Using VLBI to Probe the Orion-KL Outflow on AU Scales

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ABSTRACT

We present the first contemporaneous 43GHz and 86GHz VLBI images of the v=1 J=2→1 and J=1→0 SiO masers in the Orion-KL nebula. Both maser species exhibit the same general morphology of earlier J=1→0 maser images which appear to trace the edges of a bi-polar conical outflow. Surprisingly, the J=2→1 masers form further from the central protostar than the J=1→0 masers, a fact not readily explained by current SiO maser pumping models. The average magnitude of offsets between corresponding regions of the two masing transitions is approximately 14% of the total radial extent of the SiO maser emission. This offset indicates that each transition must trace different physical conditions.

Subject headings: ISM: individual (Orion Kleinmann-Low)—ISM: jets and outflows—masers—stars: formation—stars: winds, outflows

1. Introduction

Young massive stars spend a considerable fraction (10-20%) of their lifetimes embedded within the molecular cloud cores from which they formed (Wood & Churchwell 1989).

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Throughout this period, however, they can have a dominant effect on the inter-stellar dynamics in the surrounding region by forming complex and large scale molecular outflows. The exact mechanism by which these stars drive such outflows remains unclear, but models generally involve a stellar wind entraining molecular material (Richer et al 2000). Study of these objects at early phases of evolution before they have emerged from parental clouds is difficult due to the naturally large opacities in the IR and optical. Furthermore, angular resolutions of instruments in these wavebands are insufficient to image the very beginning of an outflow close to the young stellar object. Connected element radio interferometry relieves the opacity problem, but still cannot probe angular scales much less than 0.5 arc seconds. In some cases, high brightness and compact SiO maser emission is seen towards massive star forming regions and can be imaged with 0.1 milli arc second resolution (Greenhill et al 1998, Doeleman et al 1999 (Paper I), Eisner et al 2000). The pumping requirements of these masers ($\rho_H \sim 10^9 \text{cm}^{-3}$, $T \sim 1200K$ (Elitzur 1992)) require that they originate very close to a high luminosity source and thus offer a method of exploring the immediate circumstellar regions of select massive young stars with angular resolutions much smaller than the stellar disk.

The Orion BN/KL region is undeniably a site of intense molecular outflow activity. Bow shocks seen in H$_2$ form along “fingers” extending up to 2 arc minutes that collectively trace back to the center of the BN/KL region (Gezari, Backman & Werner 1998, Stolovy et al. 1998). A high velocity and weakly bipolar CO outflow is also centered there (Chernin & Wright 1996). Water maser features out to 15 arc seconds exhibit proper motions consistent with a common center of expansion that is also near the BN/KL center (Genzel et al 1979). A number of objects in the region probably contribute to powering this complex dynamical picture, but one in particular, the radio continuum source I (Churchwell et al 1987), is associated with powerful SiO masers. Its inverted radio spectrum makes it likely that Source I marks the position of an HII region or stellar jet associated with a young massive star, and precise astrometry places I at the exact centroid of the Orion BN/KL SiO maser features (Menten & Reid 1995, Gezari et al 1998). No definitive optical or IR counterpart to Source I has been found, a fact attributable to the visible extinction towards this object for which estimates yield values of $A_\nu \sim 60$ (Gezari et al 1998).

Compact $v=1$ J=1-0 SiO maser emission extends only $\sim 70$AU from Source I, well within the extent of the larger scale outflows described above. Early single dish polarimetry of this emission, combined with connected element array observations, led to a model in which the SiO masers formed in a rotating and expanding circumstellar disk (Barvainis 1984, Plambeck et al 1990). These efforts, however, were tainted by spectral blending. Because the angular extent of the maser emission is smaller than the synthesized beams of connected arrays, widely separated maser features at similar radial velocities cannot be distinguished
and the maps of Plambeck et al (1990) show only the centroids of emission in each observing frequency channel. These maps show the centroids to form two arcs that appear to encircle Source I, a morphology consistent with a circumstellar disk.

Recent high resolution VLBI imaging reveals that the SiO maser emission does not form in two arcs, but resolves into four main regions that appear to trace the outlines of a bipolar conical outflow oriented in the NW-SE direction of the larger CO outflow (Greenhill et al 1998, Doeleman et al 1999). The SiO emission, however, is redshifted to the NW and blueshifted to the SE, opposite the weak polarity of the CO outflow. This apparent conflict can be accommodated if the outflow is oriented close to our line of sight which would magnify the effects of small direction changes in the outflow (Doeleman et al 1999). Alternatively, limb brightening effects on the conical surfaces may allow blue maser emission from a generally red shifted cone of emission (and vice-versa) if the outflow alignment is close to the plane of the sky (Greenhill et al 1998). In either case, it is important to investigate the physical conditions and spatial extent of the maser emitting region in an effort to forge a link between the small scale SiO structures and the larger scale outflows.

In general, multi-transition SiO maser imaging holds the promise of revealing small scale temperature and density gradients in the host environment. Conclusions from previous multi-line SiO maser studies, though, have necessarily been somewhat uncertain due to their heavy reliance on data from single dish monitoring. The particular difficulty with this approach stems from the spectral blending that may occur when two spatially separated maser features emit at nearly the same frequency. Barvainis and Predmore (1985), for example, used single dish polarimetry of the $v=1 \ J=2 \rightarrow 1$ and the $J=1 \rightarrow 0$ transitions towards a set of evolved stars and inferred a low degree of spatial overlap between the lines. McIntosh and Predmore (1987), however, used similar observations of SiO masers surrounding the variable star Mira to conclude that the same transitions were cospatial. Comparison of single dish SiO maser spectra cannot definitively address the question of relative maser positions. Important connected-element interferometry work exemplified by Baudry, Herpin & Lucas (1999), Morita et al. (1992) and Colomer et al. (1996) provides inter-line comparisons of centroids of emission at a given velocity but no detailed spatial information. The first multi-line VLBI comparison of SiO masers was the claim by Miyoshi et al (1995) that the $v=1$ and $v=2 \ J=1 \rightarrow 0$ transitions were largely cospatial towards the evolved star VYCMa. They concluded that only a collisional pumping mechanism could account for the overlap. The angular resolution of their observations, however, was still much larger than the smallest SiO maser feature sizes ($\sim 0.2$ mas), and thus their observations were insufficient to definitively prove cospatiality. Indeed, more recent and higher resolution observations (Desmurs et al. 2000) suggest that on 0.2 mas scales, these two $J=1 \rightarrow 0$ transitions are offset from each other. Phillips et al. (2003) have registered VLBI maps of the $v=1 \ J=2 \rightarrow 1$ and $J=1 \rightarrow 0$
maser emission in the envelope of the evolved star RCas. For this source, some maser features from both transitions appear to arise in the same volumes of gas, but the overall morphology of emission in the two transitions differs.

Here, we report on results of mapping the Orion-KL SiO masers in both the $v=1 J = 2 \rightarrow 1 (\nu_{\text{rest}} = 86243.442 \text{ MHz})$ and $J = 1 \rightarrow 0 (\nu_{\text{rest}} = 43122.027 \text{ MHz})$ transitions. The accuracy of relative astrometry in the images allows comparison at the sub-AU level and we find that, at the resolution of our maps, the brightest masers in each transition are not cospatial. Spatial offsets between the two transitions place the $J = 1 \rightarrow 0$ emission slightly closer to the central exciting source, leading us to conclude that they trace and occur in different physical conditions.

2. Observations

We observed the Orion-KL SiO masers using the position determined by Wright et al (1990) of $\alpha = 5^h35^m14^s505$, $\delta = -05^\circ22'30.45''$ (J2000). Observations at $\lambda 7$ mm took place on 13 Dec. 1997 using seven antennas of the VLBA and one element of the VLA, both run by the NRAO. Paper I describes the $\lambda 7$ mm observations and the resulting calibration and imaging steps used to generate high resolution maps. Coordinated Millimeter VLBI Array (CMVA) observations at 86 GHz covered a time range from 13 Dec. to 15 Dec. 1997 and included the following antennas: Haystack(Westford, MA.), FCRAO 14m (Amherst, MA.), Kittpeak 12m(Kittpeak, AZ.), the phased BIMA (Redding, CA.) and the VLBA site at PieTown, NM. The overlap in time between the 43GHz and 86GHz observing sessions ensures that variability of source structure has a negligible effect on comparisons between the two maser transitions. The array was split into two sub-arrays, a 'low-resolution' array consisting of the relatively short (85 km) Haystack-Quabbin baseline and a 'high-resolution' array comprising Kittpeak, BIMA and PieTown. There were very few interferometric detections between the short baseline array and the high resolution array, forcing us to separate the analysis of the two data sets. A technical problem at the PieTown VLBA site rendered data from the 'high-resolution' array unsuitable for imaging. In this letter, we report on results only from the Haystack-Quabbin baseline. Data were recorded in three partially overlapping

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IF channels of the MKIII VLBI system, each of 4MHz bandwidth yielding a total effective velocity coverage at 86 GHz of \(\sim 34\text{km/s}\). The IF overlap was sufficient to avoid band edge effects and also allowed removal of instrumental phase shifts between IFs. Correlation at Haystack Observatory yielded 112 spectral channels in each IF for a velocity resolution of 0.12km/s which closely matches the resolution of the 43 GHz results (0.11km/s) of Paper I.

3. Calibration and Imaging

Single baseline 86 GHz VLBI has already been used to map SiO masers around the evolved giant star VXSgr (Doeleman, Lonsdale & Greenhill 1998) and the associated difficulties are well understood. The most important aspect of the reduction is the need to find a spectrally isolated component which is point-like. Phase referencing the entire data set to this reference feature simultaneously removes atmospheric effects and shifts the reference feature to the map origin. Without a point source as reference, the data set would be corrupted by the emission structure in the reference channel which cannot be satisfactorily determined in the absence of calibrated phases. To identify a point source with a single baseline, one must search through all spectral channels for one in which the visibility amplitudes are constant as a function of baseline length and orientation. This signature can easily be masked by amplitude variations due to antenna gain fluctuations and high quality antenna gain calibration is therefore essential.

Gain calibration for both sites was obtained using spectral template fitting. A 90 second total power spectrum of the maser emission at the Quabbin telescope was calibrated assuming a 40 Jy/K gain and served as a template. Spectra at all other times from both sites were fitted to the template, and relative gains as a function of time for both antennas were determined (Fig. 1) for each 90 second interval. Relative calibration errors are at the 5% level due to the high quality of the total power spectra while we estimate the absolute calibration of the template spectrum to be within 10%. Once calibrated, the channel at \(V_{\text{LSR}}=0.84\text{km/s}\) had amplitudes constant to 20% and we adopted it as the reference. For comparison, Fig. 2 shows the amplitudes as a function of time for the reference channel as well as amplitudes at a nearby velocity which exhibit dramatic “beating” indicative of complex structure.

Strong fringe detections on a single 390 second VLBI scan of the continuum source 3C273 provided the delay calibration for both days allowing removal of linear phase slopes as a function of frequency across the bandpass. Phase offsets between adjacent IFs were checked using maser features in the overlapping portions of the three IF channels and shown to be good to within a few degrees. In addition, visibility phase versus frequency was differenced for two segments of data at the same LST on both days and showed a negligible
shift in delay. The lack of phase slope in this difference validates use of the single 3C273 scan to calibrate the delay for both days.

Fringe rate solutions from the reference channel were applied to the data and synthesis image cubes constructed using standard techniques implemented in the NRAO AIPS software package. Resulting images covered 0.64'' × 0.64'' on the sky, sufficient to completely map the known extent of the maser emission (Paper I). Due to high beam sidelobe levels (71%), CLEAN deconvolution was applied conservatively in each velocity channel using a loop gain of 0.05 with a limit of 100 iterations. Deconvolution tests on these data showed that the adopted CLEAN parameters prevented divergence in the algorithm and minimized imaging artifacts. The restoring beam was 9 × 66 milli arcseconds with a PA of −18°.

4. Image Analysis

With only two antennas and the relatively sparse baseline coverage that results, the fidelity of the channel maps is limited by sidelobes of bright emission regions caused by imperfect deconvolution of the synthesized beam. Bright isolated maser emission, for example, is often accompanied by negative sidelobes which distort nearby faint emission. Faint emission that is far removed from bright map features can be more clearly distinguished against the residual map background. Setting a threshold above which map features are taken to represent maser emission, is thus position dependent and requires that each channel map be considered separately.

Composite maps for three velocity ranges corresponding to the three observed 4MHz passbands were formed by selecting the maximum intensity of all velocity channels at each image pixel (Fig. 3a-c). The lowest 3mm contours in the composite maps mark the cutoff below which sidelobe features begin to appear.

For a more detailed analysis of the 3mm image, maser spot maps were made at each velocity, where 'spot' (or component) will be defined as an isolated region of maser emission within a single frequency channel. This was done by fitting 2-D elliptical Gaussians to each map feature to determine size and integrated flux density. In almost all cases, the high spectral resolution and relatively coarse angular resolution of the observations ensured that each identified map feature could be well modeled as an unresolved source convolved with the restoring beam. Restrictive criteria were applied to these features to identify maser emission components. These included feature persistence in at least two adjacent velocity channels and a flux density threshold set by the largest negative sidelobe within 3 beamwidths. In Fig. 3d, all 3 mm maser spots meeting our selection criteria are plotted as circles with area
proportional to total flux density.

The positional accuracy of maser components relative to each other within the 3mm map depends on a number of factors. Foremost among these is the effect of non-point like structure in the reference channel which will contaminate phases for all other channels resulting in position errors. In the Orion 3mm data (Fig. 2) the observed variation in reference channel visibility amplitudes is $\sim 20\%$. The corresponding phase error can be estimated by assuming this amplitude variation is due to two spatially separated maser spots in the reference channel. The observed range of amplitudes would then imply visibility phase variations up to $\pm 6^\circ$ or $\pm 0.02$ of the synthesized beam width.

A secondary concern is the effect of combining the two days of 3mm VLBI data on relative maser positions. The data were combined primarily to increase signal to noise ratio, but if the masers exhibit very high proper motions, data between the two days could be inconsistent. Assuming the proper motions are comparable to the radial velocity range observed ($\sim 30$km/s), the two day separation corresponds to motions of 0.1 mas, a negligible offset compared to the 3mm VLBI resolution. Even if the SiO outflow were $\sim 10^\circ$ out of the plane of the sky, the corresponding proper motions would be $\sim 150$ km/s, leading to 0.5 mas positional offsets between the two days.

Mis-calibration of the interferometer delay due to geometrical and station clock errors can also lead to uncertainty in relative astrometry (Genzel et al 1981, Thompson, Moran & Swenson 1986). Such delay errors cause phase slopes across the bandpass leading to astrometry errors whose magnitudes vary as a function of frequency. The high signal to noise ratio 3C273 detections limit clock errors to $\sim 5$ns or 18 degrees of phase across the observing bandpass. The maximum geometrical delay error, in turn, is set by the uncertainty in the position of the Orion BN/KL SiO masers and the baseline length. The Orion BN/KL maser position is known to within $0.6''$ ($3\sigma$) which, coupled with the relatively short Quabbin - Haystack baseline, produces a delay error of only 0.75ns. Thus, the total delay error contributes positional errors of no more than 21 degrees of phase, or $\pm 0.06$ synthesized beam widths.

Further errors in maser spot positions (Fig. 3d) can be attributed to uncertainty in identification of individual features and fitting them with elliptical Gaussians, but in all cases, these uncertainties are a small fraction of the synthesized beam. Combining all sources of relative positional error above, we conservatively limit relative errors in maser spot positions of 0.1 of the synthesized beam. For the main purposes of the present work, the combination of all relative positional errors are small compared to the errors in aligning the 3mm and 7mm maser transitions discussed below.
5. Comparison of 3mm and 7mm Emission

5.1. Characterization of 3mm Maser Emission

Maps of the 3mm maser emission show it to be broadly similar in structure to that observed in the 7mm transition. Regions A, B, G and H marking the outlines of opposing conical outflows at 7mm in Paper I have corresponding regions at 3mm. Even region E, which does not conform to the simple bi-conical picture, is populated by both SiO transitions. At 3mm, each region comprises multiple components whose velocity widths range from 0.5 km/s to over 2 km/s. These are larger than spectral widths of typical maser features in the 7mm image, but this is likely due to the larger beam size at 86 GHz which subtends multiple closely spaced features at similar velocities. As at 7mm, there is obvious velocity overlap between region pairs (A,B) and (G,H); strong emission often appears in both paired regions at the same velocity.

5.2. 3mm and 7mm Map Alignment

Because the 3mm and 7mm data were obtained using different instruments, it is impossible to register the maps using phase referencing techniques. We note that use of these techniques may be possible in the future as experience with VLBA operation at 86 GHz increases and if the frequency switching time remains below the coherence time of the atmosphere. Instead, we necessarily explored registration techniques involving map comparisons and certain assumptions about maser structure.

Comparison of the two maps reveals that a pure translation of one map relative to the other will not allow all four main emission regions (A, B, H, (F+G)) to coincide. Exactly superposing region B, for example, at each frequency leaves the remaining regions grossly misaligned. If, however, we assume that emission in both transitions originates in similar interactions of a bi-polar outflow with the surrounding cloud, then the center of symmetry in both transitions should be coincident and reflect the position of the protostar. An approximate center of symmetry in each map can be defined as the intersection of lines that connect the emission centroids of regions A with H and B with (F+G). Registering the 3mm and 7mm emission in this manner (Fig. 3), shows that J=2→1 masers appear to form farther from the central proto-star than the J=1→0 masers.

After registration, total offsets between the 3 mm and 7 mm centroids for each emission region were measured to be: A (6.6 AU), B (7.5 AU), F+G (7 AU), H (17 AU) assuming a 450 pc distance to the source (Paper I). Variation in the offsets is directly related to the
extent of emission in each region. Region H, for example, exhibits the largest offset, due primarily to the large area over which 3mm emission is found. In all cases, the 3 mm emission appears further from the presumed location of the protostar than the 7 mm emission.

5.3. Spectra

Total power spectra of each transition in Fig. 4 show that the 3mm and 7mm masers share the same basic double peaked form with a central velocity near 5.3 km/s. This indicates a common bulk flow affecting both maser lines. In fact, individual spectra of emission in regions A-H of the 3mm map cover roughly the same velocity ranges as the corresponding 7mm spectra: Region A (11 → 17.5 km/s), Region B (13.5 → 19 km/s), Region H (2.5 → -9 km/s), Region G (-2.5 → -11 km/s). Both the red and blue shifted peaks contain multiple spectral components, a few of which have matching peaks in both transitions that correspond to within 0.5 km/s. A one-to-one correspondence in spectral features between the two transitions, though, is clearly absent. The observed spatial offset between the lines underlines the pitfalls of deriving spatial coincidence information solely from single dish spectra.

6. Discussion

6.1. Outflow Model and Dynamics

Impetus for the biconical outflow model of the Orion-KL SiO masers originated with a clear "X" morphology of the v=1 J=1→0 transition, presumed to trace the outflow boundary. Though generally not coincident with the J=1→0 masers, the J=2→1 emission displays a remarkably similar general structure consistent with the outflow model. This general structure is consistent with both SiO maser transitions inhabiting a zone of shocks and overdensities where an outflow interacts with the surrounding molecular medium (Paper I). The resolution of the J=2→1 image does not allow us to compare the two transitions on the smallest scales seen in the J=1→0 maps. We cannot rule out some overlap on scales smaller than the 3 mm beam and future high resolution work at this frequency is needed to address this. One caveat to make clear is that in both transitions, roughly half the flux density is undetected by VLBI. This “missing flux” must exist in structures larger than the 5 milliarcsecond synthesized beam of the J=2→1 data. The smallest baselines in the VLBA array also correspond to this size scale. Detection and location of this large scale emission will require connected element arrays with baselines of order 100 km.
The combined spatial and velocity information from both 3 mm and 7 mm VLBI now make it possible to explore velocity patterns within each main emission region. In region A, the combined 3 mm and 7 mm maser emission covers a range of radii from 40 to 67 AU as measured from the central registration point. Over this range, the average radial velocity across region A steadily decreases from 26 to 13 km/s implying a smooth velocity gradient of $\sim 0.5$ km/s/AU due North. Similar calculations for the other three regions yield no clear velocity gradients, arguing for a local explanation of the pattern observed in Region A.

One possibility is that in Region A, maser features closer to the protostar are also located closer to the central stellar jet. Molecular gas closer to the jet will accelerate more quickly and to generally higher terminal velocities, giving rise to the observed velocity gradient. In this scenario, the thickness of the conical shell where masers occur is sufficient to generate the velocity difference among Region A maser features. Similarly, a local gradient in the density of the medium surrounding the stellar jet could have the same effect on the radial maser velocities by altering the efficiency of entrainment as a function of distance from the central protostar. Constraining these possibilities is not possible with the measurements described herein, but future proper motion measurements of individual maser features will allow a much more detailed examination of the SiO maser dynamics and directly address this issue. For completeness, we note that one could also attribute the velocity gradient to a gravitational deceleration of a ballistic flow in which the masers form. The central mass required would then be $M_\star \sim 28 \left[ \cos^2(\theta_{\text{los}}) \sin(\theta_{\text{los}}) \right]^{-1} M_\odot$ where $M_\star$ is the enclosed central mass and $\theta_{\text{los}}$ is the angle made by the direction of propagation of the Region A SiO masers to our line of sight. At its minimum, this expression yields a central mass of $M_\star \sim 73 M_\odot$. In the case of gravitational deceleration, though, one would expect similar velocity gradients in all maser regions.

The new J=2→1 images also highlight a region not directly addressed in Paper I. Region E is the weakest of all the labeled maser complexes but appears clearly in J=2→1 and more faintly in J=1→0. This region differs importantly from the others in that the spatial relationship between the transitions is reversed with J=1→0 slightly farther from the center. The mere existence of this maser cluster in both transitions is difficult to understand in the context of a pure biconical outflow model. It cannot correspond in any simple way to a conical edge or tangent line. Since Region E emission velocities are near the centerpoint between the red and blue lobes ($V_{\text{lsr}} \sim 5$ km/s) it may result from outflow shocks propagating to a central disk or torus oriented perpendicularly to the outflow as observed by Wright et al. (1995) in thermal SiO. Another possibility is that Region E forms in an equatorial outflow modeled by Greenhill et al. (1998) to explain the morphology of the H$_2$O masers. Whatever its genesis, the 86 GHz confirmation of strong SiO emission in Region E must be accounted for in future dynamical models.
6.2. Maser Pumping

Most treatments of SiO maser pumping model the case of a spherically symmetric evolved star. Elitzur (1982) has outlined a possible explanation for the special case of the Orion-BN/KL SiO masers assuming they form in the bulk of an expanding wind from the protostar. Models of this type are not generally workable in the evolved stellar case as mass loss rates in those objects are too small to sustain maser amplification within a smooth wind. The validity of the Elitzur (1982) model, which also dealt with the specific radiation field in the region, is now called into question by the filamentary maser features seen in J=1→0 (Paper I). These high aspect ratio structures indicate maser formation in shocks and local density enhancements rather than in a smooth wind.

Many stellar SiO maser models incorporate the effects of dust grain formation and stellar pulsation driven shocks, effects that likely play a role in the Orion SiO masers. Both radiative and collisional pump mechanisms have been used to explain SiO masers in these models, but a general consensus remains elusive. VLBI results of Miyoshi et al (1994) showing the J=1→0, v=1 and v=2 masers in VYCMa and WHya to be coincident within 2 mas, strengthened the case for collisional pumping which allows these transitions to be cospatial over a wide range of physical parameters (Lockett & Elitzur 1992). Radiative pumping schemes are much more restrictive and one would not typically expect such coincidence (Bujurrabal 1994). Desmurs et al. (2000) have mapped TXCam with a resolution of 0.2 mas and claim that centroids of J=1→0, v=1 and v=2 maser features are offset by ∼1.5 mas. Their refutation of the Miyoshi et al. (1994) results must be tempered though, by the fact that their maps show a high degree of overlap between the transitions despite the measured mean offset.

The positional offset now observed between the J=2→1 and J=1→0 masers is in stark disagreement with predictions of most maser pumping models for SiO masers around evolved stars. Radiative and collisional excitation theories both predict multiple SiO maser lines among rotational levels within a given vibrational state. These rotational “chains” are due to the monotonic decrease in radiative decay rates with increasing rotational level (J) when ro-vibrational transitions become optically thick (Elitzur 1992). This produces a natural inversion between rotational states given a J-independent pump mechanism. In such a case, one would expect v=1, J=2→1 and J=1→0 masers to generally inhabit the same volumes of gas. Our results show that this is not the case for the brightest maser features at the resolution of our maps.

Some SiO maser models do allow for spatial separation of rotational masers within a vibrational state, but require specialized conditions for this to take place. Lockett & Elitzur (1992) show that collisional pumps tuned for conditions around evolved stars selectively quench higher J level transitions as SiO column densities rise, so that the J=1→0 maser is
the only one to survive above $10^{20}\text{cm}^{-2}$. These results are consistent with $J=1\rightarrow0$ masers occurring closer to the protostar where higher neutral $H_2$ densities would be found. Larger SiO column densities might also result from an increase in SiO abundance due to the liberation of SiO into a gaseous state from dust grains in shocks at the interface between the Orion outflow and the surrounding medium (Caselli, Hartquist & Havnes 1997). Such interpretations would, however, require very high column densities to suppress the higher $J$ transition. Radiative pumps typically show little change in $J=1\rightarrow0$ and $J=2\rightarrow1$ maser intensities as $H_2$ density and SiO abundance are varied (Bujurabbal 1994) and offer no clear explanation of the findings reported here.

Given the large number of SiO maser transitions possible, saturation and competitive gain effects can be important. Doel et al (1995) argue that SiO maser spot sizes and flux densities imply that much of the maser emission is in the saturated regime. These authors have extended SiO maser models for evolved stars to include these effects and find that the $J=2\rightarrow1$ maser gains can exceed those of $J=1\rightarrow0$ in a very narrow range of $H_2$ density around $5 \times 10^9\text{cm}^{-3}$. The possibility that this density range holds throughout the large SiO maser region in Orion BN/KL is unlikely.

Potentially of more relevance to the Orion BN/KL case is the work of Humphreys et al (2002) to include the effects of hydrodynamic shocks on SiO maser formation in evolved stellar envelopes. In this model, stellar pulsations drive shocks which enhance collisions and give rise to pockets of SiO masers emission. Simulations show that the $v=1\ J=2\rightarrow1$ emission occurs at slightly larger radii from the central star than the $v=1\ 1\rightarrow0$ emission. The size of this effect ($\sim 2\%$ of the maser radii) is much smaller than the $\sim 14\%$ offset between the two transitions we have observed here. Inclusion of shocks in SiO models, though, will likely be important in future specific application to the Orion BN/KL case.

In general, the relevance of these SiO maser models in the context of hard radiation fields and shocks in the environment surrounding Source I is questionable. Perhaps the clearest statement that can be made regarding the offset between the two rotational maser transitions discussed in this work, is that they appear to require distinct physical conditions for maser amplification. Use of these transitions as probes of the Orion-KL environment depends heavily on the specific predictions of theoretical models which currently cannot adequately explain our observations.
7. Conclusions

We have made the first contemporaneous spectral line VLBI observations of 3mm and 7mm wavelength SiO maser transitions towards the Orion BN/KL region. Images of the 3mm $v=1 \ J=2\rightarrow1$ transition show the masers to be grouped in four main emission regions along the arms of an 'X', similar morphology to that previously reported for corresponding observations of the 7mm $J=1\rightarrow0$ transition. These results reinforce a scenario in which the SiO masers form in the interface region between a bi-conical protostellar outflow and the surrounding medium. Long tangential maser gain paths along the edges of the outflow result in the masers appearing along the outline of the outflow. Significant SiO maser emission outside the outflow cones defined by the main maser regions is easily identified in the new $J=2\rightarrow1$ image (Region E) and exists, but is less distinct, in the $J=1\rightarrow0$ map. These maser features are inconsistent with the simple bi-conical picture and may indicate the presence of a protostellar disk or other dense outflowing material in the plane orthogonal to the stellar outflow.

In contrast with predictions of SiO maser models, we observe a positional offset between the centroids of $J=2\rightarrow1$ and $J=1\rightarrow0$ maser emission with the higher rotational transition occurring farther from the central protostar. This offset indicates a preference of the two transitions for distinct physical environments. The $J=2\rightarrow1$ masers extend the maximum radius at which SiO masers are seen in Orion-BN/KL to 67 AU and agree with a velocity gradient observed in $J=1\rightarrow0$ emission along the Northern outflow limbs. This is almost certainly due to an effect local to this region of emission as the remaining three maser regions exhibit no clear velocity gradients.

A more complete picture of the SiO masers and their use as tracers at the origins of the Orion BN/KL outflow will require further observations. Proper motion studies of individual maser features will produce three dimensional velocity information and allow detailed study of dynamics in the maser region. High resolution (0.2 mas) simultaneous observation of multiple maser lines are needed to make progress toward understanding the maser pump models. Indeed, VLBI study of SiO masers has now outpaced theoretical maser efforts. The utility of multi-line studies highlights the need to extend the spectral line VLBI technique to higher frequencies to reach other SiO maser transitions. Imaging of higher rotational level maser lines may reveal unexpected effects similar to those discussed in this work.

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8. Figure Captions

Fig. 1.— Gaincurves in units of System Equivalent Flux Density determined for the Haystack and Quabbin antennas using a total power spectrum template method averaged over 360 second intervals. Calibration points from day 1 are marked by filled circles, those from day 2 by open circles. Antenna gain is determined on the target maser source so all pointing errors and opacity effects are corrected for. In the actual data reduction, antenna gains were calculated for every 90 second interval.

Fig. 2.— Calibrated visibility amplitudes at two different velocities. Day 1 marked with filled circles, day 2 by open circles. The lower panel shows variation in the amplitude indicative of complex structure. The upper panel shows the amplitudes for the channel chosen as the phase reference. The near constant reference amplitudes are consistent with a point like brightness distribution. The degree to which structure in the reference channel deviates from a point source will add to positional errors in the final map.

Fig. 3.— Comparison of v=1 J=2→1 and J=1→0 masers in Orion-KL. Panels a through c show overlayed contour maps of both transitions (J=2→1 in green and J=1→0 in black) summed over different velocity ranges. All contour levels are spaced by powers of \(\sqrt{2}\). Contour ranges for J=2→1 are: a) 34 to 187 Jy/Beam; b) 12 to 92 Jy/Beam; c) 45 to 180 Jy/Beam. Contours for J=1→0 transition maps are: a) 42 to 469 Jy/Beam; b) 28 to 315 Jy/Beam; c) 57 to 634 Jy/Beam. The J=1→0 emission has been convolved with the J=2→1 beam for ease of comparison. Panel d shows the J=1→0 emission summed over all velocities compared with J=2→1 maser spots obtained by fitting elliptical Gaussians to map features. Circle areas are proportional to total flux density, and circle color represents velocity. A central red “X” marks the map registration point (and presumed protostar location) determined by the method described in the text. Arms of the “X” are oriented to show the outflow opening angles determined by lining up centroids of the J=2→1 emission with the map center. Regions labeled A,B,E,F,G and H correspond to similar regions defined in Paper I.

Fig. 4.— Simultaneous spectra of the v=1 J=2→1 and J=1→0 SiO maser transitions towards Orion-KL. The similar double-peaked forms suggest that both transitions are subject to the same large scale outflow velocity pattern. Spectral dissimilarities are probably due to a spatial offset between the two transitions as determined with long baseline interferometry.
Two graphs showing Amp (Jy) vs. Greenwich Hour Angle (Hours) with two different LSR velocities.

- Top graph: $V_{LSR} = 0.84 \text{ km s}^{-1}$
  - Amp range from 0 to 150 Jy
  - Hour Angle range from 6 to 16 hours

- Bottom graph: $V_{LSR} = 0.1 \text{ km s}^{-1}$
  - Amp range from 0 to 150 Jy
  - Hour Angle range from 6 to 16 hours