Triggered Star Formation in a Turbulent ISM
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Dissecting a site of massive star formation: IRAS 23033+5951

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Abstract. We present new BIMA observations of the massive star-forming region IRAS 23033+5951 in Cepheus. 3 mm continuum observations reveal that the source decomposes into at least three dusty clumps, each of which has sufficient mass to form a massive star. The most massive clump has a mass of about 225 $M_{\odot}$ and appears to house the massive protostar which drives the prominent CO outflow seen in the region. Our $H^{13}CN$ 1–0, N_2H^+ 1–0, and $H^{13}CO^+$ 1–0 maps show that the three continuum sources are all embedded in an elongated structure whose long axis is perpendicular to the outflow. Both $H^{13}CO^+$ and $H^{13}CN$ peak at the geometric center of this structure, which lies between the two prominent continuum peaks. All three lines – $H^{13}CN$, $H^{13}CO^+$, and N_2H^+–show the same velocity gradient along the long axis of their integrated intensity maps. Although the approximately 90,000 AU length of the elongated structure prohibits a disk interpretation, the fact that the dynamical and gas masses of the structure differ by only a factor of a few suggests that the structure may be partially rotationally supported. We also detect a signature of infall toward the center of the structure, seen as an asymmetrically blue HCO^+ line where its optically thin isotope, $H^{13}CO^+$, is symmetric and single-peaked.

1. Introduction

The mechanism of massive star formation is poorly understood. Compelling recent theoretical work has shown that, like low-mass stars, massive stars can and likely do form by disk accretion, rather than by other proposed mechanisms (e.g. Krumholz, McKee & Klein, 2005a,b). The observational evidence is starting to converge on the same conclusion (e.g. Whitney, 2005 and references therein). However, there remain significant uncertainties in the interpretation of the kinematics of massive star-forming objects. For example, several recent studies have claimed to find accretion disks around massive protostars (e.g. Patel *et al.*, 2005; Chini *et al.*, 2004), only to have those claims disputed (Comito *et al.*, 2005; Sako *et al.*, 2005). Other studies show evidence for > 1000 AU rotating structures but without providing direct evidence for an inner accretion disk on outflow-launching scales (∼100 AU; e.g. Cesaroni *et al.*, 2005). Moreover, the radii and masses of claimed massive protostellar disks range from 130 AU and 3 $M_{\odot}$ (Shepherd *et al.*, 2001) to 15,000 AU and 400 $M_{\odot}$ (Sandell & Sievers, 2004), suggesting that there is either tremendous diversity in the properties of massive accretion disks or ambiguity about what constitutes a "disk". For example, there may be ambiguity among true accretion disks, circumstellar tori, and flattened molecular cloud cores.

Few massive protostellar systems have been analysed kinematically over the wide range of spatial scales necessary to resolve ambiguities among the three aforementioned types of rotating structures. In this paper, we present the results of our BIMA observations of the

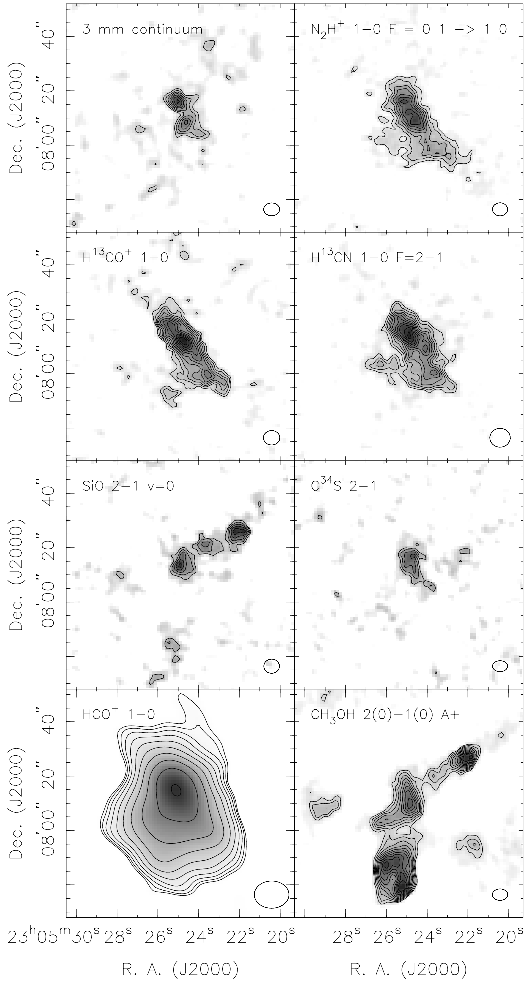

Figure 1. Integrated intensity maps of IRAS 23033+5951 in greyscale and contours. The 3 mm continuum map is shown at the upper left for comparison. Contours begin at 3σ and increase by intervals of 1σ, except for N_2H^+, where the contours interval is 2σ, and HCO^+, where the contours increase from 3σ by factors of 1.5. In each panel, the size of the synthesized beam is represented by a hollow ellipse in the lower right corner.

kinematics of the massive star-forming region IRAS 23033+5951. Previous observations of this region have revealed a massive protostar with a luminosity of about 10^4 $L_\odot$, a collimated CO outflow, and an extended envelope of total mass $\sim$2300 $M_\odot$ (Beuther *et al.* 2002a,b). These results form the first part of a more detailed study of this intriguing region.

2. General morphology of the circumstellar material

In Figure 1, we show 3 mm continuum and integrated intensity maps of IRAS 23033+ 5951 in seven molecular lines. The continuum image shows that the source decomposes

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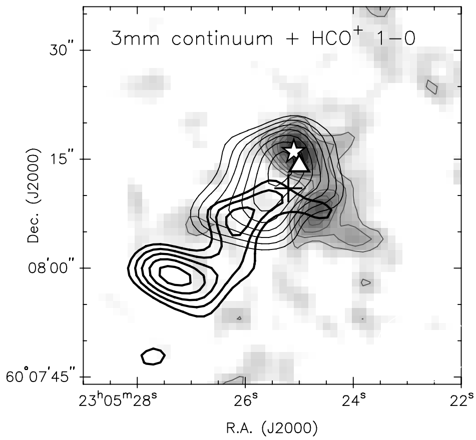

Figure 2. The primary outflow in IRAS 23033+5951. 3 mm continuum emission is shown in greyscale with grey contours. The redshifted and blueshifted HCO^+ emission are shown in thick and thin black contours, respectively. The star, triangle, and cross represent the positions of the MSX source, water maser, and IRAS point source, respectively.

into at least three components. Computing their masses from their continuum fluxes, we find that they have masses of 225 $M_\odot$, 205 $M_\odot$, 51 $M_\odot$, assuming a dust temperature of 30 K. All three components are embedded in an elongated structure seen in N_2H^+, $H^{13}CN$, and $H^{13}CO^+$. The continuum and N_2H^+ both show the same prominent double-peaked structure, whereas $H^{13}CN$ and $H^{13}CO^+$ both peak between the continuum peaks. $C^{34}S$, CH_3OH and SiO all show emission coincident with the continuum sources but they also peak between the prominent continuum clumps. The emission from all of the aforementioned molecules is embedded within a much more extended envelope seen in HCO^+.

In Figure 2, we show the red and blue lobes of the integrated high-velocity HCO^+ emission superposed on the continuum map. Note that SiO and CH_3OH also show red-shifted emission along the same axis as the outflow traced by HCO^+, though primarily on the opposite side of the continuum sources, suggesting they are tracing a separate outflow. In Figure 2, we have labeled the positions of the water maser, MSX, and IRAS point sources in the region. Clearly at least the MSX and maser sources are associated with the northern continuum source, which also appears to be the source of the HCO^+ outflow. The two lobes show significant spatial overlap, suggesting that the outflow is significantly inclined relative to the plane of the sky.

3. A flattened rotating object?

As shown in Figure 3, both $H^{13}CO^+$ and the isolated hyperfine component of N_2H^+ 1–0 show velocity gradients of several km s^{-1} along the long axis of the elongated structure, which is itself almost exactly perpendicular to the axis of the outflow emission defined by HCO^+. The same velocity gradient is seen in $H^{13}CN$, but the quality of the data is significantly lower than that of either $H^{13}CO^+$ or N_2H^+. The presence of a velocity gradient of a few km s^{-1} along an axis perpendicular to the outflow axis seen in three separate tracers suggests a rotating disk. However, at an assumed source distance of 3.5 kpc, the $\sim$25″ size of the elongated structure in which the continuum sources are embedded translates to $\sim$90,000 AU – far too large for the structure to be a genuine protostellar accretion disk. The dynamical mass of the structure computed from the

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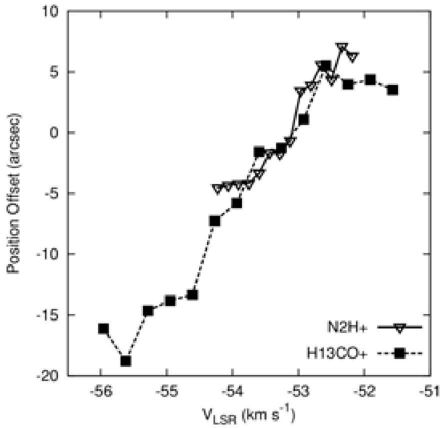

Figure 3. Position-velocity cuts taken along the long axis of the N_2H^+ 1–0 (*solid line and triangles*) and $H^{13}CO^+$ 1–0 (*dashed line and squares*) emission. Only the isolated component of the N_2H^+ 1–0 line is used in making the fit. The points represent the centroid of the emission in each velocity channel. Both lines show the same velocity gradient.

$H^{13}CO^+$ line is $520/\sin^2(i)$ $M_\odot$, which is very close to the sum of the masses computed from the dust continuum (481 $M_\odot$). The interferometric nature of our data means that much of the continuum emission is resolved out, so the continuum masses are effectively lower limits. Thus, the total mass enclosed within the area accounted for by the dynamical mass is likely considerably larger – perhaps approaching the 2300 $M_\odot$ derived from single-dish observations. Nevertheless, the large dynamical mass suggests that, if the elongated structure is rotating, it may derive significant support from rotation. We suggest that this structure may be the remnant of the original molecular cloud from which the massive protostar formed and which has now fragmented into at least two large components.

4. Conclusions

We have shown that the massive protostar in IRAS 23033+5951 is embedded in an elongated structure whose long axis is perpendicular to that of its outflow. We have also shown that all three molecular lines which trace the elongated structure show the same velocity gradient along it. Although the sheer size of the object would seem to prohibit any interpretation of it as an accretion disk, its kinematics are consistent with it being significantly rotationally supported. Planned observations at higher spatial resolution will probe the connection between the kinematics of the large-scale emission shown herein with the kinematics of the material within each continuum peak, perhaps revealing the connection between a large-scale flattened, rotating object and a true accretion disk.

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Discussion

Bonnell: One potential problem with a "torus" interpretation is that the dynamical time for this object must be of order 10^6 years, which is probably comparable to or longer than its age or formation time. A sheared filament interpretation appears far more straightforward.

Reid: We have suggested that the flattened object may be a rotating toroid because it shares so many characteristics with known low-mass disk/jet systems. First, the warm gas and radio continuum emission peak at the geometric center of the flattened structure, with colder gas appearing toward the edges. Second, the driving source of the outflow is roughly coincident with the geometric center of the structure. Third, the outflow axis is almost exactly perpendicular to the long axis of the flattened object. Finally, the rotation curve of the object is consistent with rotation. Collectively, these facts support the interpretation of the flattened structure as a rotating, circumstellar torus, although we acknowledge that they do not conclusively rule out a sheared filament interpretation.

Clarke: Is this the first of the "giant toroids" that appears to be close to centrifugal balance? Regardless of the issue of whether the rotation curve is "Keplerian", this would appear to be unique in terms of being a toroid where the dynamical mass and measured gas mass are comparable.

Reid: The measured dynamical mass is comparable to the sum of the masses of the dust continuum objects embedded within it. However, it remains an open question whether the velocity gradient we see along the long axis of the flattened structure truly represents rotation. We are seeking data with higher sensitivity to study the velocity structure of the apparent toroid.

Elmegreen: You shouldn't expect Keplerian rotation anyway. If you flatten an isothermal sphere, you will get something more like a flat rotation curve.

Reid: Agreed. The more general question we were trying to raise in referring to the possibility of Keplerian rotation is of the precise nature of the flattened structure: if it truly were a rotationally supported disk, we should expect a Keplerian rotation profile. It is primarily only the size of the object that argued against it being a true rotationally supported disk. If it is merely a flattened molecular cloud core, it would have some other rotation profile. It is also possible that the velocity gradient we see does not represent rotation.

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