IRAS 16293–2422: EVIDENCE FOR INFALL ONTO A COUNTERROTATING PROTOSTELLAR ACCRETION DISK

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ABSTRACT

We report high spatial resolution VLA observations of the low-mass star-forming region IRAS 16293–2422 using four molecular probes: ethyl cyanide (CH3CH2CN), methyl formate (CH3OCHO), formic acid (HCOOH), and the ground vibrational state of silicon monoxide (SiO). Ethyl cyanide emission has a spatial scale of ~20′′ and encompasses binary cores A and B as determined by continuum emission peaks. Surrounded by formic acid emission, methyl formate emission has a spatial scale of ~6′′ and is confined to core B. SiO emission shows two velocity components with spatial scales less than 2′′ that map ~2′′ northeast of the A and B symmetry axis. The redshifted SiO is ~2′′ northwest of blueshifted SiO along a position angle of ~135° which is approximately parallel to the A and B symmetry axis. We interpret the spatial position offset in red- and blueshifted SiO emission as due to rotation of a protostellar accretion disk, and we derive ~1.4 M⊙ interior to the SiO emission. In the same vicinity, Mundy et al. also concluded rotation of a nearly edge-on disk from OVRO observations of much stronger and ubiquitous 13CO emission, but the direction of rotation is opposite to the SiO emission findings. Taken together, SiO and 13CO data suggest evidence for a counterrotating disk. Moreover, archival BIMA array 12CO data show an inverse P Cygni profile with the strongest absorption in close proximity to the SiO emission, indicating unambiguous material infall toward the counterrotating protostellar disk at a new source location within the IRAS 16293–2422 complex. The details of these observations and our interpretations are discussed.

Subject heading: ISM: abundances — ISM: clouds — ISM: individual (IRAS 16293–2422) — ISM: molecules — radio lines: ISM

1. INTRODUCTION

IRAS 16293–2422 is a low-mass star-forming region located in the ρ Ophiuchus cloud complex at a heliocentric distance of 160 pc. It contains an underdetermined number of protostellar objects, high-velocity outflows in the east-west and northeast-southwest directions (Stark et al. 2004), and the region is dominated by two radio continuum peaks designated cores A and B. These two principal cores are separated by ~5′′ and are often referred to as the “binary” system with a mass of 0.49 M⊙ for core A and 0.61 M⊙ for core B (Looney et al. 2000). Moreover, the gas and dust toward core A appears to be at a higher temperature than the dust toward core B and most of the molecular emission lines of high-energy transitions have been detected exclusively toward core A. The measured dust temperature toward core B is ~40 K (Mundy et al. 1986), and the measured temperature toward core A from many different molecular species is between 80 and 200 K (Chandler et al. 2005).

Spectral observations with the IRAM 30 m radio telescope toward the low-mass protostellar system IRAS 16293–2422 (Cazaux et al. 2003) demonstrated an extremely rich organic inventory with abundant amounts of complex oxygen- and nitrogen-bearing molecules including formic acid (HCOOH), methyl formate (CH3OCHO), acetic acid (CH3COOH), and methyl cyanide (CH3CN), which are archetypal species often found in massive hot molecular cores (HMCs). Subsequent spatial observations by Kuan et al. (2004) with the Submillimeter Array (SMA) mapped emission from high-energy transitions of CH3OCHO, vibrationally excited vinyl cyanide (CH2CHCN), and other large molecular species. In addition, Bottinelli et al. (2004) mapped slightly lower energy transitions of CH2CN and CH3OCHO with the Plateau de Bure interferometer, noting that all the molecular emission is contained toward cores A and B and that no large molecule emission is seen associated with the molecular outflows. Recently, Chandler et al. (2005) detected large abundances of a number of different organic molecular species primarily located toward core A from SMA observations. Moreover, from observations of sulfur monoxide (SO) absorbing against the background dust continuum near binary core B, Chandler et al. (2005) suggest that there must be material from an extended molecular envelope falling onto an embedded dust disk and that there may be a low-velocity outflow coming from an embedded protostar.

The discovery of large oxygen- and nitrogen-bearing molecules in a low-mass star-forming region is significant because the molecular complexity appears to be similar to high-mass star-forming regions. Such complex molecules undoubtedly are incorporated into subsequent formation of protoplanetary bodies and would provide a rich organic inventory that could be supplied to early planetary systems similar to that expected to have occurred in our own presolar nebula. With this in mind, we conducted high-resolution observations of IRAS 16293–2422 using the NRAO4 Very Large Array (VLA) using four molecular probes: ethyl cyanide (CH3CH2CN), methyl formate (CH3OCHO), formic acid (HCOOH), and the ground

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vibrational state of silicon monoxide (SiO) to determine the implication of their relative spatial locations. Surprisingly, the location of SiO is not cospatial with either core A or B. This prompted us to process archival BIMA array $^{12}$CO data for an explanation.

2. OBSERVATIONS

Observations of IRAS 16293$-$2422 were conducted with the VLA in 2005 June 27 and 28 in its BnC configuration. Formic acid (HCOOH) and methyl formate (CH$_3$OCHO) were observed simultaneously in one correlator setting and ethyl cyanide (CH$_3$CH$_2$CN) and silicon monoxide (SiO) in another correlator setting. Table 1 lists the molecule (col. [1]), transition quantum numbers (col. [2]), rest frequency (col. [3]), upper energy level $E_u$ (col. [4]), line strength $S$ (col. [5]), dipole moment $\mu_d$ (col. [6]), and molecular parameter reference (col. [7]).

The systematic LSR velocity of +3.9 km s$^{-1}$ assumes a rotational temperature of 54 K (Cazaux et al. 2003), which is computed to be hot (Chandler et al. 2005), while core B is thought to be much cooler (Mundy et al. 1986). A warm gas-phase chemistry or grain surface chemistry can lead to enhanced emission transitions ($E_u < 7.5$ K) of large molecules had been imaged toward this region.

3. RESULTS AND DISCUSSION

3.1. CH$_3$CH$_2$CN

Figure 1 shows a contour map of the 5$_{15}$$-$$4_{14}$ transition of CH$_3$CH$_2$CN superimposed on the 0.7 cm continuum emission (gray scale). The mapped CH$_3$CH$_2$CN emission region shows two blended emission peaks. Compared to the small naturally weighted beamwidth, a relatively large synthesized beamwidth of $10.0^\prime$ at $75.5$ is necessary to detect CH$_3$CH$_2$CN, which is extended with respect to cores A and B and the oxygen-bearing species (see § 3.2). Figure 1 also shows a Hanning-smoothed emission spectrum, which was extracted from the entire region of mapped emission, with an rms noise level of $\sim 7$ mJy beam$^{-1}$ shown on the left. The spectrum shows a relatively strong emission component at a local standard of rest (LSR) velocity of $+7.7$ km s$^{-1}$ and a possible weaker component at $+2.0$ km s$^{-1}$. The systemic LSR velocity of $+3.9$ km s$^{-1}$ (Bottinelli et al. 2004) is shown as a dashed line. We determine the total beam-averaged CH$_3$CH$_2$CN column density, $N_T$, using the formula

$$N_T = 2.04 \frac{Q(T_{rot})\Delta I dv}{\Delta I dv / T_{rot}} \times 10^{20} \text{ cm}^{-2},$$

which is described in Remijan et al. (2004), where $E_u$ is the upper state energy level (K); $T_{rot}$ is the rotational temperature (K); $\theta_a$ and $\theta_b$ are the major and minor axes of the synthesized beam (arcsec); $\Delta I dv$ is the observed integrated line intensity (Jy beam$^{-1}$ km s$^{-1}$); $\nu$ is the rest frequency (GHz); $S_{ij} \Delta t$ is the product of the transition line strength and the square of the electric dipole moment (debyes$^2$); and $Q(T_{rot})$ is the rotational partition function. $N_T(\text{EtCN}) ~ 5.2 \times 10^{14}$ cm$^{-2}$, which assumes a rotational temperature of 54 K (Cazaux et al. 2003), is listed in Table 2. For a molecular hydrogen column density of $7.5 \times 10^{22}$ cm$^{-2}$ (Cazaux et al. 2003), the CH$_3$CH$_2$CN fractional abundance, $X(Y/\text{EtCN})$, is $6.9 \times 10^{-9}$. These values are consistent to the column density of CH$_3$CH$_2$CN previously measured toward this source and is typical of the fractional abundance seen toward the Orion Compact Ridge (Cazaux et al. 2003).

The Figure 1 detection of extended emission with a spatial scale of $\sim 20''$ in a low-energy transition of CH$_3$CH$_2$CN demonstrates that there is a large envelope of cold molecular gas surrounding the compact binary cores A and B. Core A is reputed to be hot (Chandler et al. 2005), while core B is thought to be much cooler (Mundy et al. 1986). A warm gas-phase chemistry or grain surface chemistry can lead to enhanced emission
from nitrogen-bearing molecules in hot molecular cores (Remijan et al. 2004; Mehringer & Snyder 1996). In previous observations of IRAS 16293–2422 that sample high-energy level transitions at 1 and 3 mm, enhanced emission of nitrogen-bearing molecules have been detected toward cores A and B (e.g., CH3CN by Bottinelli et al. 2004; HCN, H2CN, and CH2CHCN by Kuan et al. 2004) on a typical spatial scale of ∼5''. Thus, our low-energy CH3CH2CN observations are complementary to these high-energy observations of other nitrogen-bearing molecules, suggesting both increasing temperature and density gradients toward cores A and B.

3.2. CH3OCHO and HCOOH

High-energy transitions of a number of different molecules have emission centroids near core A (e.g., see Fig. 9 of Chandler et al. 2005); in particular, CH3OCHO has high-energy transitions that are associated with core A (Chandler et al. 2005; Bottinelli et al. 2004; Kuan et al. 2004). The only large oxygen-bearing molecule detected by Chandler et al. (2005) toward core B is a low-energy transition of dimethyl ether (CH3OCH3). Figures 2 and 3 show maps of low-energy transitions of CH3OCHO and HCOOH, respectively, that are in proximity to core B. This is further evidence that core B is a much cooler protostellar core than core A. In Figure 2 the averaged emission from both the A and E states of CH3OCHO are mapped using a synthesized beamwidth of ∼2''6 × 1''8.

Figure 2 also shows an emission complex centered on the A and E states if one assumes an LSR velocity of +3.9 km s⁻¹. This complex appears to be suffering from the competing effects of emission and self-absorption. In order to observe both states in the same bandpass, the average frequency (45.3966 GHz) of both states was used in the observations and this average frequency corresponds to an LSR velocity of +3.9 km s⁻¹ in Figure 2, while the A and E states appear at −1.6 and +9.4 km s⁻¹, respectively. Figure 3 shows a map of the low-energy transition of HCOOH that surrounds the peak of core B and also the CH3OCHO emission in Figure 2; no HCOOH emission was detected in the vicinity of core A. In Figure 3 the emission from HCOOH was mapped using a synthesized beamwidth of ∼2''6 × 1''8, similar to the beamwidth used to map the CH3OCHO emission. The LSR velocity of HCOOH is +3.9 km s⁻¹, as indicated by the vertical dashed line in the spectrum, also shown in Figure 3.

The spatial distributions of CH3OCHO and HCOOH toward core B of IRAS 16293–2422 compare favorably to those same spatial distributions observed toward the Orion Molecular Cloud (OMC-1) compact ridge (Hollis et al. 2003; Liu et al. 2002). For example, in the OMC-1 compact ridge, Hollis et al. (2003) observed HCOOH emission surrounding CH3OCHO emission and suggested that the HCOOH emission delineates the leading edge of a shock front as the outflow from source “I” interacts with the quiescent ambient gas; the CH3OCHO emission, which is closer to source “I,” then represents the post-shock gas. If this scenario is correct for IRAS 16293–2422, then the corresponding outflow source associated with Figures 2 and 3 is likely core B itself. Indeed, Chandler et al. (2005) report evidence for material infall toward and also low-velocity outflow from core B; both conditions undoubtedly result in shock phenomena. Toward core A, enhanced abundances of large molecules provide indirect evidence for shocks to explain the enhancements (Chandler et al. 2005). The molecular differences between cores A and B are most likely explained by temperature differences and different protostellar ages. In any case, the presence of shocks seemingly leads to abundance enhancements in oxygen-bearing molecules, including large interstellar aldehydes located in high-mass star-forming regions like Sgr B2 (e.g., see Hollis et al. 2004a, 2004b).

Because the CH3OCHO emission appears to be self-absorbed, we can only give a lower limit to the column density over the entire emission complex. Since we have observed only low-energy transitions in this work, a conservative rotational temperature of 40 K (Mundy et al. 1986) is assumed, which yields \( N(E) \text{(MeF)} > 1.9 \times 10^{14} \text{cm}^{-2} \). Assuming an H2 column density of \( 1.6 \times 10^{24} \text{cm}^{-2} \) toward core B (Kuan et al. 2004), the CH3OCHO fractional abundance is \( X(\text{MeF}) > 1.2 \times 10^{-6} \). For the same rotational...
TABLE 2
Molecular Column Densities

| Molecule       | $v_{LSR}$ Range (km s$^{-1}$) | $\int I dv$ (Jy km s$^{-1}$) | $T_{rot}$ (K) | $N_T$ ($\times 10^{14}$ cm$^{-2}$) | $X$ ($\times 10^{-9}$) |
|----------------|-------------------------------|-------------------------------|---------------|------------------------------------|-------------------------|
| CH$_3$CH$_2$CN | +0.0 to +10.0                 | 0.34(9)                       | 54            | 5.2(1.4)                           | 6.9(1.4)                |
| CH$_3$OCHO     | −5.0 to +16.0                 | >0.22                         | 40            | >187                               | >11.7                   |
| HCOOH          | +0.0 to +8.0                  | 0.07(3)                       | 40            | 41(17)                             | 2.5(1.7)                |

Note.—SiO is likely masering and is therefore not included in this table (see text).

Fig. 2.—Spectrum and map of the $S_{11}$−$A_4$ A and E state transitions of CH$_3$OCHO. The spectrum, which was taken from the entire region of mapped emission, is Hanning-smoothed over three channels. The rms noise level of $\sim$2 mJy beam$^{-1}$ is shown at the left. The average frequency of the A and E state transitions appears at an LSR velocity of $+3.9$ km s$^{-1}$. The contour map of the CH$_3$OCHO emission is shown superimposed on 0.7 cm continuum emission (gray scale). The contour levels are $0.008$, $0.010$, $0.012$, $0.014$, and $0.016$ Jy beam$^{-1}$ ($0.010$ Jy beam$^{-1} = 5\sigma$). The synthesized beamwidth is shown at the bottom left of the map.

Fig. 3.—Spectrum and map of the $2_{02}$−$1_{01}$ transition of HCOOH. The spectrum, which was taken from the southernmost region of mapped emission toward core B, is Hanning-smoothed over three channels. The rms noise level of $\sim$2 mJy beam$^{-1}$ is shown at the left. The spectrum shows the HCOOH emission is centered at the systemic LSR velocity of $+3.9$ km s$^{-1}$ (vertical dashed line). The contour map of the HCOOH emission is shown superimposed on 0.7 cm continuum emission (gray scale). The contour levels are $-0.007$, $-0.009$, $0.011$, $0.014$, $0.016$, and $0.018$ Jy beam$^{-1}$ ($0.011$ Jy beam$^{-1} = 5\sigma$). The synthesized beamwidth is shown at the bottom left of the map.
temperature, $N_T(\text{HCOOH}) \sim 4.1 \times 10^{15}$ cm$^{-2}$ and the HCOOH fractional abundance is $X(\text{HCOOH}) \sim 2.5 \times 10^{-9}$ (see Table 2).

3.3. SiO

Figure 4 shows redshifted and blueshifted SiO ($J = 1-0$, $v = 0$) emission contours mapped separately over the 0.7 cm continuum (gray scale). These two components of the SiO emission are seen at LSR velocities of $+2.3$ and $+7.9$ km s$^{-1}$, which are approximately symmetrical around the systemic LSR velocity of 3.9 km s$^{-1}$. The peak intensity maps, which are reminiscent of SiO maser spots, are shown at these velocities. The resulting synthesized beamwidth of $\sim 1.5'' \times 0.8''$ is shown at the bottom left of the map. Also shown in Figure 4 is a spectrum that is averaged over the SiO-emitting regions and Hanning-smoothed over three channels; the rms noise level is $\sim 3$ mJy beam$^{-1}$, shown to the left.

This is the first detection of the $J = 1-0$, $v = 0$ transition of SiO toward IRAS 16293$-$2422 and the first map of the compact emission from SiO in the vicinity of cores A and B. Previous surveys by Blake et al. (1994) and Ceccarelli et al. (2000) detected weak emission features of higher energy transitions of $v = 0$ SiO using single-element radio telescopes. From a chemical model of the IRAS 16293$-$2422 region, Ceccarelli et al. (2000) concluded that an enhanced abundance of SiO was necessary to account for the excess emission from the higher $J$-level transitions and that the emission must be coming from a compact ($< 3''$) region. Finally, their model calculated an infall velocity of SiO of 2.8 km s$^{-1}$ that was consistent with their observed $\sim 5$ km s$^{-1}$ line widths.

From our high-resolution VLA observations, we find that the blue- and redshifted SiO emission peaks have a spatial separation of $\sim 2''$ and the center of the SiO emission centroid is
located at $\alpha = 16^h32^m22^s875$, $\delta = -24^\circ28^\prime32^\prime\prime48$ (J2000.0). This location is within 0.6 of the pointing position and location of the $^{13}$CO emission centroid taken with the Owens Valley Radio Observatory (OVRO) millimeter array (Mundy et al. 1986) and the peak position of CS emission taken with the IRAM 30 m (Menten et al. 1987). From the red- and blueshifted emission peaks, Mundy et al. (1986) inferred a rotational velocity of 2 km s$^{-1}$ and a $2 M_\odot$ rotating disk of material internal to the $^{12}$CO emission. From the CS data, Menten et al. (1987) inferred a rotational velocity of 1.1 km s$^{-1}$ from lower resolution observations and a $4 M_\odot$ rotating disk of material. From the high-resolution SiO data, we determine a rotational velocity of $\sim 2.8$ km s$^{-1}$, and for an IRAS 16293−2422 distance of 160 pc, the mass interior to the SiO emission is $\sim 1.4 M_\odot$. However, assuming the SiO emission is associated with rotation, the compact disk containing the SiO emission is counterrotating with respect to the previously reported $^{13}$CO and CS emission. From archival BIMA array data taken of the $J = 2$−1 transition of $^{12}$CO at 230.538 GHz, we find both emission and absorption toward IRAS 16293−2422. Moreover, the spectrum of the $^{12}$CO data clearly show an inverse P Cygni profile with the strongest absorption in close proximity to the SiO emission (Fig. 5), indicating unambiguously, material infalling toward the molecular disk. Chandler et al. (2005) also suggest there is evidence for infall toward core B from the absorption profile of SO taken with the SMA.

It is important to note that we have only observed small-scale, blueshifted emission and small-scale, redshifted absorption of $^{12}$CO in the vicinity of cores A and B (see the image in Fig. 5); these data possess the characteristic signature of infalling matter (i.e., an inverse P Cygni profile shown in Fig. 5). While the $^{12}$CO emission encompasses cores A and B, the more compact absorption occurs at a discrete position $\sim 3.5$ north of core A and $\sim 2.5$ west of core B (see Fig. 4). On the other hand, large-scale $^{12}$CO has been observed in redshifted emission and blueshifted emission by other investigators, who reasonably interpret these results as outflow whose origin has traditionally been assigned to core A. Thus, $^{12}$CO on two different spatial scales indicate two different phenomena: one of infall on a small scale toward a newly detected protostellar accretion disk whose position is precisely determined and one of large-scale outflow whose exact origin may be difficult to determine. The location of the accretion disk that we have detected seems to account for our small-scale SiO observations and the somewhat larger scale $^{13}$CO observations of Mundy et al. (1986) and CS observations of Menten et al. (1987) only if the nearly edge-on disk is counterrotating since the direction of rotation is opposite for SiO when compared to either $^{13}$CO or CS. Additional observational support for this scenario can be seen in the BIMA and OVRO array images of Schöier et al. (2005), who observed a number of low-energy transitions (i.e., the $J = 1$−0 of HCO$^+$, HNC, and N$_2$H$^+$ and the $J = 2$−1 of C$^{15}$O and SiO). In these images, for example, the $J = 2$−1 transition of SiO suggests rotation in the opposite direction to the $J = 1$−0 transition of HCO$^+$. Compared to the VLA data presented in this work, these BIMA and OVRO data have an order-of-magnitude coarser spatial resolution that precludes an exact determination of the SiO emission locations that are apparent in the VLA map shown in Figure 4. Furthermore, SiO is a refractory molecule that can withstand high temperatures and would likely exist closer to a forming protostellar source than most other molecules.

Thus, the high-resolution VLA observations have shown, for the first time, evidence for a new protostellar core with a compact inner portion of the disk containing the SiO emission counterrotating with respect to the outer portion of the disk containing $^{13}$CO and CS. Counterrotating cores have been reported in disks of galaxies before (e.g., Thomas et al. 2006 and references therein), but this is the first indication of such behavior in a protostellar accretion disk.

4. CONCLUSIONS

To summarize, we find a low-temperature envelope of molecular CH$_3$CH$_2$CN emission that is encompassing the IRAS 16293−2422 cores A and B. Furthermore, low-frequency, low-energy transitions of large oxygen-bearing molecules (i.e., HCOOH and CH$_3$OCHO) are seen toward core B, where an
outflow may be responsible for a low-velocity shock that is leading to enhanced abundances of large oxygen-bearing species. Also, the SiO emission shows two velocity components with spatial scales less than 2<sup>″</sup> and a velocity separation of ~5.6 km s<sup>−1</sup>. We interpret the spatial position offset in red- and blueshifted SiO emission as due to the rotation of a protostellar accretion disk, and we derive ~1.4 <i>M<sub>S</sub></i> interior to the SiO emission.

While it could be that the SiO complex we observe is due to outflow, evidence is accumulating to the contrary that rotation is the explanation. Such evidence is best seen on a small scale. The SiO observations in the present work show two velocity components each with line widths of ~5 km s<sup>−1</sup>, suggesting rotation of a disk seen edge-on since the two components are not cospatial, are symmetric about an infall location, and have a velocity gradient perpendicular to large-scale CO outflow. Moreover, images of other molecules on a small scale also show that their velocity gradients are orthogonal to the direction of outflow seen on a large scale (e.g., Schöier et al. 2005). In this work, we have been very careful to match the synthesized beam to the source emission or absorption to pin-point the location of a new source of infall ~3<sup>″</sup> north of core source A and ~2<sup>″</sup> west of core source B. We have done this by two independent sets of observations (i.e., the VLA in SiO emission and the BIMA array in 12CO absorption). While there are no previous reports of continuum emission at this location, an inverse P Cygni profile is absolute proof of absorption against background continuum, and our BIMA data show that the location is smaller than the synthesized beam (i.e., 3<sup>″</sup>2 × 0″8). Thus, the continuum source is undoubtedly small (e.g., a disk seen edge-on) and may eventually be detected by an interferometer at high resolution with enough integration time.

However, the compact disk containing the SiO emission is counterrotating with respect to the 12CO and CS emission seen by other investigators. This is the first report of evidence for a counterrotating accretion disk toward a low-mass protostellar complex. Moreover, archival BIMA array 12CO data show an inverse P Cygni profile with the strongest absorption in close proximity to the SiO emission, indicating unambiguously, material infalling toward the counterrotating protostellar disk. The infall location is compelling evidence for a new protostellar source within the IRAS 16293−2422 complex.

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