TRACING THE BIPOLAR OUTFLOW FROM ORION SOURCE I

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ABSTRACT

Using CARMA, we imaged the 87 GHz SiO line toward Orion-KL with 0′′.45 angular resolution. The maps indicate that radio source I drives a bipolar outflow into the surrounding molecular cloud along a NE–SW axis, in agreement with the model of Greenhill et al. The extended high-velocity outflow from Orion-KL appears to be a continuation of this compact outflow. High-velocity gas extends farthest along a NW–SE axis, suggesting that the outflow direction changes on timescales of a few hundred years.

Key words: ISM: individual (Orion-KL) – ISM: jets and outflows – masers – stars: formation

1. INTRODUCTION

Bipolar outflows are ubiquitous from young low-mass stars, but are difficult to observe toward high-mass stars, which typically form in crowded, physically complex regions that are quickly disrupted by ionization fronts and stellar winds.

The nearest region of massive star formation is the Kleinmann-Low Nebula in Orion, at a distance of about 400 pc (Sandstrom et al. 2007; Menten et al. 2007). Measurements of H2O maser proper motions led Genzel et al. (1981) to suggest that two distinct outflows originate from this region—a low-velocity (18 km s−1) outflow along a NE–SW axis and a high-velocity (30–100 km s−1) flow extending roughly NW–SE. Both outflows were inferred to originate within a few arcseconds of radio source I, a young star with a luminosity of 104–105L⊙ (Gezari et al. 1998). The high-velocity outflow also manifests itself as lobes of shock-excited H2 (Beckwith et al. 1978) and as broad, weakly bipolar line wings in CO and other molecules (Zuckerman et al. 1976; Kwan & Scoville 1976; Erickson et al. 1982; Chernin & Wright 1996).

Source I is associated with a cluster of SiO masers. From fits to 2′ resolution BIMA data, Plambeck et al. (1990) found that the J = 2–1 v = 1 SiO masers were clustered along two arcs offset ~0′′.08 NW and SE of source I. Plambeck et al. (1990) reproduced this pattern with a model of maser emission from a rotating, expanding disk, tilted at 45° to the plane of the sky. The axis of the model disk was projected at P.A. 145°, suggesting that the high-velocity outflow emerged along its poles.

Later observations showed that the J = 2–1 SiO line in the v = 0 vibrational level also was masing (Wright et al. 1995) in a 1000 AU long hourglass-shaped region centered on source I. Because the hourglass was elongated NE–SW, it was natural to associate it with the outer regions of the model v = 1 maser disk. SiO line widths were ~30 km s−1 across the entire hourglass, inconsistent with Keplerian rotation, so Wright et al. (1995) suggested that the emission traced the turbulent boundary layer between an underlying, unseen disk and the high-velocity outflow.

More recent observations have cast doubt on this picture. Very Long Baseline Array (VLBA) observations of the 43 GHz v = 1 SiO masers (Greenhill et al. 1998; Doelman et al. 1999) showed that the brightest maser spots were clustered in four groups, rather than in a ring as predicted by the Plambeck et al. (1990) model. A bridge of emission connecting the two southern clusters led Greenhill et al. (2004) to propose that the v = 1 masers originate in a nearly edge-on disk rotating about a NE–SW axis, perpendicular to the previously hypothesized disk, and that the v = 0 SiO emission traces the base of the 18 km s−1 outflow. This model did not attempt to explain the high-velocity outflow.

Proper-motion measurements of source I (Rodríguez et al. 2005; Gómez et al. 2008) also pose problems for the original model. These data indicate that source I is moving to the SE at 0′′.007 year−1, plowing through the molecular cloud at ~14 km s−1. In that case, a 1000 AU diameter disk would rapidly be stripped away by the ram pressure of the ambient gas unless source I were implausibly massive.

In this Letter, we report 0′′.45 (180 AU) resolution images of the SiO v = 0 J = 2–1 line obtained with CARMA. The new maps provide the best evidence to date that the v = 0 SiO emission originates in a NE–SW outflow from source I, as in the Greenhill et al. (2004) model. The maps also suggest that the high-velocity outflow is a continuation of this compact flow.

2. OBSERVATIONS

Observations were made with CARMA in the A-, B-, and C-arrays, providing projected antenna spacings ranging from 5 to 545 kλ. The total integration time on Orion-KL was 3.4 hr in the A-array (2009 January), 3.7 hr in the B-array (2008 February), and 5 hr in the C-array (2009 May).

The correlator was configured for simultaneous observations of the J = 2–1 SiO transitions in both the v = 0 (86.847 GHz) and v = 1 (86.243 GHz) vibrational levels. For each transition, the velocity coverage was 104 km s−1 and the resolution was 3.4 km s−1 after Hanning smoothing. Observations of quasars were used to calibrate phase and amplitude ripples across the I.F. passband. After these were removed, the visibility data were self-calibrated using a 28 km s−1 wide channel that included all the bright v = 1 maser features. Only baselines shorter than 250 kλ were used in the self-calibration because the maser is slightly resolved on the longest baselines. The integration time per data record was 4 s in the A-array and 10 s in the B- and C-arrays, allowing near-complete removal of atmospheric phase
data reduction package. Uniformly weighting the visibility data
at 05h35m14′′ ± 0′′.025 adjusted the central coordinate of the maps to place source I
at ∼ 0h35m14′′.53, −5°22′′.57, as derived from VLA proper-
motion data (Gómez et al. 2008).

3. RESULTS

Figure 1 presents a series of channel maps showing the ν = 0 SiO emission in an 8′′ × 8′′ box centered on source I. The lowest
contour on these images is 75 K and the peak is 3800 K.

Although the maps in Figure 1 are consistent with those published by Wright et al. (1995) and Chandler & de Pree
(1995), the higher quality CARMA images clearly indicate that ν = 0 SiO emission originates in a NE–SW bipolar outflow
from source I, as in the Greenhill et al. (2004) model. The central
channels show the limb-brightened edges of two cones centered on source I; emission in the line wings is brightest interior
to these cones. Although the outflow appears to lie nearly in
the plane of the sky, there is a measurable red–blue asymmetry: redshifted gas at V_{LSR} = 22 km s^{-1} appears as a narrow jet to the
SW, while blueshifted gas at V_{LSR} = −9 km s^{-1} is offset to the
NE. This asymmetry is inconsistent with the old model in which
the emission originates in the turbulent boundary layer of a disk.

It is clear that the SiO outflow corresponds to the 18 km s^{-1}
H_{2}O maser outflow identified by Genzel et al. (1981); toward
source I the SiO line has a full width at zero intensity of
∼ 36 km s^{-1}, and both SiO and H_{2}O masers extend along a NE–
SW axis. It is likely, however, that this material was accelerated
by a much faster wind. Source I is traveling to the SE at
14 km s^{-1} in the plane of the sky (Gómez et al. 2008), so gas
moving outward at only 18 km s^{-1} would appear to be swept
back into an arc with arms trailing to the NW.

The high signal-to-noise level in the maps, exceeding 100:1
on the bright maser spots, makes it feasible to enhance the
resolution of the innermost region of the outflow. One can
fit the position of an isolated maser feature to an accuracy
of ∼ 0.5 θ_{FWHM}/SNR (Reid et al. 1988), where θ_{FWHM} is the
apparent FWHM of the source and SNR is the signal-to-
noise ratio. Here, the maser spots overlap heavily, however,
so fitting their positions individually is difficult. Instead, we
CLEANed the maps in the usual way, then convolved the
CLEAN components with a 0′′.25 FWHM Gaussian restoring
beam, about half the width of the synthesized beam. Figure 2
shows the resulting SiO ν = 0 image at V_{LSR} = 5 km s^{-1} in the
2″ × 2″ central region. Red contours show the 229 GHz
continuum emission from source I, which is centered in the
waist of the SiO hourglass; SiO masers in the ν = 1 vibrational
level are clustered along the edges of the continuum source.

The brightest ν = 0 SiO masers lie along two bars offset
∼ 0′′.5 NE and SW of the continuum source. The ends of the
bars are limb brightened, suggesting that the masers originate
in two annuli. Position–velocity cuts through the bars, shown in
panels (a) and (b), hint that these annuli are expanding radially
at ∼ 10 km s^{-1}, as modeled by the green ellipses.

What about the high-velocity outflow? In order to obtain
higher sensitivity for extended emission, we tapered the weight-
ing of the visibility data to produce a set of channel maps with a 1′′.13 × 0′′.93 synthesized beam. The rms noise is 4 K, increasing
to as much as 8 K in channels with strong maser emission due
to limited dynamic range. Figure 3 shows the full extent of the
SiO emission detected in these maps, color coded to indicate the
intensity-weighted LSR velocity. Brightness temperatures outside the central 8″ × 5″ hourglass are < 100 K, hence this
emission is likely to be thermal. As in previous maps of the
high-velocity outflow (Chernin & Wright 1996), the strongest
redshifted emission is E of source I, while blueshifted gas is
offset to the NW.

Figure 3 suggests that the extended high-velocity outflow is
simply a continuation of the compact outflow. For example,
The fastest-moving ejecta now are farthest from the center. The evidence for such velocity gradients.

Third, it is possible that the extended gas provides a fossil record of a precessing outflow. Currently, the outflow axis is NE–SW, with the (redshifted) SW lobe tipped slightly into the plane of the sky. Approximately 10′ from the star, the outflow axis appears to be E–W, with the E lobe tipped into the plane of the sky. If the true outflow velocity is 100 km s$^{-1}$, this ∼45° change in direction took place in 200 years. Precession occurs because of tidal interactions in noncoplanar binary systems; periods of a few thousand years are typical of systems with binary separations of tens of AU (Terquem et al. 1999). A secondary in an eccentric orbit can change both the outflow direction and the mass-loss rate periodically, as in the model of CepA presented by Cunningham et al. (2009).

Zapata et al. (2009) report that much of the emission from the high-velocity CO line wings in Orion originates from filamentary structures similar to the H$_2$ fingers, with linear velocity gradients along them. Zapata et al. (2009) argue that the high-velocity flow is not a classical stellar outflow, but instead was produced by the disintegration, about 500 years ago, of a multiple stellar system that contained source I and BN. While this scenario is consistent with the velocity gradients evident in Figure 4 and with the vaguely filamentary character of the SiO emission away from source I, it implies that the apparently continuous transition from the 18 km s$^{-1}$ flow to the high-velocity outflow seen in Figure 3 is illusory. We are reluctant to accept that conclusion, and suggest that perhaps the disintegration of the multiple system triggered an abrupt increase in the velocity or mass-loss rate of the outflow from source I, creating the finger system as in the model of Stone et al. (1995).

4. CONCLUSIONS

New maps of the SiO line in the $v = 0 J = 2–1$ transition toward Orion-KL provide some of the clearest evidence to date that radio source I, thought to be a massive young star, drives a bipolar outflow into the surrounding molecular cloud along a NE–SW axis. This outflow contains multiple water masers and...
conventionally is referred to as the 18 km s$^{-1}$ flow. The outflow velocity must be substantially greater than 18 km s$^{-1}$, however, or the outflow lobes would trail back to the NW owing to the proper motion of source I. Close to source I, the SiO $v = 0$ emission is masering. The strongest masers are clustered in two annuli offset $\sim 200$ AU from source I along the central axis of the outflow.

More extended, higher velocity gas extends along a NW–SE axis, almost perpendicular to the 18 km s$^{-1}$ flow. The SiO maps suggest that this weakly bipolar outflow is an extension of the 18 km s$^{-1}$ flow, which may change direction on timescales of a few hundred years.

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Facilities: CARMA

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