A RING/DISK/OUTFLOW SYSTEM ASSOCIATED WITH W51 NORTH: A VERY MASSIVE STAR IN THE MAKING

Luis A. Zapata1, Paul T. P. Ho2,3, Peter Schilke1, Luis F. Rodríguez4, Karl Menten4, Aina Palau5, and Robin T. Garrod6

1 Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, 53121 Bonn, Germany
2 Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA
3 Academia Sinica Institute of Astronomy and Astrophysics, Taipei, Taiwan
4 Centro de Radioastronomía y Astrofísica, UNAM, Apdo. Postal 37-72 (Xangari), 58089 Morelia, Michoacán, Mexico
5 LAEX, Centro de Astrobiología (CAB, INTA-CSIC), LAEFF, P.O. Box 78, E-28691 Villanueva de la Cañada, Madrid, Spain
6 Department of Astronomy, Cornell University, 106 Space Sciences Building, Ithaca, NY 14853, USA

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ABSTRACT

Sensitive and high angular resolution (~0′′.4) SO2[222,20 → 221,21] and SiO[5 → 4] line and 1.3 and 7 mm continuum observations made with the Submillimeter Array (SMA) and the Very Large Array (VLA) toward the young massive cluster W51 IRS2 are presented. We report the presence of a large (of about 3000 AU) and massive (~40 Msun) dusty circumstellar disk and a hot gas molecular ring around a high-mass protostar or a compact small stellar system associated with W51 North. The simultaneous observations of the silicon monoxide molecule, an outflow gas tracer, further revealed a massive (200 Msun) and collimated (~140′′) outflow nearly perpendicular to the dusty and molecular structures suggesting thus the presence of a single very massive protostar with a bolometric luminosity on the order of 104 Lsun. A molecular hybrid local thermodynamic equilibrium model of a Keplerian and infalling disk with an inner cavity and a central stellar mass of more than 60 Msun agrees well with the SO2[222,20 → 221,21] line observations. Finally, these results suggest that mechanisms, such as mergers of low- and intermediate-mass stars, might not be necessary for forming very massive stars.

Key words: accretion, accretion disks – instrumentation: interferometers – ISM: jets and outflows – molecular data – stars: formation – stars: individual (W51 North, W51N)

Online-only material: color figure

1. INTRODUCTION

In recent years a small group of candidate accreting disks in high-mass protostars has been reported in the literature (Cesaroni et al. 2006, and references therein), but with luminosities typical of B-type main-sequence stars, that is, stars with masses ≤25 Msun. Among more luminous and massive objects (presumed O-type stars) there have been no clear evidence for accretion disks, only gravitational unstable and large rotating molecular structures have been found. These molecular structures ("toroids") are infalling and thus accreting fresh gas material to a central cluster of young massive protostars (Sollins & Ho 2005; Beltrán et al. 2005, 2006) or maybe a single 40 Msun protostar (Sandell et al. 2003; Beuther & Walsh 2008). The sizes and masses of the rotating toroids are about (2–3) × 104 AU and 100–400 Msun, respectively.

Located at 5–8 kpc away in the Sagittarius spiral arm (Genzel et al. 1981; Imai et al. 2002; Schneps et al. 1981) and with a total bolometric luminosity of about 3 × 106 Lsun, the W51-IRS2 region is one of the most luminous massive star-forming regions in our Galaxy (Erickson & Tokunaga 1980).

Recently however, it has been estimated a distance of 2.3 ± 0.3 kpc to W51-IRS2 using spectroscopic parallaxes of OB stars (Fiquérdo et al. 2008). But, in other hand, a parallax of 5 kpc by triangulation using Very Long Baseline Array (VLBA) observations of methanol masers located in W51 IRS2 was found by Xu et al. (2009), a very similar value to those found earlier by the statistical H2O maser parallax (Genzel et al. 1981; Schneps et al. 1981; Imai et al. 2002). In this study, we adopt a distance of 6 kpc for the cluster.

This region might contain about 30 O-type zero-age main-sequence (ZAMS) stars with excess emission at the infrared and (sub)millimeter wavelengths, see for an example Barbosa et al. (2008). In the W51 IRS2 cluster, there are two highly obscured massive sources called W51 North and W51 d2 that seem to be the youngest objects in the cluster and that exhibit strong emission from many complex molecules (Ho et al. 1983; Rudolph et al. 1990; Zhang & Ho 1997; Zhang et al. 1998; Sollins et al. 2004; Zapata et al. 2008). In particular, toward the W51 North object very strong maser emission from various species, e.g., hydroxyl (OH), silicon monoxide (SiO), and water (H2O) has been detected (Schneps et al. 1981; Gaume & Mutel 1987; Morita et al. 1992). This type of emission is associated with the formation of the high-mass stars. Observations of the proper motions of the H2O masers, in addition, revealed the presence of a remarkable compact (~1′′–2′′) southeast–northwest outflow emanating from this protostar (Schneps et al. 1981; Eisner et al. 2002; Imai et al. 2002). Furthermore, very high spatial resolution Very Large Array (VLA) and VLBA radio observations revealed that the SiO maser emission might be tracing the innermost parts of the outflow ejected from W51 North (Eisner et al. 2002). Finally, observations of the cyanogen (CN) molecule showed that the molecular gas is falling into this central protostar with a mass accretion rate of ~10−3 Msun yr−1 (Zapata et al. 2008).

2. OBSERVATIONS

In order to study the very young massive object W51 North, we carried out observations of the SO2[222,20 → 221,21] (sulfur dioxide) and SiO[5 → 4] (silicon monoxide) molecular lines and 1.3 mm continuum with the Submillimeter Array (SMA). We also obtained 7 mm continuum data with the VLA. Both observations had high angular resolution (~0′′.4).
The SO$_2$ molecule is a good high-density gas tracer (see Leurini et al. 2007; Jiménez-Serra et al. 2007), while the SiO is an excellent tracer for molecular outflows. The SMA SiO(5 → 4), SO$_2$(22$_{20}$ → 22$_{21}$), and 1.3 mm observations were made simultaneously on 2008 January 17, and the VLA 7 mm observations were made on 2008 April 22. At that time, the SMA was in its very extended configuration, while the VLA was in its C configuration. The phase reference center of both VLA and SMA observations was R.A. = 19$^h$23$^m$40.055, decl. = +14$^d$31$'$5$''$59 (J2000.0).

For the 7 mm observations, we integrated on-source for a total of approximately 5 hr using the fast-switching mode with a cycle of 120 s. The observations were made using the continuum mode, with a total bandwidth of 100 MHz. The central frequency observed was 43.34 GHz. The absolute amplitude calibrator was 1331 + 305 (with an adopted flux density of 1.45 Jy) and the phase calibrator was 1924 + 156 (with a bootstrapped flux density of 0.65 ± 0.01 Jy).

For the 1 mm observations, the zenith opacity ($\tau_{230\text{GHz}}$), measured with the NRAO tipping radiometer located at the Caltech Submillimeter Observatory, was ~0.15, indicating excellent weather conditions (for this frequency) during the observations. Observations of Uranus provided the absolute scale for the flux density calibration. Phase and amplitude calibrators were the quasars 1925 + 211 and 2035 + 109, with measured flux densities of 0.7 ± 0.1 and 0.5 ± 0.1 Jy, respectively.

The SO$_2$(22$_{20}$ → 22$_{21}$) and SiO(5 → 4) transitions were detected in the lower side band (LSB) of the SMA at a frequency of 216.643 and 217.104 GHz, respectively. The full bandwidth of the SMA correlator is 4 GHz (2 GHz in each band). The SMA digital correlator was configured in 24 spectral windows (“chunks”) of 104 MHz each, with 256 channels distributed over each spectral window, providing a resolution of 0.40 MHz (0.58 km s$^{-1}$) per channel. Further technical descriptions of the SMA and its calibration schemes can be found in Ho et al. (2004).

The data were edited, calibrated, and imaged using the programs MIR, AIPS, MIRIAD, and KARMA. In both bands, we used the ROBUST parameter set to 0 to obtain an optimal compromise between sensitivity and angular resolution. The 7 mm data were self-calibrated in phase. For the 7 mm observations, the continuum image rms noise was 0.9 mJy beam$^{-1}$ at an angular resolution of 0.46′′ × 0.43′′ with a P.A. = −53′′6. For the 1 mm observations, the continuum image rms noise was 6 mJy beam$^{-1}$ at an angular resolution of 0.58′′ × 0.43′′ with a P.A. = 54′′8. The line image rms noise was about 80 mJy beam$^{-1}$.

3. RESULTS AND DISCUSSION

3.1. A Massive and Large Dusty Disk

At a wavelength of 7 mm (see Figure 1), we detected strong free–free continuum emission arising from the H$\text{ii}$ regions associated with the neighboring young massive ZAMS stars located in the W51 IRS2 cluster. This emission has already been mapped at centimeter wavelengths by many authors (Gaume & Mutel 1987; Eisner et al. 2002; Mehringer 1994; Lacy et al. 2007). The radio images presented by Lacy et al. (2007) were obtained from Mehringer (1994). However, in our map, we detected for the first time a faint and compact millimeter source associated with the obscured high-mass protostar located in W51 North. This 7 mm continuum source is the counterpart of the dusty sources associated with large envelopes, and reported at 2 and 1.3 mm by Zhang et al. (1998) and Zapata et al. (2008), respectively.

In Figure 2, we have constructed the spectral energy distribution (SED) for this millimeter source from the centimeter to millimeter wavelengths, combining only data presented here. The angular resolutions of two different observations are quite similar, of about 0′′.4. From these data, we estimated a spectral index of $\alpha = 2.8$. This suggests that the emission at these wavelengths likely arises from a dusty disk. A larger envelope has been already mapped at scales 10$^3$ AU as mentioned above. The hypothesis of a flattened circumstellar disk is also supported by the fact that the mm source is resolved at wavelength 7 mm (see Table 1) and show a modest east–west elongation, nearly perpendicular to the orientation of the molecular outflow that will discussed on the following sections. At 1.3 mm the orientation is not so well determined.

We noted from Figure 16 of Mehringer (1994) that there is no strong emission from the recombination lines H92α and He92α toward the mm source, both lines are associated with the compact H$\text{ii}$ regions W51d and/or d1. The nondetection of recombination lines emission from the millimeter source is consistent with our interpretation. Furthermore, taking the values of the deconvolved sizes and the flux densities for the continuum source at 7 mm and 1.3 mm, we estimated a brightness temperature of 80 ± 10 K, a very low temperature to be associated with an H$\text{ii}$ region. This temperature is more likely associated with thermal dust emission.

Possibly, the high mass accretion rates of the infalling material associated with W51 North ($\sim$10$^{-5}$ $M_\odot$ yr$^{-1}$) could be likely quenching or trapping the development of an ultracompact H$\text{ii}$ region, so that the free–free emission from the ionized material is undetectable at centimeter wavelengths, see for a reference of these phenomena: Osorio et al. (1999); Keto (2003). Another possibility is we have a quite young massive protostar that has not developed an H$\text{ii}$ region yet.

In Figure 1, we also show the morphology of the continuum source at 1.3 mm. At both wavelengths, the deconvolved sizes are similar, with a size on the order of 3500 × 1500 AU, see Table 1. Certainly, a very large disk compared with those observed in low-mass stars ($\sim$100 AU), but with similar sizes to those observed in early B-type protostars (1000–2000 AU, e.g., Cesaroni et al. 1999; Shepherd et al. 2001; Schreyer et al. 2006; Patel et al. 2005; Rodríguez et al. 2007).

Finally, assuming that the emission is optically thin, a dust temperature value of 200 K (Zhang et al. 1998), a grain emissivity spectral index $\beta = 1$ (see Figure 2), a value of the dust absorption coefficient that goes as [κν$^\beta$] = 0.1H$\nu_{100\text{GHz}}$ and a distance to W51 North of 6 kpc, we estimated a gas mass of the dusty disk of 40 $M_\odot$. This value is consistent with the mass (100 $M_\odot$) obtained for the large dusty structures found in W51 North by Zhang et al. (1998) and Zapata et al. (2008).

3.2. A Collimated Molecular Outflow

The SiO(5 → 4) zero moment map shows the presence of a compact and collimated ($\sim$14″) north–south bipolar molecular outflow centered in the dusty source associated with W51 North (see Figure 1). The redshifted radial velocities are from +60 to +95 km s$^{-1}$ and the blueshifted ones are from +20 to +58 km s$^{-1}$; the systemic LSR radial velocity of the ambient molecular cloud is about 60 km s$^{-1}$. The receding radial velocities (redshifted) of the outflow are located toward the north, while...
the approaching radial velocities (blueshifted) are toward the southwest.

In Figure 1, we have also overlaid the SiO[5 → 4] molecular emission from the bipolar outflow with the positions of the blue- and redshifted water maser spots reported by Eisner et al. (2002). It is evident how the water maser spots trace the innermost parts of the SiO[5 → 4] molecular bipolar outflow as observed on many other molecular outflows and proposed for this case by Zapata et al. (2008).

On the other hand, the SiO masers reported also in Eisner et al. (2002) and associated with very luminous high-mass star-forming regions (Zapata et al. 2009), might be tracing even more dense parts of the outflow at very small scales (as noted by Eisner et al. 2002), and also observed for the massive protostar Source I located in the closest massive star-forming region, Orion (Menten & Reid 1995; Reid et al. 2007). We have marked the position of the SiO maser source in our Figure 1. The P.A. of the SiO[5 → 4] molecular outflow is $150^\circ \pm 20^\circ$, almost perpendicular to the orientation of the dusty source, as mentioned before. The large radial velocities of the outflow and the morphology of the SiO[5 → 4] molecular emission suggest that it is nearly perpendicular to the plane of the sky. This is also suggested by the location of water maser radial redshifted and blueshifted velocities, see Imai et al. (2002) and Eisner et al. (2002).
presented. The line is a least-squares power-law fit (of the form $S_\nu \propto \nu^{\alpha}$) to the spectrum. The respective error bars were smaller than the squares and are not presented. The line is a least-squares power-law fit (of the form $S_\nu \propto \nu^{\alpha}$) to the spectrum. The respective error bars were smaller than the squares and are not presented.

Figure 2. SED for the source W51 North combining 7 and 1.3 mm continuum data. The respective error bars were smaller than the squares and are not presented. The line is a least-squares power-law fit (of the form $S_\nu \propto \nu^{\alpha}$) to the spectrum.

Table 1

| Wave./Mol. | Position $\nu_\alpha$ (GHz) | Flux Density ($S_\nu = \int S_\nu d\Omega$) (mJy) | Deconvolved Size (arcsec) | P.A. (Deg) | Gas Mass ($M_\odot$) | Dyn. Mass ($M_\odot$) |
|------------|-----------------------------|---------------------------------|-------------------------|-------------|-----------------|-----------------|
| 7 mm       | 19 23 40 05.07              | $17 \pm 3$                      | $0.58 \pm 0.02 \times 0.27 \pm 0.02$ | $70 \pm 6$  | –               | –               |
| 1.3 mm     | 19 23 40 04.5               | $1.2 \pm 0.03 \times 0.57 \pm 0.03$ | $90 \pm 40$            | –           | –               | –               |
| SO$_2$     | 19 23 40 07.4              | $7 \times 10^5 \pm 50$         | $1.8 \pm 0.1 \times 1.2 \pm 0.1$ | $72 \pm 2$  | –               | $\geq 100^b$    |

Notes.

$^a$ The units are mJy Beam$^{-1}$ km s$^{-1}$.

$^b$ The dynamical mass was obtained from our model.

Figure 3. The position–velocity diagram of the molecular outflow. The velocity structure was also found traced by the emission of other molecules, e.g., HC$_3$N, H$_2$CO, NH$_2$CHO, and CH$_3$OH. The velocity structure was also found traced by the emission of other molecules, e.g., HC$_3$N, H$_2$CO, NH$_2$CHO, and CH$_3$OH. The velocity structure was also found traced by the emission of other molecules, e.g., HC$_3$N, H$_2$CO, NH$_2$CHO, and CH$_3$OH.

3.3. A Hot Molecular Gas Ring

A large and flattened molecular ring (with an inner cavity of about 3000 AU) surrounding the dusty disk was traced by the emission of the molecule SO$_2[22_2,20 \rightarrow 22_1,21]$ (see Figure 1).

The ring has a deconvolved radius of the order of 6000 AU with an orientation (P.A. = 22°) almost perpendicular to that of the molecular outflow and similar to the presumed dusty disk. In Figure 3, we show the position–velocity diagram of the molecular SO$_2[22_2,20 \rightarrow 22_1,21]$ emission from the ring structure. From this figure, one can see a ring structure with a modest velocity gradient across the ring of ~5 km s$^{-1}$ over 20′, produced by rotation and infall. The redshifted radial velocities are located to the northeast, while the blueshifted ones to the southwest. The small velocity gradient is likely due to the small inclination angle of ring with respect to plane of sky. Similar rings velocity structures were also found traced by the emission of other molecules species, e.g., HC$_3$N, H$_2$CO, NH$_2$CHO, and CH$_3$OH.

Very recently, however, Zapata et al. (2008) reported a large structure or envelope with a size of $4 \times 10^5$ AU and with a P.A. = 90° traced by the C$_2$H$_5$CN molecule and centered on W51 North. This molecular structure seems to rotate in an opposite direction (with the blueshifted velocities to the east while the redshifted ones to the west) to the molecular compact ring traced by the SO$_2[22_2,20 \rightarrow 22_1,21]$. As discussed in Zapata et al. (2008), other molecules such as HCOOCH$_3$ and CH$_3$OH at same scales associated with W51 North were very much contaminated by the emission from the hot molecular core associated with W51d2 do not allowing to confirm the velocity shift. We thus think that the C$_2$H$_5$CN molecular core in W51 North was also contaminated with emission coming from W51d2 given therefore the impression of rotation.

We are more confident that the velocity gradient across the molecular ring is correct because we have resolved the molecular source and other molecules show similar velocity structures. In Figures 4 and 5, we additionally present the velocity channel maps and the position–velocity diagram of the SO$_2[22_2,20 \rightarrow 22_1,21]$ emission from the ring, overlaid with a simple LTE model of a large infalling Keplerian ring with an inner cavity with sizes (of the ring and the inner cavity) similar to those observed.

We assumed in this model that the thermal molecular line emission of the ring is in LTE, and took from the literature some
Figure 3. Velocity-channel image of the SO$_2$[22$_2$20 $\rightarrow$ 22$_1$11] thermal emission from the ring (contours) overlaid with our synthetic LTE model (gray scale). The spectral resolution was smoothed to velocity bins of 1 km s$^{-1}$. The central velocity is indicated (in km s$^{-1}$) in the top right-hand corner of each panel. The systemic velocity of the ambient molecular cloud is about 60.0 km s$^{-1}$. The contours are 10%–90% with a step of 10% of the peak flux. The scale bar indicates the peak flux of the molecular emission in $T_b$.

Figure 4. Position–velocity diagram of the molecular ring computed at P.A. = 22$^\circ$ (colors) overlaid with the position–velocity diagram from our model (contours). The contours are from 10% to 90% with steps of 10% of the peak of the line emission of our LTE model. The units of the vertical axis are in arcseconds. The systemic LSR radial velocity of the ambient molecular cloud is about 60.0 km s$^{-1}$. The synthesized beam of the line image is 0$^\prime$.58 $\times$ 0$^\prime$.43 with a P.A. of 54$^\circ$8. The spectral resolution was smoothed to 1 km s$^{-1}$.

known values as the excitation temperature, the density, and the infall velocity (see Zhang et al. 1998; Zapata et al. 2008). The best fit was found recurrently until we obtained similar structures in our model to those imaged (see Table 2 and Figures 3 and 4). The model fits the observations acceptably well.

This model, in addition, restricted the position of the ring on the sky. It is almost in face-on, with an inclination angle with respect to the plane of the sky less than 30$^\circ$ and a P.A. equal to 22$^\circ$. It is important to mention that if the inclination angle is smaller, the dynamical mass will increase by much more, with a reason inversely proportional to the sin$^2(i)$, where $i$ is the inclination angle. Thus, the central object could have a stellar mass of more than 60 $M_\odot$.

It is interesting to note that the mass of the disk (40 $M_\odot$) might be on the order of the stellar mass ($\geq$60 $M_\odot$). This has been seen before for the massive young disks associated with the high-mass protostars located in the star-forming region: NGC6334N(I) (Rodríguez et al. 2007).

The nature of large inner cavity in the molecular ring may be due to opacity effects, photodissociation of the molecules, or clearing of the inner disk either from a multiple system of compact circumstellar disks already formed in the center of the ring or by the outflow itself. If the nature of the ring is because of opacity effects or photodissociation of the molecules very close to the central object, it suggests that both the molecular ring and circumstellar disk could be part of a same extended and flattened structure. Observations with
a much better angular resolution of high-density tracers and the continuum at millimeter wavelengths may determine the nature of the inner cavity in the ring.

The strong feature observed toward the east of the ring might be originated from the interaction of the outflow with the ring itself. However, more observations at high angular resolution with different molecular probes sensitive to different cloud properties will be quite important for studying the higher excitation material within the ring.

In Figure 5, we show artist’s conception of the molecular ring, the bipolar outflow, and the central massive disk found in the high-mass protostar W51 North.

Table 2
Parameters for the Molecular Gas Ring LTE Model

| Name                        | Parameter | Value          |
|-----------------------------|-----------|----------------|
| Systematic velocity         | $V_{LSR}$ | 60.0 km s$^{-1}$ |
| Orientation                 | P.A.      | $22^\circ \pm 10^\circ$ |
| Inclination                 | $i$       | $\leq 30^\circ$ |
| Density                     | $\rho$    | $10^6$ cm$^{-3}$ |
| Inner radius                | $R_i$     | 3000 AU ± 200 AU |
| Outer radius                | $R_o$     | 6000 AU ± 200 AU |
| Temperature of the central object | $T$     | 500 K |
| Dust exponent               | $\beta$  | 1.0            |
| Distance                    | $D$       | 6000 pc        |
| Reference radius            | $r$       | 6000 AU        |
| Power-law index density     | $\alpha$ | 2.75           |
| Kinetic temperature         | $T_{kin}$ | 200 K          |
| at referenced radius        | $T_{exc}$ | 200 K          |
| Excitation temperature      | $\gamma$ | 0.6            |
| Power-law index $T_{kin}$   | $\delta$ | 0.6            |
| Power-law index $T_{exc}$   | $H$       | 60 AU ± 20 AU  |
| Scale height of disk        | $M$       | $\geq 100 M_{\odot}$ |
| Infall velocity             | $V_{inf}$ | 4 km s$^{-1}$ |

4. SUMMARY

W51 North presents a promising laboratory for future studies on the formation of very high mass stars. We have observed this young massive protostar at spatial scales of 0'.4 using the SMA and VLA and found the following.

1. A massive (40 $M_{\odot}$) and large (~3000 AU) dusty circumstellar disk around a single high-mass protostar or a compact small stellar system.
2. A hot and rotating molecular ring with an inner cavity of about 3000 AU and a size of about 9000 AU.
3. A highly collimated and massive (200 AU) bipolar outflow that emanates with an orientation almost perpendicular to the circumstellar disk and the ring. This collimated outflow suggests the presence of a single massive protostar in the center of the circumstellar disk.
4. Our data revealed that H$_2$O and SiO masers associated with this highly embedded protostar are tracing the innermost parts of the thermal bipolar outflow.
5. A molecular hybrid LTE model of a Keplerian infalling disk with an inner cavity (~3000 AU) and a stellar mass of more than 60 $M_{\odot}$ agree well with the SO$_2$[222,20 $\rightarrow$ 221,21] line observations.

These results suggest that mechanisms, such as mergers of low- and intermediate-mass stars, might not be necessary for forming very massive stars.

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Facilities: Submillimeter Array (SMA), Very Large Array (VLA)

REFERENCES

Barbosa, C. L., Blum, R. D., Conti, P. S., Damineli, A., & Figueredo, E. 2008, ApJ, 678, L55
Beltrán, M. T., Cesaroni, R., Codella, C., Testi, L., Furuya, R. S., & Olmi, L. 2006, Nature, 443, 427
Beltrán, M. T., Cesaroni, R., Neri, R., Codella, C., Furuya, R. S., Testi, L., & Olmi, L. 2005, A&A, 435, 901
Beuther, H., & Walsh, A. J. 2008, ApJ, 673, L55
Cesaroni, R., Felli, M., Jenness, T., Neri, R., Olmi, L., Robberto, M., Testi, L., & Walmsley, C. M. 1999, A&A, 345, 949
Cesaroni, R., Galli, D., Lodato, G., Walmsley, M., & Zhang, Q. 2006, Nature, 444, 703
Eisner, J. A., Greenhill, L. J., Herrnstein, J. R., Moran, J. M., & Menten, K. M. 2002, ApJ, 569, 334
Erickson, E. F., & Tokunaga, A. T. 1980, ApJ, 238, 596
Figueredo, E., Blum, R. D., Damineli, A., Conti, P.S., & Barbosa, C. L. 2008, AJ, 136, 221
Gaume, R. A., & Mutel, R. L. 1987, ApJS, 65, 193
Genzel, R., et al. 1981, ApJ, 247, 1059
Ho, P. T. P., Das, A., & Genzel, R. 1983, ApJ, 266, 596
Ho, P. T. P., Moran, J. M., & Lo, K. Y. 2004, ApJ, 616, L1
Imai, H., Watanabe, T., Omodaka, T., Nishio, M., Kameya, O., Miyaji, T., & Nakajima, J. 2003, PASJ, 54, 741
Jimenez-Serra, I., Martin-Pintado, J., Rodriguez-Franco, A., Chandler, C., Comito, C., & Schilke, P. 2007, ApJ, 661, L187
Keto, E. 2003, ApJ, 599, 1196
Lacy, J. H., et al. 2007, ApJ, 658, L45
Leurini, S., Beuther, H., Schilke, P., Wyrowski, F., Zhang, Q., & Menten, K. M. 2007, A&A, 475, 925
