ON THE ORIGIN OF THE MOLECULAR OUTFLOWS IN IRAS 16293–2422

Josep M. Girart1, Robert Estalella2, Aina Palau1, José M. Torrelles1,2, and Ramprasad Rao3

1 Institut de Ciències de l’Espai (CSIC-IEEC), Campus UAB, Facultat de Ciències, C5p 2, E-08193 Bellaterra, Catalonia, Spain; girart@ice.cat
2 Departament d’Astronomia i Meteorologia, Institut de Ciències del Cosmos (UB-IEEC), Martí i Franquès, Universitat de Barcelona, E-08028 Barcelona, Catalonia, Spain
3 Institute of Astronomy and Astrophysics, Academia Sinica, 645 N. Aohoku Pl., Hilo, HI 96720, USA

Received 2013 September 20; accepted 2013 November 15; published 2013 December 13

ABSTRACT

We present CO 3–2, SiO 8–7, C18O 7–6, and 878 μm dust continuum subarcsecond angular resolution observations with the Submillimeter Array (SMA) toward the IRAS 16293–2422 (I16293) multiple low-mass protostellar system. The C18O emission traces the 878 μm dust continuum well, and in addition clearly shows a smooth velocity gradient along the major axis of component I16293A. CO shows emission at moderate high velocities arising from two bipolar outflows, which appear to be perpendicular with respect to each other. The high sensitivity and higher angular resolution of these observations allows us to pinpoint the origin of these outflows at the center of component I16293A. Interestingly, the most compact outflow appears to point toward I16293B. Our data show that the previously reported monopolar blueshifted CO outflow associated with component I16293B seems to be part of the compact outflow arising from component I16293A. In addition, the SiO emission is also tracing this compact outflow: on the one hand, the SiO emission appears to have a jet-like morphology along the southern redshifted lobe; on the other hand, the SiO emission associated with the blueshifted northern lobe traces a well-defined arc on the border of component I16293B facing I16293A. The blueshifted CO lobe of the compact outflow splits into two lobes around the position of this SiO arc. All these results lead us to propose that the compact outflow from component I16293A is impacting on the circumstellar gas around component I16293B, possibly being diverged as a consequence of the interaction.

Key words: ISM: individual objects (IRAS 16293–2422) – ISM: jets and outflows – ISM: molecules – stars: formation

Online-only material: color figures

1. INTRODUCTION

The dark cloud Lynds 1689N, located in the Ophiuchus star-forming region at a distance of 120 pc (Kuiper & Hog 1998; Loinard et al. 2008; Lombardi et al. 2008), harbors IRAS 16293–2422, one of the best studied low-mass (class 0) protostellar systems (hereafter I16293; see Alves et al. 2012; Kristensen et al. 2013; Loinard et al. 2013; Zapata et al. 2013, and references therein). This system has two main components, I16293A and I16293B, separated by ~5′′ (~600 AU), first detected at cm-continuum wavelengths (Wootten 1989; Estalella et al. 1991) and later also detected at (sub)millimeter wavelengths (e.g., Chandler et al. 2005; Rodríguez et al. 2005; Rao et al. 2009; Pineda et al. 2012; Loinard et al. 2013). While I16293A shows an “hourglass” magnetic field structure, I16293B shows an ordered magnetic field (Rao et al. 2009). Wootten (1989) found that I16293A splits into two subcomponents at cm wavelengths (usually referred as A1 and A2), separated by 0.3 (36 AU) and tracing two stars in a binary system (e.g., Loinard et al. 2007). H2O maser emission is also observed toward this binary (Wilking & Claussen 1987; Wootten 1989; Imai et al. 2007), tracing zones of compressed gas produced by shocks in the presence of very strong line-of-sight magnetic fields (~113 mG, Alves et al. 2012). I16293 has two bipolar outflows at scales of ~0.1 pc (Walker et al. 1988; Mizuno et al. 1990), one of them centered on I16293A (Yeh et al. 2008). A third, more compact bipolar molecular outflow has been also reported through Submillimeter Array (SMA) observations, centered on I16293A and extending along an axis through I16293A and I16293B (SE–NW direction; Rao et al. 2009). The observations indicate that most of the outflow activity in this region is concentrated on the sources within I16293A, with little outflow activity (if any) in the nearby I16293B component, where a compact, possibly isolated, protoplanetary disk around a protostar has been inferred (Rodríguez et al. 2005). However, very recent ALMA CO 6–5 observations with an angular resolution of ~0′′.3 led Loinard et al. (2013) seem to suggest that I16293B is ejecting a blueshifted bubble-like outflow with low velocity and moderate collimation. Based on these results, together with the small kinematic age estimated for this outflow, these authors proposed that I16293B is the youngest object in the region, and one of the youngest protostars known (Loinard et al. 2013).

In this Letter, we present new SMA CO 3–2, SiO 8–7, C18O 7–6, and continuum observations at 345 GHz toward I16293. Our observations are more sensitive to extended structures (~20′′) than those of the recently reported 690 GHz ALMA observations (the visibility range for ALMA is 62–943 kλ, and for the SMA is 20–240 kλ). Due to these observational properties, our data show that the blueshifted outflow reported previously with ALMA data seems to be part of a bipolar outflow originating from one of the stars within I16293A, rather than originating from I16293B as was recently proposed. More importantly, this bipolar outflow is interacting with I16293B producing a shock structure at its southwest edge seen in SiO.

2. OBSERVATIONS

The SMA observations were taken on 2010 August 28 in the extended configuration. These observations were performed in
the polarimetric mode. The results of the polarization data have been presented in a different paper (Rao et al. 2013). The receiver was tuned to cover the 333.5–337.5 GHz and 345.5–349.5 GHz frequencies in the lower side band (LSB) and upper side band, (USB) respectively. The phase center of the telescope was R.A. (J2000.0) = 16^h 32^m 22^s 90 and decl. (J2000.0) = −24° 28′ 35″ 73. The correlator provided a spectral resolution of about 0.8 MHz (i.e., 0.7 km s⁻¹ at 345 GHz). The gain and bandpass calibrators were QSO J1733-130 and QSO 3C454.3, respectively. The absolute flux scale was determined from observations of Neptune. The flux uncertainty was estimated to be ≃20%. The data were reduced using the MIRIAD software package (Wright & Sault 1993). Self-calibration was performed independently for the USB and LSB on the continuum emission of I16293. We have selected the CO 3–2 (345.796 GHz) and SiO 8–7 lines (347.331 GHz), to trace the outflow activity in I16293, and the C³⁴S 7–6 (337.396 GHz) line to trace the circumstellar gas in the region. In addition, the dust continuum at 878 μm is also presented. Maps were obtained from the visibilities using natural weighting, which yielded a synthetic beam size of ≃0.8′′, and allowed the tracing of smaller spatial scales (≃100 AU) around I16293 than the scales (≃300 AU) traced by Rao et al. (2009).

3. RESULTS

Figure 1 shows the channel maps of the high velocity component of the CO 3–2 emission. This figure shows that the high velocity gas exhibits a quadrupolar morphology well centered in I16293A, apparently forming two bipolar molecular outflows, an extended east–west outflow and a compact northwest–southeast outflow (the direction of these two outflows are delineated in Figure 1(b)). The east–west outflow consists of blueshifted emission in the eastern lobe (with some redshifted gas at low flow velocities) and redshifted emission in the western lobe. This bipolar outflow has been previously well studied and extends to distances of 0.1 pc from its powering source (Mizuno et al. 1990; Hirano et al. 2001; Yeh et al. 2008), far beyond the SMA field of view.

The northwest–southeast bipolar outflow extends only ≃8″ (0.005 pc, 1000 AU), so it is very compact compared with the other two bipolar outflows detected in the region (Mizuno et al. 1990). This compact northwest–southeast bipolar outflow was already reported by Rao et al. (2009), but our new SMA observations now reveal it more clearly (in particular from the SiO data; see below). At low outflow velocities the blueshifted lobe appears to split in two parts just before reaching I16293B (Figures 1(c) and (d)). At higher velocities (Figures 1(a) and (b)) the blueshifted gas ends at the position of I16293B. Another characteristic of the outflow is an apparent acceleration of the gas, with the higher velocities appearing further from the driving source. This is more evident in the position–velocity cut along the blueshifted lobe (Figure 2(a)): the terminal outflow velocity increases with distance from the source. A cut across the blueshifted lobe (Figure 2(b)) shows that the highest outflow velocities are spatially more compact than the outflow component at velocities closer to the systemic velocity of the I16293A core, suggesting that the outflow is more collimated at higher outflow velocities.

The SiO 8–7 emission (Figure 3) appears to arise mainly from two patches of emission. One of them extends from I16293A, in a jet-like structure, toward the southeast following well the redshifted lobe of the compact northwest–southeast outflow seen in CO 3–2. Most of the emission in the jet-like structure appears close to the cloud velocity but slightly redshifted (v_{LSR} ≃ 3.0–12.0 km s⁻¹). On the other hand, the northern patch of SiO emission shows a clear partial ring surrounding I16293B, facing I16293A (Figure 3), and appears near the position where the blue lobe of the CO compact northwest–southeast outflow diverges spatially (Figure 1).

The C³⁴S 7–6 mainly traces the circumstellar gas around I16293A at scales of a few hundreds AU and matches the 878 μm dust emission very well (Figure 4). Both the circumstellar molecular gas and the dust structures are elongated along the northeast–southwest direction (P.A. ≃ 41°), with position–velocity cuts of the CS emission along and across the major axis suggesting that the gas is rotating with a Keplerian-like pattern. Below, we describe the procedure to fit the C³⁴S 7–6 emission toward I16293A with a rotating geometrically thin disk.

3.1. Thin Disk Model for I16293A

We considered a geometrically thin disk, with an inner (r_i) and outer (r_o) radius. The angle between the disk axis and the plane of the sky is i (i = 0° for an edge-on disk). We consider a rotation velocity given by a power law of the radius, v_r (r/r_o)^(β), where r_o is an arbitrary reference radius and v_r is the rotation velocity at the reference radius.

We computed, for each point of a regular grid in the plane of the sky, the projection of the rotation velocity of the corresponding point of the disk along the line of sight v_r. A Gaussian line profile of width Δv and centered on v_r was added to the channels associated with the grid point. Finally, each channel map was convolved spatially with a Gaussian beam of width Δs. However, the intensity scale of the channel maps is arbitrary. A scaling factor, the same for all channel maps, was obtained by minimizing the sum of the squared differences between the data channel maps and the synthetic channel maps. The model depends on a total of ten parameters, namely the beamwidth, Δs; the linewidth, Δv; the disk center, (x_0, y_0); the disk systemic velocity, v_0; the disk inner and outer radii, r_i and r_o; the disk rotation velocity at the reference radius, v_r; the radial dependence power-law index of the rotation velocity, q_r; and the disk inclination angle, i. Some of the parameters are known beforehand, such as Δs and Δv. Some other can be guessed based on physical grounds (i.e., q_r = −0.5). These considerations leave seven free parameters, the first three are geometrical (x_0, y_0, v_0), and the last four have physical interest (r_i, r_o, v_r, and i), which can be estimated through model fitting to the data.

The fitting procedure was the sampling of the seven-dimensional parameter space, using the same procedure as that described in Estalella et al. (2012) and Sánchez-Monge et al. (2013). The parameter space was searched for the minimum value of the rms fit residual. Once a minimum of the rms fit residual was found, the uncertainty in the parameters fitted was found as the increment of each of the parameters of the fit necessary to increase the rms fit residual by a factor of [1 + Δ(m, α)/(n – m)]^1/2, where n is the number of data points fitted, m is the number of parameters fitted, and Δ(m, α) is the value of χ^2 for m degrees of freedom (the number of free parameters) and α is the significance level (0 < α < 1). For m = 7, and for a significance level of 0.68 (equivalent to 1 σ for a Gaussian error distribution), the increment in the rms fit residual is given by Δ(7, 0.68) = 8.17 (Sánchez-Monge et al. 2013).

The model was fitted to the C³⁴S 7–6 emission associated to I16293A. The rotation axis in the plane of the sky (derived from the CS velocity gradient) was found to be at a position...
Figure 1. Channel maps of the CO 3–2 for the blueshifted (blue contours) and redshifted (red contours) emission, overlapped with the 878 μm dust emission (black contours and gray scale). Panels (a)–(c): the CO contour’s step level and the first contour are 0.47 Jy beam$^{-1}$. Panel (d): the CO contour’s step level as well the first contour is 0.65 Jy beam$^{-1}$. In all panels the first contour is at 2σ level. The dust contours show the emission at the 5%, 30%, 55%, and 80% level of the maximum intensity, 1.88 Jy beam$^{-1}$. The outflow velocity (i.e., the velocity of the gas with respect to the systemic velocity of I16293A, ≃3.5 km s$^{-1}$) of each channel is indicated in the top left corner of each panel. The offset spatial positions are with respect to the phase center (given in Section 2). The green dashed line in panel (b) shows the cavity traced by the E–W CO lobe at scales of ~3000 AU (Yeh et al. 2008). The synthesized beam size of the maps is shown in the bottom left corner of panel (d). (A color version of this figure is available in the online journal.)
Figure 2. Position–velocity plots of the CO 3–2 emission along (panel (a)) and across (panel (b)) the blueshifted lobe of the northwest–southeast compact outflow. The reference position (0″ offset) is R.A. (J2000.0) = 16h32m22.65 and decl. (J2000.0) = −24°28′35″. I16293A, the driving source of this outflow, is located approximately at the top of panel (a) (offset position of +3″). The vertical dashed line indicates the systemic velocity of I16293A. The red lines are shown to better indicate the velocity gradient of the blueshifted CO emission. (A color version of this figure is available in the online journal.)

Table 1
Parameters of the Best-fit Model

| Parameter                  | Units  | Value  |
|----------------------------|--------|--------|
| **Fixed:**                 |        |        |
| Beamwidth Δs               | arcsec | 0.82   |
| Linewidth Δv               | km s⁻¹ | 1.20   |
| Rotation power-law index qₚ |        | −0.50  |
| **Fitted:**                |        |        |
| Disk center x₀             | arcsec | −0.12 ± 0.02 |
| Disk center y₀             | arcsec | 0.20 ± 0.01  |
| Disk systemic velocity v₀  | km s⁻¹ | 3.49 ± 0.09  |
| Disk inner radius rᵢ       | AU     | 1 ± 1   |
| Disk outer radius rₒ       | AU     | 140 ± 2  |
| Rotation velocity vₒa      | km s⁻¹ | −6.5 ± 0.2  |
| Disk inclination i          | deg    | 44.2 ± 0.9 |

*Note.* a For a reference radius r₀ = 0′.4 (48 AU).

The fit for the disk inner radius can only be interpreted in the sense that the contribution of the emission near the disk center is low. The simple kinematical model used here cannot discard the idea that the inner radius is actually larger, as suggested by the binarity of the central source, with a semi-major axis of 0′.35 (Loinard et al. 2007).

The mass of the protostar in source A can be estimated from the values derived from the disk fitting. Assuming Keplerian rotation (M = r v² / G), the mass is M₁₁₆₂₉₃A = 2.3 ± 0.1 M☉. This mass is similar to the mass derived from the relative motions of the A1 and A2 objects (Pech et al. 2010, these two objects are embedded in the C³⁴S structure).

4. DISCUSSION AND CONCLUSIONS

The first single-dish observations in I16293 showed two bipolar molecular outflows, one extended along the northeast (redshifted)–southwest (blueshifted) direction, and another angle of −40°.8. The best fit values and their errors are shown in Table 1. Figure 4 shows the comparison of the synthetic position–velocity cuts for the best solution with those for the SMA C³⁴S 7–6 data, with the best fit values matching the data very well. The model used assumes that the intensity is proportional to the geometrical depth of the disk along the line of sight (i.e., optically thin emission, and constant density and temperature), which is reasonable for the C³⁴S emission, except near the disk center. Thus, the non-zero value obtained from
Figure 4. Bottom panel: color image of the first order moment (velocity field) of the C$^{34}$S 7–6 line toward I16293A. The color scale (in km s$^{-1}$) is shown on the right side of the panel. The black thick dashed contours show the 878 μm continuum emission. The thick dashed blue and red arrows show the direction of outflows. Top panels: velocity–position plots of the C$^{34}$S 7–6 lines taken along the minor (panel (a)) and major (panel (c)) axes. Panels (b) and (d) show the modeled data. (A color version of this figure is available in the online journal.)
along the east (blueshifted)–west (redshifted) direction (Walker et al. 1988; Mizuno et al. 1990). The northeast–southwest outflow has not been detected at smaller scales through interferometric observations, suggesting that it might be a fossil outflow (Yeh et al. 2008; Rao et al. 2009). The east–west outflow has been well detected and studied with the SMA at arcsecond angular resolution (Yeh et al. 2008; Rao et al. 2009). The CO emission associated with the western lobe at scales of ∼3000 AU appears to follow a parabolic cavity with an inclination angle of 30° with respect to the plane of the sky (see the green dashed line in Figure 1; Yeh et al. 2008). However, our maps show that near the protostars the CO outflow emission does not follow this parabolic cavity. At the position of I16293A the CO 3–2 outflow is very bright and extends roughly in the direction of the east–west outflow. At the highest velocity channel (Figure 1(a)) the CO emission around I16293A is compact and the blue and redshifted peaks form a position angle of ∼100°, so they are possibly also associated with the east–west outflow.

The relatively high velocity CO 3–2 emission as traced by the SMA delineates a well-defined bipolar compact outflow of only 0.005 pc in the northwestern–southeast direction, well centered around I16293A, as was already suggested by Rao et al. (2009). However, this differs from what has recently been reported from ALMA CO 6–5 observations (Loinard et al. 2013; Kristensen et al. 2013). There are some observational features that support our statement. First, the northwestern–southeast outflow appears to be parallel to the rotation axis of the circumstellar disk-like structure, traced by the C³⁴S, around I16293A (see Figure 4). Second, the overall kinematical and morphological features of the northwestern blue lobe appear to be very consistent with those of the prototypical molecular outflows associated with class 0 protostars (e.g., Arce & Sargent 2006; Palau et al. 2006) if it is powered by I16293A: it has a conical-like structure starting in this source; the CO 3–2 channel maps show an apparent Hubble-like velocity structure (higher velocities arise farther from the powering protostar: see also the position–velocity cut along the blue lobe in Figure 2); and a cut across the blue lobe shows (Figure 2) that the highest CO 3–2 velocities occur along the outflow axis (i.e., the highest velocities are more collimated than the lowest). Third, the SiO emission is found only along the southeastern–northeast direction. The SiO is a molecule that traces shocks strong enough to produce dust sputtering, releasing silicates from the dust mantles (e.g., Anderl et al. 2013). The morphology of the SiO emission associated with I16293B suggests that the SiO arises from the external shells of the circumstellar material of this component. Its location, facing component I16293A and overlapping with the northwestern blueshifted lobe, suggests that the SiO traces the region where the northwestern–southeast outflow (powered by I16293A) is impacting on the circumstellar gas around I16293B. In fact, the SiO spectrum of the emission around I16293B is much broader than the acetaldehyde (CH₃CHO) spectrum (see Figure 2(b)). Acetaldehyde is a hot core tracer and is likely tracing the quiescent (apparently unperturbed) circumstellar gas in I16293B.

The terminal velocity of this compact outflow is small, ∼13 km s⁻¹. This outflow is in projection perpendicular to the major axis of the disk-like structure associated with I16293A, so we can fairly assume that this configuration holds in three dimensions. Thus correcting for the outflow inclination (44°, see Table 1), we find a dynamical timescale of ∼400 yr. This is much smaller than the kinematic timescale of the extended east–west outflow (5000 yr, Mizuno et al. 1990). We also estimated the outflow parameters of the compact northwest–southeast outflow following Palau et al. (2007), and assuming the same inclination given above, optically thin emission, and an excitation temperature of ∼18 K (derived from the line peak of the CO 3–2 spectrum). We obtained a total mass of ∼2 × 10⁻⁴ M⊙, a mass outflow rate of ∼5 × 10⁻⁷ M⊙ yr⁻¹, and a momentum rate of ∼6 × 10⁻⁹ M⊙ km s⁻¹ yr⁻¹. The momentum rate and the bolometric luminosity of I16293A (somewhat smaller than ∼25 L⊙, which is the total luminosity in the region) match the correlation between bolometric luminosity and outflow momentum rate found in the literature (Beltrán et al. 2008; Takahashi & Ho 2012). Yet, the small outflow mass and dynamic time scales suggest that this is a very young molecular outflow, possibly being powered by the youngest protostar in the region. Finally, we note that the water masers detected in the region appear to be redshifted and located only 0.'1 (12 AU) south and south-east (P.A. = 157°–182°) from source A1 (Pech et al. 2010; Alves et al. 2012). This suggests that A1 could be the powering source of the compact outflow (its south-east lobe is also redshifted).

In summary, the SMA data presented suggest a scenario where I16293A consists of at least two protostars, one driving the east–west outflow, and another driving a more compact and chemically rich northwest–southeast outflow (possibly A1). Both protostars in I16293A are embedded in a circumbinary disk traced by the 878 μm continuum and the C³⁴S 7–6 emission, which is elongated perpendicular to the northwestern–southeast outflow and presents a velocity gradient also perpendicular to this outflow. This situation is similar to what is found in the intermediate-mass protostellar system IRAS 22198+6336, where a binary is driving two perpendicular outflows, and is embedded in a disk rotating perpendicularly to the most chemically rich outflow (Sánchez-Monge et al. 2010; Palau et al. 2011). Finally, the northwestern–southeast outflow driven by one of the protostars in I16293A seems to be impacting on I16293B, as revealed by the SiO 8–7 emission showing an arc-morphology at the border of I16293B facing I16293A. The physical and chemical effects of such an interaction on the dynamics and evolution of I16293B remain to be studied.

The SMA, a joint project between the Smithsonian Astrophysical Observatory and the Academia Sinica Institute of Astronomy and Astrophysics, is funded by the Smithsonian Institution and the Academia Sinica. J.M.G. thanks the SMA staff at Hilo for their support. R.E., J.M.G., A.P., and J.M.T. are supported by the Spanish MINECO AYA2011-30228-C03 and Catalan AGAUR 2009SGR1172 grants. The ICC (UB) is a CSIC-Associated Unit through the ICE (CSIC).

REFERENCES

Alves, F. O., Vlemmings, W. H. T., Girart, J. M., & Torrelles, J. M. 2012, A&A, 542, A14
Anderl, S., Guillet, V., Pineau des Forêts, G., & Flower, D. R. 2013, A&A, 556, A69
Arce, H. G., & Sargent, A. I. 2006, ApJ, 646, 1070
Beltrán, M. T., Estalella, R., Girart, J. M., Ho, P. T. P., & Anglada, G. 2008, A&A, 481, 93
Chandler, C. J., Brogan, C. L., Shirley, Y. L., & Loinard, L. 2005, ApJ, 632, 371
Estalella, R., Anglada, G., Rodríguez, L. F., & Garay, G. 1991, ApJ, 371, 626
Estalella, R., López, R., Anglada, G., Gómez, G., Riera, A., & Carrasco-González, C. 2012, AJ, 144, 61
Hirano, N., Mikami, H., Umemoto, T., Yamamoto, S., & Taniguchi, Y. 2001, ApJ, 547, 899
Imai, H., Nakashima, K., Bushimata, T., et al. 2007, PASJ, 59, 1107
Knude, J., & Hog, E. 1998, A&A, 338, 897
