ALMA and VLA observations of the outflows in IRAS 16293–2422

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ABSTRACT
We present Atacama Large Millimeter/submillimeter Array (ALMA) and Very Large Array (VLA) observations of the molecular and ionized gas at 0.1–0.3 arcsec resolution in the Class 0 protostellar system IRAS 16293–2422. These data clarify the origins of the protostellar outflows from the deeply embedded sources in this complex region. Source A2 is confirmed to be at the origin of the well-known large-scale north-east–south-west flow. The most recent VLA observations reveal a new ejection from that protostar, demonstrating that it drives an episodic jet. The central compact part of the other known large-scale flow in the system, oriented roughly east–west, is well delineated by the CO(6-5) emission imaged with ALMA and is confirmed to be driven from within component A. Finally, a one-sided blueshifted bubble-like outflow structure is detected here for the first time from source B to the north-west of the system. Its very short dynamical time-scale (~200 yr), low velocity and moderate collimation support the idea that source B is the youngest object in the system, and possibly one of the youngest protostars known.

Key words: techniques: interferometric – stars: formation – stars: individual: IRAS 16293–2422 – ISM: jets and outflows

1 INTRODUCTION
Outflows constitute one of the most spectacular, emblematic and relevant early manifestations of the star formation process (e.g. Lada 1985; Arce et al. 2007). By removing angular momentum, they allow accretion to proceed (Bodenheimer 1995), and through their injection of mechanical energy, they can affect the overall evolution of star-forming regions (Reipurth, Bally & Devine 1997). Their morphologies can also provide clues on the properties of the driving sources. For instance, the degree of collimation of outflows is believed to correlate with the age and mass of the driving protostars (Arce et al. 2007; Machida, Inutsuka & Matsumoto 2008), while multipolar outflows are often an indication that the central engine is a multiple system (e.g. Carrasco-González et al. 2008).

IRAS 16293–2422 (Ceccarelli et al. 2000; Crimier et al. 2010) is located at a distance of 120 pc (Loinard et al. 2008) in the eastern part of the Ophiuchus complex. Soon after its discovery (Walker et al. 1986), it was found to power two bipolar outflow structures (Mizuno et al. 1990). One is oriented in the north-east–south-west direction [at a position angle (PA) of about 55° and hereafter called the NE-SW flow], while the other is oriented nearly east–west (PA ~110°, hereafter the EW flow). The existence of at least two protostellar sources was also established early thanks to high-resolution radio observations (Wootten 1989; Mundy et al. 1992). These objects are known as component A to the south-east and component B to the north-west, and their projected separation is about 5 arcsec (Fig. 1). While component B remains single even at the highest angular resolution available (~0.05 arcsec; Chandler et al. 2005; Rodríguez et al. 2005), component A breaks up into two centimetre subcomponents called A1 and A2 at resolutions better than about 0.2 arcsec (Fig. 1). Because the relative orientation of the A1/A2 pair at the time of its discovery was very similar to the direction of the NE-SW flow, A1 was initially believed to be an ejecta from A2. However, analysis of the relative motion of A1 and A2 favours a

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2 OBSERVATIONS

2.1 ALMA data

IRAS 16293–2422 was observed at $\lambda = 0.45$ mm with 15 12-m antennas of ALMA in 2012 April, during the science verification data programme. The 105 independent baselines ranged in projected length from 26 to 403 m. The primary beam of ALMA at 0.45 mm has a full width at half-maximum of 8 arcsec, so the observations were made in mosaicking mode with half-power point spacing between field centres to cover both source A and source B. The digital correlator was configured in four spectral windows of 1875 MHz and 3840 channels each. This provides a channel spacing of 0.488 MHz ($\sim 0.2 \text{ km s}^{-1}$) per channel, but the spectral resolution is a factor of 2 lower (0.4 km s$^{-1}$) due to online Hanning smoothing. Observations of Juno provided the absolute scale for the flux density calibration while observations of the quasars J1625–254 and NRAO 530 (with flux densities of 0.4 and 0.6 Jy, respectively) provide the gain calibration. The quasars 3C 279 and J1924–292 were used for the bandpass calibration. The data were calibrated, imaged and analysed using the Common Astronomy Software Applications (CASA) and KARMA software (Gooch 1996). The continuum emission as well as many spectral lines were detected in these ALMA data (see Jørgensen et al. 2012). Here, we concentrate on the analysis of the continuum emission and of the CO$(J = 6–5; \nu = 0)$ at a rest frequency of 691.473 08 GHz. The rms noise, measured in line-free channels on either side of the CO line, is about 50 mJy beam$^{-1}$ at an angular resolution of 0.32 arcsec $\times$ 0.18 arcsec; $-69^\circ$. Only a small number of line-free channels were averaged to calculate the continuum, so the rms noise of the continuum image is only moderately better (20 mJy beam$^{-1}$) than that in the individual spectral channels.

2.2 VLA data

IRAS 16293–2422 was observed with the VLA in its most extended (A) configuration on 2011 June 5 and 8 at $\lambda = 7$ mm and on 2011 August 12 at $\lambda = 4$ cm. In all cases, the absolute flux calibrator was 3C 286 (J1331+3030), while the amplitude and phase gains were monitored using observations of J1625–2527. At 7 mm, 16 contiguous spectral windows, each containing 64 spectral channels 2 MHz wide were recorded simultaneously to produce a total bandwidth of 2 GHz (between 40 and 42 GHz). At 4 cm, eight contiguous spectral windows, each containing 64 spectral channels 2 MHz wide were recorded simultaneously to produce a total bandwidth of 1 GHz (between 6.8 and 7.8 GHz). The data calibration was performed using the CASA software. The data were manually inspected and flagged, and calibrated following standard procedures. The calibrated visibilities at 4 cm were imaged using a nearly uniform weighting scheme (Robust parameter set to $-2$ in CASA) yielding a synthesized beam of 0.44 arcsec $\times$ 0.16 arcsec; $-11^\circ$ and a noise level of 16 $\mu$Jy beam$^{-1}$. The visibilities at 7 mm were imaged both with natural weighting (Robust = +2) to obtain the highest sensitivity (at the detriment of angular resolution) and with intermediate weighting (Robust = 0) to obtain higher angular resolution (at the detriment of sensitivity). The synthesized beam was 0.14 arcsec $\times$ 0.12 arcsec; $+69^\circ$ and the sensitivity was 19 $\mu$Jy beam$^{-1}$ in the former case, while they were 0.08 arcsec $\times$ 0.07 arcsec; $-35^\circ$ and 31 $\mu$Jy beam$^{-1}$ in the latter. While the sensitivity at 4 cm is near the theoretically expected value

\footnote{A second spectral band, corresponding to the frequency range from 4.2 to 5.2 GHz was observed simultaneously with the 4 cm data presented here, but will not be discussed in this Letter.}
given the integration time, the sensitivity at 7 mm is about 50 per cent worse than expected. Additional analysis will be needed to understand the origin of this degradation, but we note that in spite of this effect, the maps presented here are roughly five times deeper that the best previous 7 mm images (Rodríguez et al. 2005).

3 RESULTS AND DISCUSSION

3.1 Continuum emission and the NE-SW flow

The submillimetre continuum emission ($\lambda = 0.45$ mm) measured by ALMA reveals the usual double source structure of IRAS 16293–2422 (Fig. 1). Component B is resolved but compact, with a peak brightness temperature of about 160 K. The total flux measured here with ALMA ($\sim 12.2$ Jy) is consistent with the trend observed at lower frequencies that the spectral index of source B is between 2 and 2.5 from centimetre to submillimetre wavelengths (Chandler et al. 2005). Component A is elongated along the NE-SW direction, with its peak at the position of source Aa, and the faint extension to the NE corresponding to the position of source Ab reported by Chandler et al. (2005). Interestingly, the centimetre subcomponents A1 and A2 are not identifiable in this image, although the angular resolution would be sufficient to separate them. The peak brightness temperature of the submillimetre emission in component A is about 30 K. The overall properties of the ALMA image of component A suggest that the submillimetre continuum is dominated by the circumbinary envelope rather than by the individual discs around the protostars. This is not particularly surprising since the individual circumstellar discs are expected to be heavily tidally truncated in this very compact binary system (projected separation of the order of 40 au). In contrast, the continuum at 7 mm is dominated by free–free radiation from the bases of the thermal jets and enables us to pinpoint the embedded sources A1 and A2 (Fig. 2). This demonstrates the complementarity of ALMA and the VLA to study young stellar sources.

When it is reconstructed to optimize sensitivity, the 7 mm emission from source A also reveals a faint elongation towards the NE similar to that seen in the submillimetre map, and extended emission surrounding the sources A1 and A2. Like the submillimetre continuum, this extended emission likely traces the circumbinary envelope. The emission associated with the extension of source A to the NE (i.e. with source Ab from Chandler et al. 2005) contributes roughly 1.4 mJy at 41 GHz, 0.5 Jy at 305 GHz (Chandler et al. 2005) and 3 Jy at 696 GHz (all values with relative uncertainties of the order of 50 per cent). This yields a spectral index of 2.7 ± 0.5, consistent with that of the more compact emission from source A (Chandler et al. 2005). We argue that this elongation traces faint extended emission from the circumbinary envelope (possibly related to dust accumulated in that direction by the NE-SW flow), rather than a new protostellar source in the system.

Both the 7 mm and the 4 cm continuum maps (Fig. 2) reveal a new compact source to the NE of source A2. This is strikingly similar to the situation encountered in the 2006 image of IRAS 16293–2422 at $\lambda = 1.3$ cm (Loinard et al. 2007) when a bipolar ejection from A2 was seen for the first time. The bipolar ejection that occurred in 2006 produced the sources A2a and A2b that are still clearly seen in the 4 cm image (Fig. 2c) and, faintly, in the 7 mm map (Fig. 2a). They are moving away from A2 at projected velocities of several tens of km s$^{-1}$ (Pech et al. 2010). We interpret the new source to the NE of A2 (which we shall call A2$\delta$) as a new ejection from A2. In the high-resolution 7 mm image, there is a faint extension to the SW of A2 which might correspond to the bipolar counterpart of A2$\delta$. We note that in the first image following the ejection of the A2a/A2b pair (Loinard et al. 2007), the SW ejecta (A2a) was not immediately detached from A2 either.

IRAS 16293–2422 has been regularly monitored at centimetre wavelengths since the late 1980s (Chandler et al. 2005) and the 2006 ejection was the first to be detected. The new ejection reported here suggests that source A2 might be entering a period of enhanced outflow activity. Regular observations in the coming years and decades will be required to confirm this possibility, and will enable a detailed study of the kinematics and behaviour of the ejecta. Interestingly, A2a, A2$b$, A2$\delta$ and A2$\delta$ itself are well aligned (Fig. 2c) but the PA ($\sim 70^\circ$) of the line joining them is somewhat larger than the PA ($\sim 55^\circ$) of the large-scale outflow known to originate from A2 (e.g. fig. 5 in Mizuno et al. 1990). This suggests that the jet driven by...
source A2 is precessing as a consequence of the A1–A2 binarity. We note, finally, that there is no detectable CO(6-5) emission associated with the NE-SW flow in the ALMA observations (Fig. 3). This is in agreement with the results of Yeh et al. (2008) who also failed to detect such emission in their SMA CO observations at arcsecond resolution.

3.2 The EW flow

Strong CO(6-5) is detected in the ALMA data around the position of source A. In agreement with the results of Yeh et al. (2008), it is largely concentrated to an EW structure with blueshifted emission to the east and redshifted emission to the west. This emission traces the central part of the well-known EW (PA $\sim110^\circ$) flow (Fig. 3). In spite of the high angular resolution of the ALMA observations, the origin of the flow stall cannot be traced back to a specific source within component A.

3.3 A compact outflow from source B

As reported by Yeh et al. (2008) and confirmed by Rao et al. (2009), there is very strong blueshifted CO emission to the south of source B (the location of component b2 in Yeh et al. 2008). Fig. 4 displays the first moment CO(6-5) map of this component (in colours) overlaid with the 0.45 mm continuum image (in contours). It is clear that the CO emission defines a 3 arcsec long bubble-like structure oriented along the south-east–north-west direction (at PA $\sim130^\circ$) with source B at its north-west apex. This structure points from source B towards source A, but there appears to be no material connection (i.e. no bridge of emission) between the two. In particular, its south-east apex (corresponding to the point nearest to A) is located about 2 arcsec to the north-west of source A. We conclude that this structure is associated with source B and unrelated to source A. We should point out, here, that there is a significant amount of extended CO emission around the systemic velocity of IRAS 16293–2422 (V$_{lsr}$$\sim$4 km s$^{-1}$) in the ALMA observations. This emission is poorly recovered by the interferometer, and its structure cannot be assessed; we filtered it out by ignoring the velocity channels around 4 km s$^{-1}$, but note that our fluxes (as given, for instance, in Fig. 4) are clearly underestimated since they do not include the ambient gas. Interestingly, Rao et al. (2009) recently reported on the possible detection of a new outflow in IRAS 16293–2422 seen in SiO(8-7) along a PA very similar to that of the CO structure seen here. The structure seen in SiO, however, is most prominent towards south of source A, and entirely at positive velocities. While there is SiO(8-7) emission in the general direction of the CO structure reported here, it is at $+4$ km s$^{-1}$ rather than at $-4$ km s$^{-1}$. Higher resolution SiO observations will clearly be needed to establish the relation (if there is any) between the SiO structure reported by Rao et al. (2009) and the CO structure reported here.

To our knowledge, ours is the first direct indication for the existence of an outflow driven by source B. Interestingly, there is no strong redshifted counterpart to the north-west. While this might reflect an intrinsic asymmetry of the flow, it could also at least partly reflect the structure of the circumstellar environment. As discussed by Pineda et al. (2012) and Zapata et al. (in preparation), at submillimetre wavelengths, both the CO lines and the continuum emission towards source B are optically thick, so the red-shifted emission might be at least partly hidden from view. Alternatively, IRAS 16293–2422 might be located close to the back side of the cloud where it is located. Besides explaining the lack of a redshifted lobe, this would be consistent with the very high optical depth towards source B.

Since the systemic velocity of source B is about 3 km s$^{-1}$ (Jørgensen et al. 2011) while the most negative velocities reached by the outflow are $\sim$8 km s$^{-1}$, the (radial) expansion velocity of the bubble relative to source B is about 10 km s$^{-1}$. At the distance of Ophiuchus, the angular extent of the bubble (3 arcsec) corresponds to 5.4 $\times$ 10$^{15}$ cm (360 au), and the dynamical age of the flow is of the order of 200 yr. While this calculation might only provide a crude estimate of the true age of the structure, similar calculations for the other outflows in the system (Mizuno et al. 1990) yield much larger dynamical ages, of the order of 10$^3$ yr. This is consistent with the commonly held view that source B is the youngest object in IRAS 16293–2422 (e.g. Chandler et al. 2005). It could be argued that the true angular extent of the outflow is significantly larger than reported here, because the CO(6-5) line might only pick the most
highly excited gas in the vicinity of source B. This is unlikely because lower J CO observations (e.g. Yeh et al. 2008) did not reveal any conspicuous emission on larger scales along the direction of this structure.

The 7 mm continuum emission around source B has usually been interpreted as a nearly face-on disc (Rodríguez et al. 2005). Recent ALMA spectroscopic observations further revealed unambiguous evidence for infall and rotation (Pineda et al. 2012; Zapata et al. in preparation) towards that source, and the rotation is also consistent with a nearly face-on orientation. In this configuration, the flow driven by source B ought to be oriented nearly along the line of sight, and the expansion velocity would be mostly radial. This suggests that the true expansion velocity of the flow is not significantly larger than the observed 10 km s\(^{-1}\).

The overall morphology of the outflow driven by source B is qualitatively different from that of typical flows powered by low-mass young stars. In particular, there is no evidence for a collimated jet-like structure along the symmetry axis. Instead, the highest (i.e. most negative) velocities are associated with the inner layer of the structure, while the outer layers are at less negative velocities (typically at about \(-2\) km s\(^{-1}\); see Fig. 4). This behaviour suggests that source B drives a moderately collimated wind, that impinges into the stationary circumstellar medium, in a situation resembling that described theoretically by Shu et al. (1991).

In summary, the flow driven by source B has a number of peculiar properties. It is fairly slow (\(-10\) km s\(^{-1}\), outburst-like, and only moderately collimated. Those are characteristics theoretically expected from flow driven by adiabatic (first) cores (Machida et al. 2008; Price, Trichko & Bate 2012; see also Chen et al. 2010; Enoch et al. 2010; Dunham et al. 2011; Pineda et al. 2011 for observational aspects). However, the evidence for strong accretion reported by Pineda et al. (2012) and Zapata et al. (in preparation) and the fact that component B is such a bright submillimetre continuum source would be more consistent with the idea that it has already entered the protostellar phase. In any case, the properties of the outflow driven by this object do suggest that it might be one of the youngest known protostars.

4 CONCLUSIONS AND PERSPECTIVES

In this Letter, we used combined ALMA and VLA observations to examine the outflow activity in the very young (Class 0) protostellar system IRAS 16293−2422. The well-known NE-SW and EW large-scale molecular flows are confirmed to be driven from within component A to the south-east of the system. The NE-SW flow can unambiguously be associated with source A2 which might be entering a phase of enhanced activity. The ALMA CO(6-5) observations have enabled us to discover a new outflow towards source B with peculiar properties: it is highly asymmetric, resembles an outburst, is fairly slow (10 km s\(^{-1}\)) and lacks a jet-like feature along its symmetry axis. In addition, its dynamical age is only about 200 yr. We argue that these properties result from the extreme youth of source B, which might be one of the youngest known protostars. Given the short dynamical age of the structure, significant morphological changes are expected to take place over the next few decades. Observing this time evolution would help constrain the formation and early evolution of molecular outflows in general, and would have a fundamental impact on our understanding of these objects.

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