Revista Mexicana de Astronomía y Astrofísica, **31**, 39-44 (1995)

ULTRACOMPACT H II REGIONS: ARE THEIR LIFETIMES EXTENDED BY DENSE, WARM ENVIRONMENTS?

C.G. De Pree[1,3], L.F. Rodríguez[2], and W.M. Goss[3]

Received 1994 November 21

RESUMEN

Las regiones H II ultracompactas están definidas como aquellas que tienen diámetros menores que $\sim$ 0.1 pc (Wood & Churchwell 1989a). Se espera que estas regiones H II se expandan a velocidades del orden de la velocidad del sonido (10 km s^{-1}), hasta alcanzar equilibrio con diámetros del orden de algunos pc. En regiones moleculares con densidades de $n_0 \sim 10^5$ cm^{-3}, las regiones H II deberían permanecer como ultracompactas durante $\sim$ 3000 años y sólo unas docenas de ellas tendrían que existir en la Galaxia. Sin embargo, las observaciones sugieren muchas más regiones H II ultracompactas y que sus vidas deben de ser uno o dos órdenes de magnitud más largas. Varios modelos han sido propuestos para explicar esta "paradoja de la duración de la vida"; todos tienen problemas. La paradoja podría resolverse si el gas molecular en el cual se forman las estrellas O es más denso y caliente que lo que anteriormente se creía. Esta sugerencia encuentra apoyo en observaciones recientes que muestran que, en los núcleos moleculares densos, densidades de 10^7 cm^{-3} y temperaturas de 100 K no son atípicas. Comparamos los radios de las regiones H II ultracompactas esperados (usando las densidades y temperaturas mayores) con los observados y encontramos una concordancia significativa entre los dos.

ABSTRACT

Ultracompact H II regions (UCHIIs) are defined as regions of ionized gas with diameters smaller than $\sim$ 0.1 pc (Wood & Churchwell 1989a). H II regions are expected to expand at velocities on the order of the sound speed (10 km s^{-1}) until reaching equilibrium at dimensions of a few pc. In regions with density of $n_0 \sim 10^5$ cm^{-3}, H II regions should remain ultracompact for $\sim$ 3000 years and only a few dozen should exist in the Galaxy. However, observations suggest that many more UCHIIs exist and that lifetimes should be one to two orders of magnitude larger. Several models have been proposed to explain this "lifetime paradox"; all have shortcomings. The paradox could be resolved if the molecular gas in which an O star forms is denser and warmer than previously believed, resulting in an initial Strömgren sphere much smaller than originally estimated. This suggestion finds support in recent observations, which show that in dense molecular cloud cores densities of 10^7 cm^{-3} and temperatures of 100 K are not atypical. We compare the expected UCHII radii (using the higher temperatures and densities) with the observed radii of a sample of UCHII regions and find significant agreement between the two.

Key words: **H II REGIONS**

[1] University of North Carolina at Chapel Hill.
[2] Instituto de Astronomía, Universidad Nacional Autónoma de México.
[3] National Radio Astronomy Observatory.

[4] The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under cooperative agreement with the National Science Foundation.

1. INTRODUCTION

Dreher & Welch (1981) originally discussed the problem of ultracompact H II regions (UCHIIs) in their Very Large Array (VLA)[4] continuum study of W3(OH). Their estimate of the age of W3(OH) (300 years) was surprisingly low. A subsequent study of the compact sources in W49N (Dreher et al. 1984) estimated that the UCHIIs in this region had lifetimes of 2000–3000 years, based on simply dividing the observed source size by the thermal sound speed. The question arose: if the lifetime of UCHIIs is indeed this short, why do we observe so many of them in the Galaxy? The large number of UCHIIs detected in the VLA Galactic survey of compact H II regions (Wood & Churchwell 1989a) only compounded this problem. A simple calculation, included in their paper and made assuming the then available parameters for the ionizing star and the surrounding neutral medium, suggested that UCHIIs should always expand at velocities comparable with the sound speed of the ionized gas (~ 10 km s^{-1}) until reaching equilibrium at dimensions of order 1 pc. Under these conditions, H II regions remain ultracompact (that is, with a diameter smaller than about 0.1 pc) for ~ 3000 years. This amount of time is $\leq 0.1\%$ of the lifetime of an O star.

Adopting an O star formation rate of order 10^{-2} stars yr^{-1} (Miller & Scalo 1979; Scalo 1986), a few tens of UCHIIs are expected to exist in the entire Galaxy at any given moment. However, the Wood & Churchwell (1989a) survey, as well as other studies made at the VLA by Kurtz, Churchwell, & Wood (1994) and Miralles, Rodríguez, & Scalise (1994) have detected large numbers of UCHIIs. At present, even though only a small fraction of the Galaxy has been sampled, several dozen UCHIIs have been detected. Therefore, the lifetime of UCHIIs appears to exceed significantly the value expected for an expanding H II region.

Several models have been proposed to explain the lifetime paradox. In their recent paper, Hollenbach et al. (1994) review and criticize three previous scenarios proposed to explain the lifetime problem: 1) the gravitationally infalling circumstellar cloud (Reid et al. 1981), 2) the bow shock model (van Buren et al. 1990), and 3) the champagne flow model (Tenorio-Tagle 1979). All three models have shortcomings that are enumerated by Hollenbach et al., and these authors propose a fourth model to explain UCHIIs: the photoevaporating circumstellar disk. In this model, UCHIIs have a long lifetime because, even though ionized gas is continuously outflowing, new gas is photoevaporated from the surface of a circumstellar disk. This model has a specific prediction, namely that if UCHIIs are photoevaporating disks then their free-free emission in the centimeter range should exhibit the characteristic spectral index of $\alpha = 0.6$ ($S_\nu \propto \nu^{0.6}$) expected for ionized sources where the electron density decreases as the square of the distance (as in the case of outflowing gas in a biconical wind).

We have reviewed the data available for UCHIIs (in particular the surveys of Wood & Churchwell 1989a and Kurtz et al. 1994) and find that, while a small fraction of the regions do have spectral indices consistent with $\alpha = 0.6$, most have values distributed in the range $-0.1 \leq \alpha \leq 2$. This result suggests that not all UCHIIs are ionized disk winds, and many are more likely to be confined, homogeneous sources with a normal thermal spectrum. As a result, we decided to review the assumptions made by Wood & Churchwell (1989a) that first defined the UCHII region lifetime problem. We have found that in a large fraction of our sample sources from the literature, the observed diameter of the radio continuum emission from UCHIIs can be explained simply by the presence of warm, dense molecular gas now observed in many cloud cores. If a star forms in this dense medium, its initial Strömgren sphere radius will be much smaller, and its diameter after 10^5 years will be < 0.1 pc.

2. THE SIZE OF UCHII REGIONS

The evolution of an H II region may be divided into three stages, (1) the formation of the initial Strömgren sphere, (2) the expansion of the H II region, and (3) the final pressure equilibrium between the H II region and the ambient medium. We discuss these stages below.

2.1. The Initial Strömgren Sphere

The crucial assumption in Wood & Churchwell (1989a) is to take as characteristic values of the molecular gas that surrounds the UCHII a molecular density of 10^5 cm^{-3} and a kinetic temperature of 25 K. These were the most widely accepted values available at the time of their study. Following the arguments of Spitzer (1968) and Dyson & Williams (1980), these input values lead to an initial Strömgren sphere radius of ~ 0.025 pc, and an equilibrium radius for the UCHII of a few pc after $\sim 10^6$ years. Wood & Churchwell (1989a) note that these choices of values were motivated by the analysis of G34.26+0.15 by Henkel, Wilson, & Mauersberger (1987). However, the more recent study of the same source made with the VLA by Garay & Rodríguez (1990) suggests that the selected values for the density and temperature are greatly underestimated.

When fusion begins, and stellar photons ionize the circumstellar region, the initial Strömgren sphere radius will be determined by the volume of material that the embedded star can ionize. This quantity may be expressed (Dyson & Williams 1980) as

$$r_i = (\frac{3S_*}{4\pi n_0^2 \beta_2})^{1/3} ,$$

where S_* is the flux of ionizing photons, n_0 is the ambient density, and β_2 is the recombination coefficient to all levels except the ground state at a given temperature,

$$\beta_2(T_e) = 2.6 \times 10^{-10} T_e^{-3/4} \text{ cm}^3 \text{ s}^{-1}.$$

Using values of $n_0 = 2 \times 10^7$ cm^{-3}, $T_e = 10^4$ K, and $S_* = 10^{49}$ s^{-1}, we derive an initial radius of 1×10^{-3} pc. The S_* value is typical for an O6 star. For later type stars the S_* value will be smaller. Also, this calculation of the initial radius assumes a pure hydrogen nebula. The presence of ambient dust will further reduce r_i from its calculated value (the dust absorbing some fraction of the UV photons), making r_i an upper limit to the size of the initial Strömgren sphere. For a given star, the initial radius depends strongly on the density in which the star forms, $r_i \propto n_0^{-2/3}$. Therefore, a star forming in a medium 10^3 times more dense than previously assumed will have an initial Strömgren sphere smaller by a factor of ~ 100. The subsequently expanding UCHII region will have a smaller diameter after a given period of time.

2.2. The Expanding H II Region

Once a Strömgren sphere has formed around a star, the ionized region (suddenly at 10^4 K) will be overpressured with respect to the surrounding material and begin to expand. The expansion of the UCHII region will approximately follow the relation

$$r(t) = r_i \left[1 + (7c_i t/4r_i)\right]^{4/7} ,$$

(Spitzer 1968) where r_i is the initial Strömgren sphere radius, c_i is the sound speed (10 km s^{-1}), and t is the time in seconds. Using the initial radius value of r_i=1 × 10^{-3} pc determined above, we find that the source will have a radius of ~ 0.07 pc after 10^5 years. The expansion of the UCHII region initially proceeds at the sound speed, so the crucial factor is the initial density of the ambient medium. This parameter determines the size of the initial ionized sphere. Figure 1 demonstrates this effect by showing the calculated radius as a function of time for UCHII regions in different ambient densities. The upper curves (solid) represent the radius in a region with an ambient density of 10^5 cm^{-3}; the lower curves (dashed) represent the radius evolution of H II regions around similar stars in a region of higher density (2×10^7 cm^{-3}). A horizontal line is drawn at the radius that characterizes an UCHII region (0.05 pc), and a vertical line is drawn at an age of 10^5 years. Clearly, for the lower density case, none of the H II regions will be classified as "ultracompact" after 10^5 years. In the higher density case, H II regions may remain ultracompact (d < 0.1 pc) for 10^5 years. These radii are calculated using the mean ambient density ($n_0 = 2 \times 10^7$ cm^{-3}), and we note that the mean ionizing flux is $< \log N_c > = 47.3$. Stars with ionizing fluxes less than this mean value will have radii of $r \leq 0.05$ pc for 10^5 years. Furthermore, after 10^4 years H II regions in the high density environment will start to achieve pressure equilibrium with the surrounding medium and the radii given in Figure 1 above 10^4 years can be taken as upper limits.

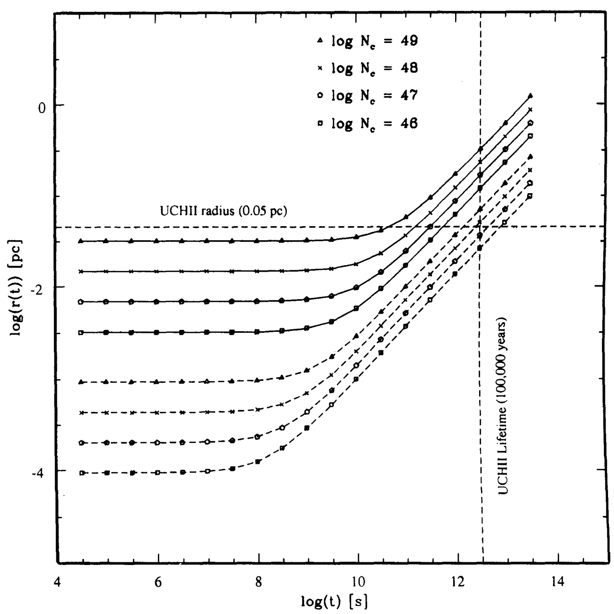

Fig. 1. Plots show the radius of an UCHII as a function of time for a variety of ionizing fluxes (indicated in the figure). The solid curves are calculated assuming an ambient density of $n_0 = 10^5$ cm^{-3}, and the dashed curves are calculated assuming an ambient density of $n_0 = 2 \times 10^7$ cm^{-3}. Curves are calculated assuming $T_e = 10^4$ K. A horizontal line is drawn at the radius of an UCHII (0.05 pc); a vertical line is drawn at 10^5 years.

It is possible, then, that the prevalence of UCHIIs has a very simple explanation. *The observed number of UCHII regions may be due simply to the fact that they start with small diameters in the dense cloud core region, and are still "ultracompact" (d <0.1 pc) after 10^5 years.* If so, more exotic models such as "cometary" bowshocks (van Buren et al. 1990), and circumstellar photoionized disks (Hollenbach et al. 1994) may not be necessary to explain the large number of UCHII regions.

2.3. Pressure Equilibrium

Given sufficient time to evolve, an expanding H II region will come into pressure equilibrium with the surrounding ISM. We have said above that stars appear to be embedded in regions that are warmer and denser than previously assumed. The equilibrium radius of an UCHII depends upon the ambient temperature and density (Wood & Churchwell 1989a) as

$$r_{eq} \propto (n_0 T_0)^{-2/3},$$

where T_0 is the density of the ambient material. We note that if the temperature is greater by a factor of 10, and the density by a factor of 100, that the equilibrium radius of an UCHII will be reduced by a factor of 100. Using values of $n_0 = 10^5$ cm^{-3} and $T_0 = 25$ K, Wood & Churchwell (1989a) calculated that an H II region will come into pressure equilibrium with a radius of a few pc after $\sim 10^6$ years. Using revised values (based on recent observations) of $n_0 = 10^7$ cm^{-3} and T = 100 K, we calculate that an H II region will come into pressure equilibrium at a much smaller radius (0.02 pc) after only 10^4 years.

Clearly, the actual equilibrium radius and timescale will be somewhere between these two extremes, since the molecular material close to the star is in fact observed to be dense and warm, but its extent is finite. For an UCHII region to come into pressure equilibrium at a radius of 0.02 pc would require the dense material to be infinite in extent. Therefore, on timescales of $\sim 10^5$ years (the required longevity of UCHIIs to explain their number density in the Galaxy), UCHIIs are probably still not in pressure equilibrium and will be expanding. The molecular material will expand at a slower rate ($\sim$ 1 km s^{-1}) due to its lower temperature and molecular composition. The issues of the stability of these massive molecular envelopes and of the expected H II region morphologies require further investigation.

3. COMPARISON WITH EXISTING OBSERVATIONS

3.1. Age and Radius Calculations

We have searched the literature and found that even for the smallest UCHIIs, the observed densities of the molecular material appear to explain the observed radius of the associated UCHII region. Aside from the Sgr B2 regions, the 12 sources tabulated are "spherical or unresolved" sources detected in the radio continuum (Wood & Churchwell 1989a; Kurtz et al. 1994) with $r < 0.05$ pc, that also had existing complementary ammonia observations. Table 1 summarizes the observed and derived parameters for our sample of UCHIIs.

For each source, we have calculated an age, using the observed molecular density for the ambient den-

TABLE 1

EXPANDING UCHII REGIONS

Source	Ambient Material T (K)	Ambient Material n_0 (10^6 cm^{-3})	Observed Diameter of H II region (pc)	Minimum Derived Age of H II region (10^4 yr)	Diameter of ISS[a] (pc)	Refs.[c]
G15.04–0.68	55	5	0.006	0.1	0.014	1, 4
W75S	200	4	0.020	0.3	0.02	2, 5
NGC 7538B	200	30	0.013	0.7	0.014	1, 5
W31c	100	50	0.048	2.3	0.06	1, 5
W51d	240	25	0.084	3.0	0.096	1, 5
W51e_1/e_2	250	25	0.011	0.3	0.028	3, 5
W51e_3/e_4	100	10	0.005	0.1	0.006	3, 7
G10.47+0.03A	75	12	0.024	1.0	0.016	1, 6
G10.47+0.03B	75	12	0.023	1.2	0.012	1, 6
G10.47+0.03C[b]	75	12	0.042	3.0	0.014	1, 6
Sgr B2 F2	180	20	0.018	0.8	0.016	8, 9
Sgr B2 K1	200	20	0.023	1.3	0.016	8, 9

[a] Initial Strömgren sphere, assuming $n_0 = 10^5$ cm^{-3}.
[b] Located $\sim 5''$ from the dense cloud core.
[c] References: (1) Wood & Churchwell 1989a; (2) Kurtz et al. 1994; (3) Gaume et al. 1994; (4) Cesaroni et al. 1992; (5) Mauersberger et al. 1986; (6) Garay et al. 1993; (7) Ho et al. 1983; (8) Gaume et al. 1995; (9) Hüttemeister et al. 1993.

sity in which the star formed, and the flux of ionizing photons as calculated from the continuum brightness for each source. Ionizing flux values are taken from the references in Table 1. The average source age is $< \tau > = 1.2 \times 10^4$ years. Our selection criterion of r< 0.05 pc will insure that $< \tau >$ is somewhat less than 10^5 years. If the source has begun to come into pressure equilibrium with the ambient medium, then the source is older. Therefore, this age is a lower limit.

One argument that can be made against this scenario is the following: the high densities that are observed are the *result*, not the *cause* of the UCHII region. That is, as the UCHII region expands, it creates a shocked "cocoon" of dense, hot material around it, but the initial densities in the cloud are more likely to be lower, closer to those previously assumed (i.e., 10^5 cm^{-3}). To address this argument, we have derived for each tabulated UCHII region an initial Strömgren sphere diameter, assuming that the UCHII formed in a region of density $n_0 = 10^5$ cm^{-3}. In seven of the 12 sources, we derive an initial diameter larger than the currently observed UCHII diameter. The radius of each overpressured UCHII must increase with time, so this disagreement indicates that these regions must have formed in an ambient medium of density significantly higher than 10^5 cm^{-3}. For the remaining 5 sources, the assumption that they formed in an ambient density of 10^5 cm^{-3} would result in the conclusion that they are < 1000 years old.

3.2. Some Comments on Individual Sources

3.2.1. Sgr B2

Vogel, Genzel, & Palmer (1987), and Hüttemeister et al. (1992) have found a warm, dense core in the well-studied star-forming region Sgr B2. Vogel et al. (1987) derive molecular hydrogen densities of $\sim 10^7$ cm^{-3} and kinetic temperature of 200 K. Hüttemeister et al. (1992) derive similar results from their multi-level study of ammonia, with T $\sim$ 200 K and densities of $\sim 10^7$ cm^{-3}. There are a large number of UCHIIs embedded in the two dense cores, particularly in the Sgr B2 Main region. We have only given observed diameters for one source in each of the two regions, Main and North. If the UCHIIs in Sgr B2 formed in an ambient density of $n_0 = 10^5$ cm^{-3}, then 80% of them currently have observed diameters *smaller* than the predicted initial Strömgren sphere (Gaume et al. 1995). As argued above, this result suggests that in Sgr B2, the UCHIIs must have formed in a denser medium.

3.2.2. G10.47+0.03

A dense molecular core has also been observed in the G10.47+0.03 region (Garay, Moran, & Rodríguez 1993). Here the dense core has temperatures of 75 K and densities of 1.2×10^7 cm^{-3}. Using this density in the radius evolution equations given above, we derive that the observed radii of the embedded UCHIIs imply source ages ranging from 1×10^4 to 3×10^4 years. We note that the UCHII region G10.47+0.03C has a larger radius (0.02 pc) than the other two sources, but is also located farthest in projection from the position of peak molecular density and is most likely in a region of lower density.

3.3. Timescales

Wood & Churchwell (1989b) suggest that approximately 10% of O stars should be in the UCHII phase of their lifetime, based on the finding that $\sim$ 10% of O stars in the solar neighborhood are embedded in molecular clouds. As they point out, this number is in agreement with Mezger & Smith's (1975) estimate that a typical O star spends 10% to 20% of its main-sequence lifetime embedded in the molecular cloud. We have shown above that in dense cores, UCHIIs will remain ultracompact (d < 0.1 pc) for $\sim 10^5$ years. This longevity ($\sim$ 10% of an O star lifetime) is sufficient to explain the observed number density of UCHIIs in the solar region.

Given the typical observed size of these dense cloud cores ($\sim$ 0.1 pc; e.g., Vogel et al. 1987; Hüttemeister et al. 1992), and an average velocity of UCHIIs with respect to the molecular material of about 1 km s^{-1}, the UCHIIs should remain confined in the dense part of the molecular cloud for $\sim 10^5$ years. Once the sources leave the cloud core, the combined effect of molecular density gradients and stellar winds may lead to the formation of the edge-brightened "arc-like" or "cometary" regions frequently observed. The sound speed in this warm gas ($\sim$ 1 km s^{-1}) is high enough that the motion of a star and its H II region at $\sim$ 1 km s^{-1} through the core should not produce significant shocks as modeled by van Buren et al. (1990). The rarer star moving at higher velocities ($\sim$ 10 km s^{-1}) may still produce shocks as they describe.

3.4. Stellar Winds

The evolution of an UCHII may be significantly affected by the presence of a stellar wind. Castor, McCray, & Weaver (1975) discuss the evolution of a stellar wind blown shell. Their equation (6) is parameterized in terms of the mass-loss rate of the star, the stellar wind velocity, and the density of the ambient medium. Given the ambient density assumed by Castor et al. (1975) of $n_0 = 10^4$ cm^{-3}, the wind blown shell should have a radius of 1.1 pc after 10^5 years. However, higher ambient densities significantly alter this derived radius and the densities typically observed in molecular cloud cores produce a radius of $\sim$ 0.2 pc after 10^5 years. This size is slightly larger than, but consistent with, the defined size of an UCHII region. We conclude that if strong stellar winds are present in very compact objects, then further detailed modeling may be required to explain the observed diameters of UCHIIs.

4. CONCLUSIONS

We propose that an explanation for the long lifetime of UCHIIs is that they are often embedded in dense and warm molecular cores. When a star "ignites" in this dense environment, its initial Strömgren sphere is very small (≤ 0.001 pc). If the dense material had infinite extent, its temperature and density would limit UCHIIs to sizes of ~ 0.02 pc. However, molecular clouds are clumpy, with dense cores of d ~ 0.1 pc. Therefore, the dense molecular material is also likely to be overpressured and expand. However, even after 10^5 years of expansion, a Strömgren sphere in this dense environment will grow to a diameter of < 0.1 pc. If stars do form in dense molecular environments, there is no lifetime paradox.

Of a sample of twelve UCHIIs that have existing NH_3 observations, seven must have formed in an environment more dense than 10^5 cm^{-3}. If the tabulated UCHIIs formed in molecular cloud cores with densities equal to the currently observed values ($< n_0 > = 2 \times 10^7$ cm $^{-3}$), then we derive reasonable ages with $< \tau > = 1.2 \times 10^4$ years. Though most studies of warm dense gas to date have been made with single dish instruments, these cores can be searched for using the VLA.

The authors would like to thank J. Cantó, E. Churchwell, R. Gaume, R. Olling, P. Palmer and especially D. Wood for several helpful discussions of this topic.

REFERENCES

Castor, J., McCray, R., & Weaver, R. 1975, ApJ, 200, L107
Cesaroni, R., Walmsley, C.M., & Churchwell, E. 1992, A&A, 256, 618
Dreher J.W., & Welch, W.J. 1981, ApJ, 245, 857
Dreher, J.W., Johnston, K.J., Welch, W.J., & Walker, R.C. 1984, ApJ, 283, 632
Dyson, J.E., & Williams, D.A. 1980, Physics of the Interstellar Medium (New York: John Wiley & Sons), 132
Garay, G., & Rodríguez, L.F. 1990, ApJ, 362, 191
Garay, G., Moran, J.M., & Rodríguez, L.F. 1993, ApJ, 413, 582
Gaume, R.A., Johnston, K.J., & Wilson, T.L. 1994, ApJ, 417, 645
Gaume, R., Claussen, M., De Pree, C.G., Goss, W.M., & Mehringer, D. 1995, ApJ, in press
Henkel, C., Wilson, T.L., & Mauersberger, R. 1987, A&A, 182, 137
Ho, P.T.P., Genzel, R., & Das, A. 1983, ApJ, 266, 596
Hollenbach, D., Johnstone, D., Lizano, S., & Shu, F. 1994, ApJ, 428, 654
Hüttemeister, 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
Mauersberger, R., Henkel, C., Wilson, T.L., & Walmsley, C.M. 1986, A&A, 162, 199
Mezger, P.G., & Smith, L.F. 1975, Proc. 3rd European Astronomical Meeting, ed. E.K. Kharadze (Tblisi: Gregorian SSR Academy of Sciences), 369
Miller, G.E., & Scalo, J.M. 1979, ApJS, 41, 513
Miralles, M., Rodríguez, L.F., & Scalise, E. 1994, ApJS, 92, 173
Reid, M.J., Haschick, A.D., Burke, B.F., Moran, J.M., Johnston, K.J., & Swenson, G.W. 1981, ApJ, 239, 89
Scalo, J.M. 1986, Fund. Cosmic Phys., 11, 1
Spitzer, L. 1968, Diffuse Matter in Space, (New York: Interscience Publishers), 183
Tenorio-Tagle, G. 1979, A&A, 71, 59
Vogel, S.N., Genzel, R., & Palmer, P. 1987, ApJ, 316, 243
van Buren, D., Mac Low, M.-M., Wood, D.O.S., & Churchwell, E. 1990, ApJ, 353, 570
Wood, D.O.S., & Churchwell, E. 1989a, ApJS, 69, 831
_______. 1989b, ApJ, 340, 265

C.G. De Pree and W.M. Goss: National Radio Astronomy Observatory, P.O. Box O, Socorro, NM 87801, USA. (cdepree@nrao.edu).
L.F. Rodríguez: Instituto de Astronomía, UNAM, Apartado Postal 70-264, 04510 México, D.F., México. (luisfr@astroscu.unam.mx).