ON TURBULENT PRESSURE CONFINEMENT OF ULTRACOMPACT H II REGIONS

TAOLING XIE, LEE G. MUNDY, AND STUART N. VOGEL

Laboratory for Millimeter-Wave Astronomy, Department of Astronomy, University of Maryland, College Park, MD 20742; tao@astro.umd.edu

AND

PETER HOFNER

Universität zu Köln, I. Physikalisches Institut, Zülpicherstrasse 77, 50937 Köln, Germany

Received 1996 July 14; accepted 1996 October 7

ABSTRACT

It has been proposed recently that the small size and long lifetime of ultracompact (UC) H II regions could be due to pressure confinement if the thermal pressure of the ambient gas is higher than previous estimates. We point out that confinement by thermal pressure alone implies emission measures in excess of observed values. We show that turbulent pressure, inferred from observed nonthermal velocities, is sufficient to confine UC H II regions and explain their longevity. We predict an anticorrelation between the size of UC H II regions and the velocity dispersion of the ambient neutral gas and show that it is consistent with existing observations.

Subject headings: H II regions — ISM: kinematics and dynamics — stars: formation — turbulence

1. INTRODUCTION

Ultracompact (UC) H II regions are very small (<0.2 pc) dense regions of ionized gas in molecular clouds first noted by Ryle & Downes (1967) and Dreher & Welch (1981). Deeply embedded, the ionized gas is seen only through free-free emission at radio wavelengths. The importance of this type of object for our understanding of the birth of massive stars is well recognized (Churchwell 1993; Welch 1993; Vogel 1994). A key unsettled question is the discrepancy between the characteristic age (~10^7 yr) of UC H II regions implied by their ubiquity (Wood & Churchwell 1989, hereafter WC89; Kurtz, Churchwell, & Wood 1994, hereafter KCW94) and the very short dynamical lifetime (~10^5 yr) estimated from the sound crossing time. This disparity implies the presence of physical mechanisms that confine the UC H II regions. Proposed possibilities include (1) ram pressure due to gravitational infall of ambient gas onto the H II region (see Reid et al. 1981; Dreher & Welch 1981; Ho & Haschick 1986), (2) stellar wind bow shock/ram pressure confinement (see WC89; van Buren et al. 1990), and (3) photoevaporating disks (Vogel, Genzel, & Palmer 1987; Welch 1993; Hollenbach et al. 1994), photoevaporating clumps (Lizano & Cantó 1995; Williams, Dyson, & Redman 1996), or champagne-flow/blisters (Tenorio-Tagle 1979; Yorke, Tenorio-Tagle, & Bodenheimer 1983; Forster et al. 1990).

2. CONFINEMENT BY THERMAL PRESSURE

De Pree, Rodríguez, & Goss (1995) (see also García-Segura & Franco 1996 and Akeson & Carlstrom 1996) have recently suggested that the compactness of the UC H II regions can be explained if the density and temperature in the ambient neutral gas are much higher than commonly assumed. Their basic argument is twofold. First, the initial Strömgren radius \( R_s \) scales inversely with gas density (see, e.g., Spitzer 1978) as

\[
R_s = \left( \frac{3S_\alpha}{4\pi\beta_2^2} \right)^{1/3} n_0^{-2/3}
\]

\[
= 1.99 \times 10^{-2} \left( \frac{S_\alpha}{10^{49} \text{ s}^{-1}} \right)^{1/3} \left( \frac{n_{\text{H}_2}}{10^5 \text{ cm}^{-3}} \right)^{-2/3} \text{ pc}
\]

where \( S_\alpha \) is the flux of ionizing photons, \( n_0 = 2n_{\text{H}_2} \) is the initial electron density in the ionized gas, and \( \beta_2 = 2.6 \times 10^{-13} \text{ cm}^{-2} \text{ s}^{-1} \) is the recombination coefficient. Thus, for a sufficiently high ambient molecular density, the initial Strömgren sphere can be very small. Second, a higher ambient gas temperature reduces the amount that the ionized gas expands before reaching pressure equilibrium with the ambient material.

The emission measure of the ionized gas predicted by this simple scenario, however, is significantly larger than the values generally observed. This point can be verified easily from the calculations and discussions by De Pree et al. (1995). For a sample of small UC H II regions, De Pree et al. showed that an ambient molecular density of \( 10^5 \text{ cm}^{-3} \) together with a gas temperature of \( \sim 200 \text{ K} \) would suffice to explain the compactness of the UC H II regions. They estimated an initial Strömgren radius \( R_s = 1.0 \times 10^{-7} \text{ pc} \) at such high density, corresponding to an initial emission measure \( \text{EM}_0 = 2n_0^2R_s = 8 \times 10^{11} \text{ cm}^{-6} \text{ pc} \) Overpressured, the initial ionized sphere expands outward until it reaches pressure equilibrium with ambient neutral gas. At a later time, when the ionized sphere has a radius \( R_\text{e} \) and electron density \( n_e \), the emission measure will drop to

\[
\text{EM} = 2n_e^2R = \left( \frac{R_s}{R} \right)^2 \text{EM}_0.
\]

For \( R = 0.01 \text{ pc} \), the emission measure is thus expected to be \( \sim 8 \times 10^8 \text{ cm}^{-6} \text{ pc} \). The observed average emission measures for spherical UC H II regions with sizes \( \sim 0.01 \text{ pc} \) are mostly around a few \( 10^7 \) to a few \( 10^9 \text{ cm}^{-6} \text{ pc} \) in the WC89 and KKW94 surveys, lower than the predicted value by an order of magnitude, although there clearly are some UC H II regions that have very high emission measures (see Turner & Matthews 1984; Garay, Moran, & Rodríguez 1993a). It seems unlikely that the assumption of optical thinness for the radio emission could have underestimated the emission measure by such a large factor. Therefore, although the gas density around some UC H II regions is indeed higher than \( 10^5 \text{ cm}^{-3} \) (the density originally adopted by WC89) as recent observations have revealed (see Huttemeister et al. 1993; Akeson & Carl-
strom 1996; Plume et al. 1997), a gas density of \( n_H = 10^7 \text{ cm}^{-3} \) as adopted by De Pree et al. (1995) seems too high for the material around typical spherical UC H II regions with \( R \sim 0.01 \text{ pc} \) in WC89 and KCW94 surveys. Other physical processes such as swept-up shells or dust absorption of Lyman photons may modify the predicted emission measure somewhat, but it is not difficult to see that the former would further increase the emission measure, while the latter can reduce the emission measure by only a factor of \( (1 - x)^{1/3} \), where \( x \) is the fraction of Lyman photons absorbed by dust grains (Franco, Tenorio-Tagle, & Bodenheimer 1990; Churchwell 1993). For \( x = 0.9 \), the emission measure is reduced by a factor of 0.46 (WC89). While not necessarily irrelevant, dust absorption alone is not likely to be able to account for the observed low emission measure for a significant fraction of UC H II regions. We conclude that confinement by thermal pressure requires UC H II regions to have higher emission measures than observed in most cases.

3. TURBULENT PRESSURE CONFINEMENT

3.1. Plausibility

That the gas pressure in the interstellar medium is not limited to the thermal pressure alone is evident from emission-line profiles and has recently been brought up in connection with UC H II regions by García-Segura & Franco (1996). Ever since the discovery of molecular clouds, it has been known that the Doppler-broadened line profiles of all molecular tracers indicate the presence of significant nonthermal motions, referred to as turbulence, down to the smallest scales probed even for low-mass molecular structures (see Falgarone, Puget, & Pérault 1992). Since massive star-forming regions are well known to have stronger turbulence (see Plume et al. 1997), it is likely that turbulence exists ubiquitously on the scales of UC H II regions. Regardless of whether the origin is hydrodynamic or hydromagnetic, the presence of turbulence implies a significant pressure in addition to the thermal pressure. Massive star-forming regions, where UC H II regions are found, are particularly turbulent, often with velocity dispersions well in excess of a couple of kilometers per second (Cesaroni et al. 1991; hereafter CWKC; Plume et al. 1997). The turbulent pressure implied is considerably larger than the thermal pressure. For example, the turbulent pressure \( P = n_H \sigma_d^2 \) corresponding to a velocity dispersion of \( \sigma_d = 2 \text{ km s}^{-1} \) is equivalent to a thermal pressure at an effective kinetic temperature of \( T_{eb} \sim 10^9 \text{ K} \). In fact, if massive star-forming cores where UC H II regions reside are indeed close to virial equilibrium (CWKC), the implied molecular gas pressure ought to be comparable to the ram pressure due to free-fall collapse. Therefore, as long as turbulence exists down to the scales of UC H II regions, it seems safe to conclude that turbulent pressure could provide significant opposition to the expansion of the ionized gas, just as the ram pressure would owing to gravitational collapse of the molecular envelope (Reid et al. 1981).

The validity of the above hypothesis can be clarified by further considering the two conceptual phases of UC H II region development (Dyson & Williams 1980; WC89). The first phase, i.e., the establishment of an initial Strömgren sphere, is not affected much by the turbulence, so the general results and conclusions in Dyson & Williams (1980) and WC89 remain valid, and the Strömgren sphere with radius determined by equation (1) will form in a matter of a few years.\(^1\) The temperature of the newly ionized gas jumps to \( T_{l} \sim 10^4 \text{ K} \), and the number density of the particles in the gas increases by roughly a factor of 4 owing to dissociation and ionization. This, together with the ram pressure due to stellar winds, causes the ionized gas to expand outward at its sound velocity until it reaches approximate pressure equilibrium with the ambient molecular gas. Instead of completely neglecting the pressure due to stellar winds and turbulence in the ionized gas (Dyson & Williams 1980; De Pree et al. 1995), we introduce a factor \( \xi > 1 \) to take them partially into account (it can be argued that the ram pressure due to stellar winds may be reflected by an enhanced actual electron density in a swept-up shell). The final average electron density \( n_e \) in the H II region can then be estimated from the following condition (Dyson & Williams 1980; WC89):

\[
2\xi n_e k_1 T_{l} = n_H (m_H \sigma_d^2 + k T_k)
\]

\[
= n_H (m_H \sigma_d^2 / (8 \ln 2)),
\]

where \( T_k \) is the molecular gas kinetic temperature and \( \sigma_d^2 = (8 \ln 2) \sigma_t^2 \) is the FWHM of an optically thin molecular line tracing the high-density gas around the UC H II regions. \( \delta v_{\text{tot}} \) includes both nonthermal and thermal components. If \( S_\lambda \), the flux of ionizing photons, remains largely unchanged during the expansion and if the H II region is ionization bounded, one has

\[
S_\lambda (1 - x) = \frac{4}{3} \pi n^3 \beta^2 = \frac{4}{3} \pi n^3 \beta^2.
\]

Equations (3) and (4) give

\[
R = R_0 \left( \frac{4k_1 T_{l} \sigma_t^2}{m_H \sigma_d^2 + k T_k} \right)^{1/3} = R_0 \left( \frac{32 \ln 2}{m_H \delta v_{\text{tot}}^2} \right)^{1/3}.
\]

So, turbulent pressure can significantly reduce the final equilibrium size of the UC H II region. If \( \sigma_d = 2 \text{ km s}^{-1} \) and \( T_k \approx 100 \text{ K} \), we have \( R \approx 9.54 \xi^{1/3} R_0 \) (vs. \( R = 54.3 R_0 \) with thermal pressure alone). For \( n_H = 8 \times 10^3 \text{ cm}^{-3} \) and \( S_\lambda = 10^{49} \text{ s}^{-1} \) (for an O6 star), we have \( R = 0.05 (1 - x)^{1/3} \text{ pc} \) and \( EM_0 = 2.5 \times 10^{10} (1 - x)^{1/3} \text{ cm}^2 \text{ pc} \). Thus, \( EM_0 = R_0 \left( \frac{R_0}{R} \right)^{3/2} \sim 2.8 \times 10^{43} (1 - x)^{1/3} \text{ cm}^2 \text{ pc} \) and \( R = 0.05 \xi^{1/3} (1 - x)^{1/3} \text{ pc} \). For reasonable dust absorption coefficient \( x \) and factor \( \xi \), both the predicted size and emission measure are reasonable in comparison with those inferred from observations (WC89; KCW94), especially considering the expected variation in \( n_H \), \( S_\lambda \), and \( \delta v_{\text{tot}} \) from region to region. In particular, it appears that the initial Strömgren sphere expands by a factor of 0.1, say from 0.01 to 0.1 pc, before reaching pressure equilibrium with the turbulent ambient molecular gas. The time for the expansion can be roughly estimated from the sound crossing time, \( \tau_{\text{expansion}} \sim R / C_\lambda \sim 10^4 \text{ yr} \), where \( C_\lambda \) is the sound speed in ionized gas taken as 10 km s\(^{-1}\). Since the average age of the UC H II regions observed is close to 10^4 yr (WC89; KCW94), most UC H II regions might indeed have had enough time to expand to reach pressure equilibrium with their ambient molecular gas (see García-Segura & Franco 1996).

Note that this scenario, just as the classic picture for H II regions, predicts that H II regions with larger sizes will have a

\(^1\) Note that a uniform density is assumed.
lower average electron density. This is consistent with observations by Garay et al. (1993b), Churchwell (1993), and KCW94. Such a size-density correlation is somewhat less obvious for UC H II regions, with cometary and core-halo morphologies (KCW94; Churchwell 1993). But it is somewhat difficult to define the average electron density for nonspHERical UC H II regions, and thus the determined densities for these sources in the literature are likely subject to relatively large systematic errors (S. Kurtz 1996, private communication). Further careful observational studies on this aspect will be useful.

3.2. Velocity Dispersion–UC H II Size Relation

Equation (5) indicates that the size of UC H II regions ought to be anticorrelated with the total gas pressure or velocity dispersion of the ambient molecular gas if the gas pressure is indeed responsible for the compactness of UC H II regions. In the case that $R_S$ (i.e., $S_\alpha$) does not vary much from one region to another, equation (5) predicts $\delta v_{tot} \propto D_{UC}^{-1.5}$. However, the surveys by WC89, Garay et al. (1993b), and KCW94 imply that $S_\alpha$ has a strong dependence on $R$ in the sense that larger UC H II regions tend to have a larger ionizing flux $S_\alpha$ (E. Churchwell & S. Kurtz 1996, private communication). Assuming that the UC H II regions are ionization-bounded, the $S_\alpha$-$R$ dependence can be derived from the proposed $n_e$-$R$ relation, $n_e = n_{e0.1 \text{pc}} (R/0.1 \text{ pc})^{-\alpha}$, where $n_{e0.1 \text{pc}}$ is the average electron density for UC H II regions with $R = 0.1$ pc. Therefore, $S_\alpha (1 - x) = (4/3) \pi R^2 n_e^2 \beta_2 \propto R^{-2.5}$, and we have

$$\delta v_{tot} = \left( \frac{16 \ln 2 kT_H}{m_{H_2}} \right)^{1/2} \left( \frac{\xi_{H_20.1 \text{pc}}}{n_{H_2}} \right)^{1/2} \left( \frac{R}{0.1 \text{ pc}} \right)^{-\alpha^2}.$$  

Churchwell (1993) and KCW94 found that $\alpha \sim 0.65$ provides a reasonable fit to their data for a sample of spherical and unresolved UC H II regions, while Garay et al. (1993b) preferred $\alpha \sim 0.98$ for a larger sample of UC H II regions with various morphological types, some of which have relatively large sizes.

While the size of the UC H II regions can be determined easily from the VLA maps, it is not entirely trivial to obtain $\delta v_{tot}$ observationally. Specifically, the following criteria must be considered in choosing molecular lines for a reliable determination of $\delta v_{tot}$. First, the molecular line used must have a relatively high critical excitation density in order to sample the dense gas in the immediate neighborhood of UC H II regions. Second, to reduce foreground and background confusion as well as line broadening by optical depth effects, the molecular line must be optically thin. Third, the spatial and spectral resolutions must be adequate. Existing systematic surveys of molecular gas associated with UC H II regions using lower transitions of ammonia and CO and isotopes can be immediately ruled out by the above criteria. At this time, it appears that the $^{34}$S $J = 2–1$ data from the survey by Cesaroni et al. (1991). Despite a large scatter, the data are remarkably consistent with the theoretical predictions for reasonable parameters, as discussed in the text.

show significantly larger line widths, which indicate possible additional broadening due to other physical processes such as optical depth effects and outflows.

Figure 1 shows the data points for all eight UC H II regions observed in $^{34}$S $J = 2–1$ by CWKC in comparison with the expected correlation for pressure-confined UC H II regions. The dotted, solid, and dashed lines represent equation (6) with $\alpha = 0.65$ (Churchwell 1993; KCW94) for $\xi_{H_20.1 \text{pc}}/n_{H_2} = 2.55 \times 10^{-2}$, $\xi_{H_20.1 \text{pc}}/n_{H_2} = 4.04 \times 10^{-2}$, and $\xi_{H_20.1 \text{pc}}/n_{H_2} = 8.08 \times 10^{-2}$, respectively, i.e., $\delta v_{tot} = (3.16, 2.24, 1.78) D_{UC}^{0.32}$, where $D_{UC} = 2 R$. Despite a large scatter, an anticorrelation between $\delta v_{tot}$ and $D_{UC}$ is evident and is in excellent agreement with the theoretical prediction with $\alpha = 0.65$. In fact, a least-squares fit to the eight data points gives $\delta v_{tot} = (2.45 \pm 1.17) D_{UC}^{-0.25 \pm 0.07}$ with a correlation coefficient $r = 0.87$, which is almost identical to the solid line. Equation (6) with $\alpha = 0.98$ (Garay et al. 1993b) does not fit the eight data points as well, but it is worth noting again that the Garay et al. sample of UC H II regions contains not only larger UC H II regions but also nonspherical UC H II regions for which the determined mean electron density is subject to larger uncertainties. Since $\delta v_{tot}$ does not show any correlation with the distances to these H II regions, the possibility that the above anticorrelation results from the different physical sizes probed by the same telescope beam at different distances appears unlikely. From Churchwell (1993) and KCW94, we have $n_{e0.1 \text{pc}} \sim 10^4 \text{ cm}^{-3}$. Therefore, the solid line in Figure 1 implies an average molecular gas density $n_{H_2} \sim 2.5 \times 10^4 \text{ cm}^{-3}$. Given the uncertainties involved, this
implied mean molecular density is in reasonable agreement with the densities derived for these regions (CWKC) and other massive star-forming cores (Plume et al. 1997), especially considering the fact that some UC H II regions may not reside in the densest molecular gas in massive star-forming cores (see Churchwell 1993; Hofner et al. 1996; Xie et al. 1996). Considering the large uncertainty in $D_{UC}$ owing to the highly uncertain distances to these regions, the consistency between the observations and the theoretical prediction for $\delta_{v_{tot}}$-R relation with $\alpha = 0.65$ is surprisingly good.

Finally, we note that $\delta_{v_{tot}}$ may include systematic motions such as collapse and outflow or expansion, as observations indeed suggest (see Ho & Haschick 1986; Peng 1995; Hofner et al. 1996; Shepherd & Churchwell 1996; Xie et al. 1996). The infall of gas provides additional confining pressure, just like the turbulent motion. In the extreme case that $\delta_{v_{tot}}$ is largely dominated by outflowing motion, however, there appears an alternative interpretation for the $\delta_{v_{tot}}$-$D_{UC}$ anticorrelation in the sense that younger and thus smaller UC H II regions may be associated with larger outflowing motions. We feel that this interpretation is less attractive, given the interferometric observations which indicate that an UC H II region is often just one of a few massive stars in a cluster on a considerably larger scale, and the energy input due to an UC H II region alone is unlikely to be dominant (see Wilner, Welch, & Forster 1995; Xie et al. 1996).

4. DISCUSSION

We also note that it would be naive to expect turbulent gas pressure to be the dominant confining mechanism for every UC H II region. A desirable aspect of the simple turbulent pressure confinement idea is that it does not deny the possible role that any other mechanisms may play in addition to the turbulent pressure.

One natural prediction of the turbulent pressure confinement of UC H II regions is that UC H II regions in relatively quiescent molecular clouds must be rare because they will be short-lived. Unfortunately, it is difficult to check this prediction observationally, because it has long been known that massive stars tend to form in massive molecular cloud cores where turbulence is known to be stronger. However, since even an initially quiescent molecular cloud would become turbulent as soon as the first generation of stars forms and injects kinetic energy as outflows, one interesting speculation is that the first massive stars may develop larger H II regions around them and trigger the formation of a later generation of stars owing to the enhanced gas pressure. The stars of these later generations formed in the high pressure environment would have to spend considerably longer time embedded in their ambient molecular gas and dust.

Systematic surveys of the molecular gas around a large number of UC H II regions using optically thin, high density-sensitive molecular lines with resolution on the order of <1° would be highly useful in confirming or rejecting the reality of the proposed velocity dispersion–UCH II region size relationship and in clarifying the role that gas pressure plays in the development of H II regions around newly formed massive stars. More detailed studies of $n_{H}^{-1/2}$ or $\delta_{v_{tot}}$-$R$ relations for UC H II regions of various morphologies and sizes will also be very helpful. In particular, it would be highly desirable if high-quality multitransitional data could be taken for a large number of UC H II regions with a wide range of sizes, which could then be used to determine the density of the molecular gas as well and thus to check if most of the UC H II regions are indeed in rough pressure equilibrium with ambient molecular gas.

T. X. thanks Ed Churchwell and Jack Welch for stimulating discussions and in particular for their kind encouragement. He further thanks Neal Evans, Pepe Franco, Paul Goldsmith, David Hollenbach, Stan Kurtz, Yuan Peng, Debra Shepherd, Frank Shu, Frank Wilkin, and Qizhou Zhang for useful discussions and Pepe Franco, Paul Goldsmith, Paul Ho, Luis Rodriguez, and the anonymous referee for reading the manuscript with helpful comments. This research is partly supported by NSF grant AST9314847 to the Laboratory for Millimeter-wave Astronomy at the University of Maryland.

REFERENCES

Akeson, R. L., & Carlstrom, J. E. 1996, ApJ, 470, 528
Cesaroni, R., Walmsley, C. M., Köhme, C., & Churchwell, E. B. 1991, A&A, 252, 278 (CWKC)
Churchwell, E. B. 1993, in ASP Conf. Proc. 35, Massive Stars: Their Lives in the ISM, ed. J. P. Cassinelli & E. Churchwell (San Francisco: ASP), 35
De Pree, C. G., Rodríguez, L. F., & Goss, W. M. 1995, Rev. Mexicana Astron., Astrofis., 31, 39
Dreher, J. W., & Welch, W. J. 1981, ApJ, 245, 857
Dyson, J. E., & Williams, D. A. 1980, Physics of the Interstellar Medium (New York: John Wiley & Sons), 132
Falgarone, E., Puget, J.-L., & Péruault, M. 1992, A&A, 257, 715
Forster, J. R., Caswell, J. L., Okumura, S. K., Hasagawa, T., & Ishiguro, M. 1990, A&A, 231, 473
Franco, J., Tenorio-Tagle, G., & Bodenheimer, P. 1990, ApJ, 349, 126
Garay, G., Moran, J. M., & Rodríguez, L. F. 1993a, ApJ, 413, 582
Garay, G., Rodríguez, L. F., Moran, J. M., & Churchwell, E. 1993b, ApJ, 418, 368
García-Segura, G., & Franco, J. 1996, preprint
Ho, P. T. P., & Haschick, A. D. 1986, ApJ, 304, 501
Hohlfner, P., Kurtz, S., Churchwell, E., Walmsley, C. M., & Cesaroni, R. 1996, ApJ, 465, 359
Hollenbach, D., Johnstone, D., Lizano, S., & Shu, F. 1994, ApJ, 428, 654
Huttemeester, S., Wilson, T. L., Henkel, C., & Mauersberger, R. 1993, A&A, 276, 445
Kurtz, S., Churchwell, E., & Wood, D. O. S. 1994, ApJS, 91, 659 (KCW94)
Lizano, S., & Cantó, J. 1995, Rev. Mexicana Astron. Astrofís., Ser. Conf., 1, 29
Peng, Y. 1995, Ph.D. thesis, Univ. of Maryland College Park
Plume, R., Jaffe, D. T., Evans, N. J., II, Martín-Pintado, J., & Gomez-Gonzalez, J. 1997, ApJ, in press
Reid, M. J., Haschick, A. D., Burke, B. F., Moran, J. M., Johnston, K. J., & Swenson, G. W., Jr. 1981, ApJ, 239, 89
Ryle, M., & Downs, D. 1967, ApJ, 148, L17
Shepherd, D. S., & Churchwell, E. 1996, ApJ, 457, 267
Spitzer, L. 1978, Physical Processes in the Interstellar Medium (New York: Wiley)
Tenorio-Tagle, G. 1979, A&A, 71, 59
Turner, B. E., & Matthews, H. E. 1984, ApJ, 277, 164
van Buren, D., Mac Low, M.-M., Wood, D. O. S., & Churchwell, E. 1990, ApJ, 353, 570
Vogel, S. N. 1994, in ASP Conf. Proc. 59, Astronomy with Millimeter and Submillimeter Wave Interferometry, ed. M. Ishiguro & Wm. J. Welch (San Francisco: ASP), 176
Vogel, S. N., Genzel, R., & Palmer, P. 1987, ApJ, 316, 243
Welch, W. J. 1993, in ASP Conf. Proc. 35, Massive Stars: Their Lives in the ISM, ed. J. P. Cassinelli & E. Churchwell (San Francisco: ASP), 15
Williams, R. J. B., Dyson, J. E., & Redman, M. P. 1996, MNras, 280, 667
Wilner, D. J., Welch, W. J., & Forster, J. R. 1995, ApJ, 449, L73
Wood, D. O. S., & Churchwell, E. 1989, ApJS, 69, 831 (WC89)
Xie, T., Hohlfner, P., Mundy, L., & Vogel, S. 1996, in preparation
Yorke, H. W., Tenorio-Tagle, G., & Bodenheimer, P. 1983, A&A, 127, 313