^{13}CO ratio. The mass of each lobe is then obtained by summing up the column densities of each position, as is summarized in Table 1. Using these masses and the opening angle of the flow, $\sim 45°$, we obtain the inclination angle i to be $\sim 10°$ from equation (1).

TABLE 1

MASSES OF THE FLOW

Lobe	East Lobe ($M_\odot$)	West Lobe ($M_\odot$)
Major	0.16 (blue)[a]	0.13 (red)[b]
Minor	0.07 (red)[b]	0.09 (blue)[a]
Total	0.22	0.22

[a] Velocity range: $V_{\rm LSR} = 2.8$–7.8 km s^{-1}.

[b] Velocity range: $V_{\rm LSR} = 8.8$–13.8 km s^{-1}.

c) *Dynamical Properties of the Flow*

The dynamical parameters of the flow are summarized in Table 2; in each row two values are given, one is corrected for the inclination effect (corrected), the other without the correction (uncorrected). The mass-weighted mean radial velocity of the flow relative to the quiescent cloud in B335 is very small, only 2.2 km s^{-1}. However, corrected for the effect of the inclination angle, the actual velocity of the flow is estimated to be ~ 13 km s^{-1}, not so small compared to those of typical molecular outflows (e.g., Lada 1985). By this correction, the momentum and kinetic energy of the flow are also increased by one and two orders of magnitude, respectively. The kinetic energy of 7×10^{44} ergs indicates that the flow in B335 is more energetic than previously suggested (e.g., Goldsmith *et al.* 1984).

The dynamical time scale, τ_d, estimated from the size of the flow, 0.3 pc, and its velocity, 13 km s^{-1}, is $\sim 2.3 \times 10^4$ yr, indicating that the flow in B335 is relatively young. Langer, Frerking, and Wilson (1986) detected the blueshifted emission centered at 10′ east of IRAS 19345+0727. We suggest that this is a part of the blue lobe driven by the same *IRAS* source. ^{12}CO wing emission may extend to the distance twice as large as that we observed; even so, the dynamical time scale does not exceed 6×10^4 yr.

To summarize, the high-resolution observations of the ^{12}CO ($J = 1$–0) emission in B335 shows a single bipolar flow the axis of which has a small inclination angle of $\sim 10°$. There is no evidence of overlapping of the two bipolar outflows, one of which is an evolved one as suggested by Langer, Frerking, and Wilson (1986). This implies that B335 contains no evolved flow source. Thus our observational results give further support to the idea that B335 is a site of very recent star formation as suggested by far-infrared and submillimeter observations. The infrared source IRAS 19345+0727 deserves further intensive research as one of the most probable candidates for the solar-type protostar.

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TABLE 2

ENERGETICS AND DYNAMICAL PARAMETERS

Parameter	Corrected for Inclination of 10°	Uncorrected for Inclination
Mean velocity: v (km s^{-1})[a]	13	2.2
Momentum ($M_\odot$ km s^{-1})[b]	5.7	0.97
Energy (ergs)[c]	7.4×10^{44}	2.1×10^{43}
Dynamical time scale (yr)	2.3×10^4	1.4×10^5
Mechanical luminosity: $L_{\rm mech}$ ($L_\odot$)	0.27	0.0013
Force: F (dyne)	1.7×10^{27}	4.6×10^{25}
$L_*/L_{\rm mech}$	10	2100
$(L_*/c)/F$	0.0002	0.0078

[a] Mass-weighted mean velocity of the flow material: $\Sigma \int m(v) \cdot v\,dv$/flow mass.

[b] Calculated by (flow mass) × v.

[c] Calculated by $\frac{1}{2} \cdot$ (flow mass) × v^2.

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