IMAGING THE IONIZED DISK OF THE HIGH-MASS PROTOSTAR ORION I

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ABSTRACT

We have imaged the enigmatic radio source I (Orion I) in the Orion KL nebula with the VLA at 43 GHz with 34 mas angular resolution. The continuum emission is highly elongated and is consistent with that expected from a nearly edge-on disk. The high brightness and lack of strong molecular lines from Orion I can be used to argue against emission from dust. Collisional ionization and H− free-free opacity, as in Mira variables, require a central star with \( \gtrsim 10^5 L_\odot \), which is greater than infrared observations allow. However, if significant local heating associated with accretion occurs, lower total luminosities are possible. Alternatively, photoionization from an early B-type star and \( p^+/e^- \) bremsstrahlung can explain our observations, and Orion I may be an example of ionized accretion disk surrounding a forming massive star. Such accretion disks may not be able to form planets efficiently.

Subject headings: infrared: stars — ISM: individual (Orion Kleinmann-Low) — planetary systems: formation — stars: formation — stars: individual (I, IRc 2)

1. INTRODUCTION

The nearest massive star forming region, the Kleinmann-Low (KL) nebula in the Orion molecular cloud, is at a distance 480 pc (Genzel et al. 1981). While the brightest near-infrared source in Orion KL (Kleinmann & Low 1967) is the Becklin-Neugebauer (BN) object, it contributes only a small fraction of the total nebular luminosity of \( \sim 10^5 L_\odot \) (see Thronson et al. 1986, and references therein). Other young stellar objects (YSOs) are deeply embedded and hidden from view at infrared (IR) wavelengths. An object giving rise to strong mid-IR emission, IRc 2, has been long suspected to be the dominant energy source in Orion KL (Downes et al. 1981; Genzel et al. 1981; Shuping et al. 2004), but hidden by >60 mag of visual extinction (Gezari et al. 1998; Greenhill et al. 2004a). However, IRc 2 breaks up into several compact regions (Douglas et al. 1993; Greenhill et al. 2004a).

Moreover, Gezari (1992) and Menten & Reid (1995) showed that IRc 2 is offset from the compact radio source I (hereafter Orion I), and some components of IRc 2 could arise from reflected light (see also Morino et al. 1998). Orion I is very deeply embedded, and Greenhill et al. (2004a) estimate optical depths >300 at 8 and 22 \( \mu \)m wavelengths.

The radio source Orion I is an enigmatic object. Proper motion measurements suggest that Orion I might have been part of a multiple system that disintegrated \( \approx 500 \) years ago (Gómez et al. 2005). Strong \( \text{H}_2\text{O} \) and OH (Cohen et al. 2006) masers are concentrated near Orion I, and the \( \text{H}_2\text{O} \) masers are distributed in an elongated pattern along position angle (PA) \( \approx 45^\circ \) (east of north). The \( \text{H}_2\text{O} \) masers seem to be expanding about a central position in the general vicinity of Orion I (Genzel et al. 1981). Orion I also displays strong SiO masers, which are usually associated with evolved asymptotic giant branch (AGB) or supergiant stars and are very rare in star-forming regions (Hasegawa et al. 1985). Interferometric maps of the SiO masers with the BIMA array at an angular resolution of \( \approx 1'' \) indicated the possibility that they came from a rotating and expanding disk (Plambeck et al. 1995). Higher resolution observations with the VLA (Menten & Reid 1995) located Orion I at the center of the SiO masers. Menten & Reid argued that the presence of vibrationally excited SiO masers, which require temperatures exceeding 1000 K (e.g., Lockett & Elitzur 1992) at a radius of \( \approx 50 \) AU from Orion I, was strong evidence that it must be a very luminous object (\( \sim 10^5 L_\odot \)).

Observations by Greenhill et al. (1998) with the VLBA at a resolution of \( \sim 1 \) mas clearly resolved the SiO masers into four “arms” that together make an \( 0.2'' \) X-like pattern. Since an X-like pattern has two symmetry axes, two models for the SiO masers have been forwarded. The SiO masers could form in the limbs of a high-velocity biconical outflow projected along a northwest-southeast axis (Greenhill et al. 1998; Doeleman et al. 1999). In this model, the western (eastern) arms are moving away from (toward) the observer and hence are redshifted (blueshifted) with respect to the systemic velocity. Alternatively, the SiO masers could form in material being expelled from a rotating disk, whose spin axis is projected northeast-southwest. In this model, the western (eastern) arms are moving away from (toward) the observer owing to rotation (Greenhill et al. 2004b). As discussed in § 3, evidence favors the latter model of a rotating, nearly edge-on, disk centered on Orion I.

We have used the VLA at 43 GHz and imaged the radio continuum emission associated with Orion I and located it precisely toward the center of the SiO maser X-like pattern. These data together give the clearest picture yet presented of the nature of a high-mass YSO disk on scales of \( \approx 16 \) AU. In this paper we concentrate on understanding the properties and nature of the continuum emission from the disklike structure of Orion I.
2. OBSERVATIONS AND RESULTS

Our observations were made on 2000 November 10 with the NRAO\footnote{The National Radio Astronomy Observatory (NRAO) is operated by Associated Universities, Inc., under a cooperative agreement with the National Science Foundation.} Very Large Array (VLA) in a manner similar to those of Menten & Reid (1995). All 27 antennas had 40–50 GHz receivers, compared to our previous observations with only nine antennas. The recently installed receivers had better noise performance than the ones available in 1994 and were placed on antennas providing longer interferometer baselines. Thus, the present data yielded lower noise levels and higher angular resolution compared to our previous data.

In order to image the continuum emission from Orion I and to locate this emission with respect to the SiO masers, we employed a dual-band continuum setup with a narrow band (1.56 MHz), covering redshifted SiO $v = 1, J = 1-0$ masers between LSR velocities of 10.8–21.3 km s$^{-1}$ (assuming a rest frequency of 43,122.08 MHz), and a broad band (50 MHz), centered at 43,164.9 MHz on a line-free portion of the spectrum. Both frequency bands were observed in dual-circular polarizations. We observed from 0050 to 1030 local sidereal time. Absolute flux density calibration was obtained from an observation of 3C286, assuming the flux density spectrum of Baars et al. (1977). Observations of the quasar 0501-019, measured to be 0.74 Jy, were interspersed with Orion I to monitor gain variations and to determine electronic phase offsets between the bands.

The narrowband data were then “self-calibrated” with the very strong maser signal as a phase reference. The phase and amplitude corrections were then applied to the broadband data, and a high quality map of the continuum emission was produced. A detailed description of this cross-calibration procedure can be found in Reid & Menten (1997). Once the continuum signals were “cross–self-calibrated” with the SiO maser signals, the data were imaged with the Astronomical Image Processing System (AIPS) task IMAGR. We produced maps with two different weightings of the $(u,v)$ data, shown in Figure 1. Using IMAGR weighting parameter “ROBUST = 5,” the dirty beam was $58 \times 45$ mas at a PA of $-20^\circ$, and we restored the image with a round beam of 50 mas (approximately the geometric-mean size). Using “ROBUST = 0,” the dirty beam was $41 \times 28$ mas at PA of $-30^\circ$, and we restored the image with a round beam of 34 mas. At a distance of 480 pc, 34 mas corresponds to 16 AU. These maps had rms noise levels of 0.13 mJy beam$^{-1}$ and 0.14 mJy beam$^{-1}$, respectively.

In order to image the SiO maser emission at high spectral resolution, several scans in spectral-line mode were interspersed with the dual-band continuum observations. We covered all of the SiO maser emission with a bandwidth of 6.25 MHz and 128 spectral channels, which provided a velocity resolution of 0.34 km s$^{-1}$. The line data were self-calibrated by choosing a channel with strong emission as a reference, and the resulting phase and amplitude corrections were applied to the other channels. Scans of the strong extragalactic continuum sources 3C 84 and 3C 273 provided bandpass calibration. We produced a spectral-line data cube, which we restored with a 30 mas beam, taking advantage of the high signal-to-noise ratio and slightly “overresolving” the dirty beam of $43 \times 27$ mas.

Alignment of the continuum and maser emission to about 5 mas accuracy was achieved by producing a pseudocontinuum map from the line data, using spectral channels covering the velocities that were within the 1.56 MHz passband of the dual-band

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**Fig. 1.** — Continuum images of Orion I at 43 GHz made with the VLA in the A configuration. The image in the upper panel is at 50 mas (FWHM) resolution, and the image in the middle panel is at 34 mas resolution. The emission is elongated northwest-southeast and may be from a disk surrounding a massive YSO. The brightest component near the center of the disk may be unresolved. When we subtract a pointlike 2.2 mJy component from the (13 mJy total) emission, we obtain the image in the lower panel. In all images the contour levels are at integer multiples of 0.5 mJy beam$^{-1}$. The FWHM of the restoring beams are shown in the bottom right corner of each panel. At a distance of 480 pc, 0.1" corresponds to 48 AU.
colors are chosen to approximate those used in Fig. 1a of Greenhill et al. (1998); contouring levels start at 3 Jy beam$^{-1}$ and increase by factors of 2. Center LSR velocities of the 5.43 km s$^{-1}$ wide channels are given in the lower left corner of each panel. Continuum contours are integer multiples of 0.5 mJy beam$^{-1}$. The bottom right panel shows a map of the integrated SiO emission, with light contours at integer multiples of 0.18 Jy beam$^{-1}$ km s$^{-1}$. All position offsets are relative to Orion I, whose position is ($\alpha, \delta$)$_{2000} = (05^{h}35^{m}14.5121^{s}, -05^{\circ}22^{\prime}0.521^{\prime\prime})$ at 2000 November 13 (Gomez et al. 2005).

2.— Orion I SiO $v = 1, J = 1$–0 maser channel maps (colored contours) superposed on the 34 mas resolution continuum emission (heavy black contours). The colors are chosen to approximate those used in Fig. 1a of Greenhill et al. (1998); contouring levels start at 3 Jy beam$^{-1}$ and increase by factors of 2. Center LSR velocities of the 5.43 km s$^{-1}$ wide channels are given in the lower left corner of each panel. Continuum contours are integer multiples of 0.5 mJy beam$^{-1}$. The bottom right panel shows a map of the integrated SiO emission, with light contours at integer multiples of 0.18 Jy beam$^{-1}$ km s$^{-1}$. All position offsets are relative to Orion I, whose position is ($\alpha, \delta$)$_{2000} = (05^{h}35^{m}14.5121^{s}, -05^{\circ}22^{\prime}0.521^{\prime\prime})$ at 2000 November 13 (Gomez et al. 2005).

3. RESULTS AND DISCUSSION

Our images of the continuum emission from Orion I at 43 GHz are shown in Figure 1. The top and middle panels of the figure are maps made with resolutions of 50 and 34 mas, respectively. The total flux density of Orion I is 13 mJy, and the peak brightness at 34 mas resolution is 3.0 mJy beam$^{-1}$. The emission appears to be composed of a compact component, near the center of the source, and a component elongated northwest-southeast. Assuming the elongated component is approximately uniformly bright, it would contribute about 0.8 mJy beam$^{-1}$ at the center of the source, leaving 2.2 mJy for the compact component. Subtracting a 0.8 mJy point source centered at the position of peak brightness, we obtain the image shown in the bottom panel of Figure 1. This reveals a disklike feature with a radius of $\approx 35$ AU and a brightness of about 1 mJy beam$^{-1}$. Away from the center of the source, the true brightness is a lower limit, since the feature is not well resolved perpendicular to its elongation. We also note that the peak brightness along the disklike feature does not follow a straight line on the sky. Instead, it appears to bend as might be expected from a warped disk.

In the following discussion, we assume that the compact emission comes from the immediate environment of a YSO, and that the elongated component traces a nearly edge-on disk, whose spin axis is aligned northeast-southwest. Briefly, the evidence supporting this model is as follows. Greenhill et al. (2004b) report detection of a curved arc of SiO maser emission bridging the gap between the base of the south and west arms. Evidence of this emission can also be seen in the $-3.47$ and 12.8 km s$^{-1}$ channel maps (Fig. 2). The bridge emission displays a radial velocity gradient, and some features have tangential proper motions, consistent with material rotating close to the nearside of a disk. Such emission is not anticipated for a bipolar outflow. In addition, Greenhill et al. (2004b) note that H$_2$O maser emission comes from “caps” displaced predominantly 0.2”–0.7” toward the northeast and southwest of Orion I, i.e., along the disk spin axis. These caps show outward motion and indications of rotation; the red and blueshifted emission tend to lie on opposite sides of the spin axis, consistent with the inferred direction of disk rotation. A more complete presentation of these findings will appear in L. J. Greenhill et al. (2007, in preparation).

At the center of the disk, the source appears slightly extended perpendicular to its elongation (i.e., along PA = +45$^\circ$). It is possible that a weak jet emanates from the YSO, perpendicular to the disk, resulting in the extended appearance at the center. Clearly, higher sensitivity observations are needed to understand this structure.

What are the physical conditions in the Orion I source? To answer this question, one must know the emission mechanism (opacity source) for the centimeter-wave photons. The centimeter-to-millimeter wavelength spectrum of the entire source can be characterized as a power law with flux density, $S_{\nu}$, rising with observing frequency, $\nu$, as $S_{\nu} \propto \nu^{1.6}$ (Menten & Reid 1995; Beuther et al. 2006), approaching that of a black body. Since the source is not well resolved spatially at lower frequencies with the VLA, the spectral index does not allow us to discriminate between an inhomogeneous, single-component model (where the spectral index is shallower than 2.0, because unity optical depth occurs at a smaller radius at higher frequencies) and a two-component model (with an optically thick central component and a partially optically thin disklike structure).

We think it unlikely that dust emission could be a dominant contributor to the centimeter-to-millimeter wavelength emission of Orion I. A dense, warm, dusty disk would be expected to show a plethora of molecular lines at millimeter/submillimeter wavelengths. While Beuther et al. (2006) find numerous, strong, molecular lines toward the nearby “hot core,” they find no strong
lines toward the position of Orion I (only weak SO lines and, of course, the strong SiO masers slightly offset from Orion I). Thus, we look to other emission mechanisms to explain both the YSO peak and the elongated disk components.

The observations could be modeled with gas at $\approx 8000$ K, where hydrogen is fully ionized (proton-electron bremsstrahlung). In this case, the data require an optically thick central component and a partially optically thin disk component. Alternatively, the emission could be partially optically thick from gas at $< 5000$ K, where hydrogen is predominantly neutral and free electrons come from low ionization-potential metals (H$^-$ free-free). The latter case applies in the “radio photospheres” of Mira variables at roughly 2 stellar radii (Reid & Menten 1997). In the following subsections, we present two classes of models for the Orion I centimeter-wave emission. These models are exploratory and designed only to elucidate characteristic physical conditions.

3.1. Collisonal Ionization: H$^-$ Free-Free Opacity

In several ways Orion I appears similar to a Mira-like variable star. Such stars display OH, H$_2$O, and SiO masers, as seen in Orion I. In addition, Mira variables have continuum emission detectable with the VLA at centimeter wavelengths, with brightness temperatures of $\approx 1600$ K (Reid & Menten 1997). The radio continuum of Mira variables occurs in an optically thick (spectral index $\approx 1.9$) “radio photosphere” with characteristic temperature of $\approx 1600$ K and density of $\approx 10^{12}$ cm$^{-3}$. Under these conditions the dominant opacity source is H$^-$ free-free interactions, coming from free electrons interacting with neutral hydrogen (either atomic or molecular). This is analogous to normal proton-electron bremsstrahlung, except that the interaction is about $10^4$ weaker (Dalgarno & Lane 1966), requiring correspondingly higher densities. At these temperatures and densities, sufficient free electrons can be created by collisional ionization of Na and K (Reid & Menten 1997).

The SiO $v = 1, J = 1$–0 maser emission at 43 GHz originates from the first vibrationally excited state at $\approx 1800$ K above the ground state, and models of maser pumping require temperatures of $\approx 1200$ K and hydrogen densities of $\approx 10^9$–$10^{10}$ cm$^{-3}$ for strong maser action (Alcolea et al. 1989; Lockett & Elitzur 1992; Bujarrabal 1994). Since the continuum emission region is more compact and has a higher (brightness) temperature than required for SiO maser excitation, finding the loci of SiO maser emission extending outward from the continuum, as shown in Figure 2, is reasonable and as observed for Mira-like variables (Reid & Menten 2003). As both Miras and Orion I display similar centimeter-to-millimeter wavelength spectral indexes and have a similar configuration of continuum and maser emission, there is circumstantial evidence for similar physical conditions and mechanisms.

We have explored models for the discrete emission of Orion I owing to H$^-$ free-free opacity. Assuming conditions similar to a Mira-like radio photosphere, material at density $\approx 10^{11}$ cm$^{-3}$ and temperature $\approx 1500$ K requires a path length of $\approx 2$ AU in order to achieve an optical depth of $\approx 0.5$ (Reid & Menten 1997), possibly explaining the observed disk brightness temperature of $\approx 450$ K. This path length is about 10% of the disk radius and, thus, is easily achievable. Such a model has the benefit that a single power law can explain the observed spectral energy distribution for the entire Orion I source between 8 and 350 GHz. However, recently Beuther et al. (2006) have measured the flux density of Orion I at 690 GHz to be between 3.5 and 9.9 Jy. Since the extrapolation of the centimeter-wave continuum spectrum to 690 GHz predicts under 2 Jy, an additional component (e.g., dust on a scale of $0.2^\prime \prime$ to $2^\prime \prime$) seems required to explain the submillimeter wavelength spectrum of Orion I, making a single emission mechanism unlikely.

For Orion I, we observe a disklike component that extends to about $0.08^\prime \prime$ ($\approx 40$ AU) from the star. We have attempted to model the brightness profile of such a disk in a manner similar to that done for the radio photospheres of Miras (Reid & Menten 1997), but with a disk geometry. Specifically, we assume an edge-on disk that is centrally heated and is optically thick to most of the radiation from the YSO. In Figure 3 we plot the observed brightness temperature in the map with 34 mas resolution (middle panel of Fig. 1) as a function of position along the disk elongation. The physical parameters of the central star and disk are listed in Table 1 for model A. In Figure 3 we overplot the model brightness (blue dotted line) convolved with the observed restoring beam. While model A provides a reasonable fit to the observations, the model requires the central star to have a total luminosity of $\approx 3 \times 10^5 L_\odot$ and a disk mass of $\approx 3 M_\odot$. These are general characteristics of this class of models and are not sensitive to details of the parameters. Note that a similarly large luminosity may also be required to explain the SiO masers (Menten & Reid 1995). Reducing the stellar luminosity requires substantially increasing the disk mass (in order to increase opacity and maintain a high disk brightness temperature). Thus, such a model requires a fairly massive disk and a luminosity exceeding that from the IRc 2 region (Gezari et al. 1998; Greenhill et al. 2004a) and, perhaps, even that of the entire Orion KL nebula (Thronson et al. 1986). Since other energetic sources exist nearby (e.g., source n), we conclude that the disk component of Orion I probably is not thermally (collisionally) excited by a central source.

While central heating of the disk component (and also the SiO masers) may be ruled out on energetic grounds, the material in the disk and the SiO masers may be partially locally heated by accretion processes. Dissipation of energy in the disk could raise the temperature above that allowed by radiative equilibrium with the central star. Since the volume of the disk can be considerably less than that of a sphere of the same radius, increasing the disk temperature in this manner can require less total energy than for central heating alone. Thus, we evaluated models that allowed the disk temperature to fall with radius, $r$, more slowly than $r^{-1/2}$.
One such model, described in Table 1 as model B and shown in Figure 3, fits the data well and requires a central star luminosity of $5 \times 10^4 L_\odot$, comfortably below the observational limits. As pointed out by Menten & Reid (1995) the SiO maser excitation also requires a very high luminosity source, were it to be centrally heated (i.e., assuming radiative equilibrium: $L = \sigma T^4 \pi r^2$). However, infalling material might interact with outflowing material (and possibly magnetic fields) in the conical walls of a bipolar outflow. This may add heat, augmenting the central source and providing the necessary high temperatures ($\approx 1200$ K) for strong SiO maser emission.

### 3.2. Photoionization: $p^+ / e^-$ Bremsstrahlung

Given the high luminosities and disk masses characteristic of models involving thermal ionization and H$^-$ free-free opacity, we now consider a hotter central star. The observed brightness can be modeled with an early B-type star, which photoionizes a moderate density plasma. Indeed, since proton-electron bremsstrahlung is $\sim 10^4$ times stronger than H$^-$ free-free per interaction, the disk plasma need only have a density $\sim 10^{-4}$ times lower.

Assume that Orion I contains a hot central star and a photoionized disk (or a photoionized surface layer). The disk may contain a neutral central layer, which provides a reservoir for material that can be photoionized by the YSO (Hollenbach et al. 1994). The submillimeter wave spectrum of Orion I measured by Beuther et al. (2006) suggests a dust component dominates above 300 GHz, leaving a bremsstrahlung spectrum that becomes optically thin above $\approx 100$ GHz. Such a turnover frequency can come from an electron density of $\sim 10^7$ cm$^{-3}$ over a path length of 35 AU, comparable to the observed radius. These parameters yield an excitation parameter, $U_e$, of $\sim 10$ pe cm$^{-2}$, which could come from a ZAMS B0–B1 star (Panagia 1973) of $\approx 10 M_\odot$ and a luminosity approaching $10^3 L_\odot$. A star of $\gtrsim 6 M_\odot$ is consistent with the rotation and expansion seen in VLBA maps of the SiO masers (Greenhill et al. 2004b; Cunningham et al. 2005).

In Figure 3 (dashed green line), we present a simple model of a brightness temperature profile along an edge-on, photoionized disk with a constant temperature. The physical parameters of the star and disk are given in the Table 1 as model C. This model provides a reasonable fit to the data, demonstrating that a photoionized disk can explain our observations.

Recently, Keto (2002, 2003) and Keto & Wood (2006) have shown that the inner portion of a disk can be fully ionized and still allow for continued accretion onto a massive protostar. They point out that inside a critical radius $r_c = GM/2c_s^2$, where $G$ is the gravitational constant, $M$ is the mass of the central protostar, and $c_s$ is the sound speed in the (neutral or ionized) material, the protostar’s gravity exceeds the thermal pressure. For the stellar parameters given above for a ZAMS B0–B1 star, ionized accretion can proceed inside of the critical radius of about 25 AU. This critical radius is similar to the 35 AU radius of the disk observed at 43 GHz in Orion I.

Keto (2007) explored models of ionized accretion in the presence of significant angular momentum. The example shown in the right-hand panel of his Figure 1 corresponds to a star of 20 $M_\odot$, an ionizing flux of $3 \times 10^{33}$ photons s$^{-1}$ (approximately a B0–09.5 star), and accreting material with specific angular momentum of 0.16 km s$^{-1}$ pc$^{-1}$. The resulting critical radius for accretion of ionized gas is 54 AU. Scaling this to a 10 $M_\odot$ star gives a critical radius of 27 AU, reasonably consistent with our observations.

An ionized accretion disk offers a natural explanation for the dearth of submillimeter wavelength spectral lines, observed by Beuther et al. (2006) toward Orion I, that would otherwise be expected for a dense and warm neutral disk. Thus, Orion I may be a good example of a massive YSO accreting material after ionizing its inner accretion disk. If the disk is maintained at a temperature greater than $\approx 1500$ K out to a radius of 35 AU, as we observe in Orion I, this may preclude planetary formation. Planet formation is thought to occur on a much longer timescale than the formation of a massive star. In order to form planets around massive stars, the early phases of planetesimal formation would have to overcome temperatures high enough to sublime dust, and certainly not conducive to rapid grain growth. This difficulty is in addition to the well-known problem of the short timescales for the formation of massive stars and dispersal of their disks.

### 4. OTHER HIGH-MASS PROTOSTARS

While Orion I is probably the nearest high-mass protostellar object, more distant candidates include CRL 2136, W 33, AFGL 2591, and NGC 7538/IRS 9. These objects display centimeter-to-millimeter wavelength spectra closely resembling that of Orion I, and whose continuum emissions are unresolved (or only marginally resolved) at 40 mas resolution (Menten & van der Tak 2004; van der Tak & Menten 2005). While none of these candidates have been observed to have SiO maser emission, Menten & van der Tak (2004) find that CRL 2136 has H$_2$O masers very close (in projection) to the continuum emission; the masers might arise in dense, hot gas following an accretion shock.

### 5. FUTURE OBSERVATIONS

Our current image of Orion I, at a resolution of 34 mas ($\approx 16$ AU), appears to show an ionized disk around a massive
YSO. While this may be the best image to date of such a disk, our data are limited both in sensitivity and angular resolution. We have only about five resolution elements along the disk, and we have not clearly resolved the emission perpendicular to the disk. In order to improve significantly the sensitivity, of this image, we probably must await the completion of the EVLA phase-I project. Improved angular resolution, with the required higher sensitivity, could be achieved with the planned increase in baseline length of the EVLA phase II or, in the long term, with the Square Kilometer Array.

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