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EXCITED-STATE OH MAIN-LINE MASERS IN AU GEMINORUM AND NML CYGNI

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ABSTRACT

Excited-state OH maser emission has previously been reported in the circumstellar envelopes of *only two* evolved stars: the Mira star AU Geminorum and the hypergiant NML Cygni. We present Very Large Array (VLA) observations of the 1665, 1667, and excited-state 4750 MHz main-line OH transitions in AU Gem and Expanded Very Large Array (EVLA) observations of the excited-state 6030 and 6035 MHz OH main-line transitions in NML Cyg. We detect masers in both main-line transitions in AU Gem but no excited-state emission in either star. We conclude that the excited-state OH emission in AU Gem is either a transient phenomenon (such as for NML Cyg, outlined below) or possibly an artifact in the data and that the excited-state OH emission in NML Cyg was generated by an episode of enhanced shock between the stellar mass loss and an outflow of the Cyg OB2 association. With these single exceptions, it therefore appears that excited-state OH emission indeed should not be predicted nor observable in evolved stars as part of their normal structure or evolution.

Subject headings: circumstellar matter — masers — stars: individual (AU Geminorum, NML Cygni) — stars: late-type — stars: mass loss

1. INTRODUCTION

The topic of hydroxyl (OH) maser pumping in the circumstellar envelopes of evolved stars has received increased focus over recent years due to observational and theoretical advances. On the observational side, detections of far-infrared OH lines toward evolved stars have confirmed the role of radiative pumping routes and allowed for estimation of pump efficiencies (Sylvester et al. 1997; Neufeld et al. 1999; He & Chen 2004; He et al. 2005). On the theoretical side, the recent Gray et al. (2005) model demonstrates the complexity of OH pumping routes and is quite successful at explaining observed OH maser properties from OH/IR stars. Pump models generally do not predict detectable excited-state emission in circumstellar envelopes of evolved stars, due to either a lack of inversion or insufficient optical depth (e.g., Elitzur et al. 1976; Bujarrabal et al. 1980; M. D. Gray 2006, private communication). For a comprehensive overview on circumstellar shells around evolved stars, we refer to Habing (1996).

Excited-state OH masers have been sought in the 4.8 and 6.0 GHz transitions toward the circumstellar environments of a variety of evolved high mass losing stellar sources by many authors (Thacker et al. 1970; Zuckerman et al. 1972; Baudry 1974; Rickard et al. 1975; Claussen & Fix 1981; Jewell et al. 1985; Desmurs et al. 2002; Fish et al. 2006). These searches universally failed to detect excited-state emission except in two circumstellar environments. Claussen & Fix (1981) report on a 5 σ detection of a 4750 MHz maser in AU Gem, a Mira variable. Subsequent observations by Jewell et al. (1985) failed to confirm this emission, but the rms noise level of their observations does not rule out the 100 mJy detection of Claussen & Fix (1981).

The second evolved star with an excited-state maser detection is NML Cyg, a supergiant and recently more often referred to as a hypergiant (van Genderen et al. 1982; Schuster et al. 2006). Zuckerman et al. (1972) report a clear ($\gg$10 σ) detection at 6035 MHz and possible emission ($\sim$3 σ) at 6030 MHz as well. Their spectra indicate strong (2.2 Jy) 6035 MHz maser emission at $V_{\rm LSR} \approx 4$ km s^{-1}. This is close to the stellar velocity of about $0(\pm 4)$ km s^{-1} (Zhou 1981; Diamond et al. 1984), usually found as the average velocity of the outer boundaries or emission peaks of the characteristic double-peaked 1612 MHz OH emission or as the center of the SiO emission in OH/IR stars (Bowers et al. 1983; Habing 1996). With ample sensitivity to follow up on this initial detection, Jewell et al. (1985) did not detect any emission from NML Cyg a decade later. In 1999, Desmurs et al. (2002) also did not detect the emission at 4 km s^{-1} but note possible weak ($\sim$20 mJy) emission at -17 km s^{-1}, corresponding in velocity to an inner 1612 MHz peak near -18 km s^{-1} (e.g., Herbig 1974; Engels 1979). The original spectra of Zuckerman et al. (1972) are suggestive of weak emission at both 6030 and 6035 MHz near this velocity but not at significant levels compared to their rms noise.

The confirmed detection of excited-state OH masers in the circumstellar environments or ejecta of evolved stars would provide a challenge to modern pumping models, or at least highlight novel portions of pumping phase space heretofore not considered. To date, neither report of a detection of an excited-state OH maser in an evolved star has been confirmed, which in view of the pumping models therefore needs to be followed up. In this Letter, we present new observations of the OH masers in AU Gem and NML Cyg in the excited-state OH lines originally reported as detections as well as ground-state 1665 and 1667 MHz main-line OH emission in AU Gem.

2. OBSERVATIONS

AU Gem and NML Cyg were observed with the Very Large Array (VLA) using the settings as outlined in Table 1. The AU Gem observations occurred in DnC configuration. Due to the Expanded VLA (EVLA) upgrade (McKinnon & Perley 2001; Ulvestad et al. 2006), only 22 antennas were available, including three EVLA antennas. All these antennas were used.

For NML Cyg, we were able to profit from the special call for proposals in 2007 April for using the new 5 GHz (C-band) receivers on the EVLA. These receivers are part of the EVLA upgrade and allow observing at a much wider frequency range, in our case at 6030 and 6035 MHz. With the configuration in A array, three EVLA antennas were spread near homoge-

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TABLE 1
OBSERVATIONAL SUMMARY TABLE

Observing Date	Line (MHz)	$\Delta\nu$ (kHz)	ΔV (km s^{-1})	Beam (arcsec × arcsec, deg)	rms[a] (mJy beam^{-1})
AU Gem, Centered at $V_{LSR} \approx 10$ km s^{-1}					
2007 Jan 25	1665	195	0.28	40.3 × 21.5, 73	4.9[b]
	1667	195	0.28	40.4 × 20.4, 72	4.7[b]
	4750	781	0.19	13.0 × 12.4, 94	3.3[c]
NML Cyg, Centered at $V_{LSR} \approx 0$ km s^{-1}					
2007 May 26/30	6030	1563	0.61	0.56 × 0.23, 118	8.2[d]
	6035	1563	0.61	0.58 × 0.23, 118	7.1[e]

[a] Typical rms noise in a spectral channel.
[b] Assuming a flux density of 2.0 Jy at 1.7 GHz for J0741+312.
[c] Assuming a flux density of 1.6 Jy at 4.8 GHz for J0741+312.
[d] With a measured flux density of 2.67(±0.10) Jy for J2052+365.
[e] With a measured flux density of 2.62(±0.07) Jy for J2052+365.

neously over the north and west arm each. Although the east arm had a similar distribution of EVLA antennas, the outer two were not operational at 6.0 GHz.

For AU Gem, 2 hours were devoted to the 4750 MHz line followed by 2 hours on the 1665 and 1667 MHz lines of OH. Due to the lack of observations of an absolute standard calibrator (e.g., 3C 286), the source 0741+312 was used for bandpass, phase and amplitude, and primary flux calibrations, using assumed flux densities of 2.0 Jy at 1.7 GHz and 1.6 Jy at 4.8 GHz as taken from the VLA calibrator list. System flux monitoring suggests this is in error with less than 20%. As a temporary inconvenience, online Doppler tracking was not used due to differences in the VLA and EVLA antenna control systems. Instead, the sky frequency was calculated from the LSR velocity using the NRAO online Dopset tool and the observations were taken in fixed-frequency mode. The LSR velocity scale is set to the mean sky frequency of the observations. Maximum deviations from this frequency (at the beginning and end of observing in each band) correspond to 0.50 channel widths at 4.8 GHz ($\lesssim$0.1 km s^{-1}) and 0.36 channel widths at 1.7 GHz ($\lesssim$0.1 km s^{-1}).

Two 1.5 hr blocks were devoted to observations of the 6030 and 6035 MHz lines in NML Cyg. By using only the EVLA antennas, online Doppler tracking was available. The data were calibrated in the standard way for VLA antennas using 3C 48 as standard flux calibrator and J2052+365 as phase calibrator. The new EVLA system required more careful flagging of bad data than usual with the established VLA system. Data from some antennas were discarded entirely: one antenna did not have phase stability, while another antenna had no signal in the 6030 MHz left-circular polarized (LCP) intermediate frequency. A third antenna showed occasional phase jumps of about 60°. The absolute flux calibration at 6.0 GHz has not yet been determined; flux densities and rms noise levels given in Table 1 assume a scaling with frequency for 3C 48 as calculated in the AIPS task SETJY (Greisen 2003).

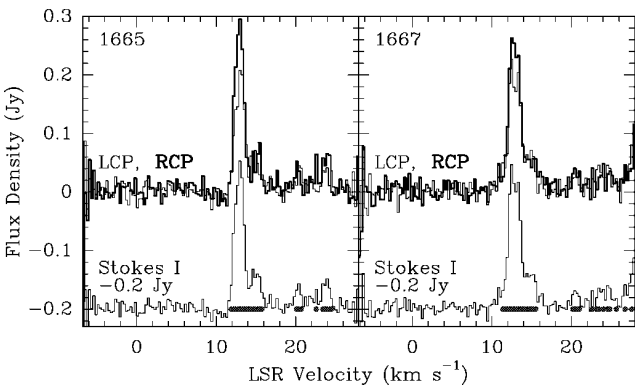

FIG. 1.—*Left*: Spectra of the 1665 MHz emission in AU Gem. RCP emission is shown with a thick line and LCP with a thin line. The Stokes *I* spectrum has been shifted vertically for clarity. Gray filled circles indicate channels in which emission is detected at the phase center at more than 5 times the rms noise. *Right*: Spectra of the 1667 MHz emission in AU Gem.

3. RESULTS

3.1. *AU Gem*

Figure 1 shows the emission at 1665 and 1667 MHz in AU Gem. We detect ~250 mJy emission in each of the 1665 and 1667 MHz transitions in the 12–13 km s^{-1} range, corresponding to similarly bright 1667 MHz emission detected by Nguyen-Q-Rieu et al. (1979). Right-circular polarized (RCP) emission is stronger in each transition than LCP emission. The second peak near 15 km s^{-1} corresponds to the broader redshifted shoulder of the emission in the lower resolution Nguyen-Q-Rieu et al. (1979) spectrum. We detect weaker features at higher LSR velocity as well, including emission in the edge spectral channels at ~28 km s^{-1} at 1667 MHz, but we do not detect the weaker (~70 mJy) emission at 0 km s^{-1} claimed by Nguyen-Q-Rieu et al. (1979). If we assume that the 1665 and 1667 MHz main-line OH peaks at the systemic velocity of 13 km s^{-1} define the stellar velocity, and if we conclude that the Nguyen-Q-Rieu et al. (1979) ~0 km s^{-1} 1667 MHz weak feature is convincing, then these features could indicate an expanding OH shell with an expansion velocity of about 14–15 km s^{-1}. If we were to dismiss the Nguyen-Q-Rieu et al. (1979) ~0 km s^{-1} 1667 MHz feature, the systemic and expansion velocities would be 20 and 8 km s^{-1}, respectively. Both expansion velocities are reasonable for Mira-type stars, with the latter for a less optically thick (lower metallicity) shell (Habing 1996), but the uncertainties in the spectra do not allow a firm conclusion on this. In this respect, it is unfortunate that AU Gem has never been detected in the 1612 MHz OH transition (Fix & Weisberg 1978; Nguyen-Q-Rieu et al. 1979; Olnon et al. 1980) nor shows any H_2O nor SiO emission (Nyman et al. 1986). All emission is consistent with being pointlike at the 40″ × 20″ resolution of the VLA in DnC configuration, which is as expected since a typical Mira OH shell size (10^{16} cm; from Herman & Habing 1985) would subtend an angle of less than 0.3″ at the distance of AU Gem (2.4 kpc; from Nguyen-Q-Rieu et al. 1979).

As to the 4750 MHz transition, we do not detect any emission at a 3 σ noise level of 10 mJy beam^{-1} in AU Gem.

3.2. *NML Cyg*

No emission was found over 4.2 σ (34.2 mJy beam^{-1}) in the 6030 MHz data, nor was any emission found over 4.9 σ (35.3 mJy beam^{-1}) in the 6035 MHz data within the beam of the Jewell et al. (1985) observations. We cannot rule out tentative (>4.8 σ single-channel) 6035 MHz line emission at -21.2, $+16.4$, and $+20.6$ km s^{-1} (Fig. 2). This would support the notion of tentative 6035 MHz OH features at ≈ -17 km s^{-1} (Desmurs et al. 2002; Zuckerman et al. 1972) and could be related to a new episode of high mass loss or compression of circumstellar material close to the star as traced by the collisionally excited SiO maser (Boboltz & Marvel 2000). However, we would not claim such emission without extensive high-sensitivity follow-up observations, e.g., when all VLA antennas have new C-band receivers installed (in 2010).

4. DISCUSSION

Theoretical work on OH pumping in model, well-behaved circumstellar shells predict that excited-state OH masers should not be seen, and observations in most circumstellar shells to date agree. Our nondetections of excited-state OH in AU Gem in the 4750 MHz line and in NML Cyg in the 6030 and 6035 MHz lines support the prediction that excited-state OH should not be observable in circumstellar shells as part of their normal structure and evolution. Excepting temporary events that cannot easily be reobserved, the previous reports of detection of the excited-state OH lines in AU Gem and NML Cyg cannot be explained.

4.1. *AU Gem*

If we dismiss the not very sensitive observation by Jewell et al. (1985), our 10 mJy beam^{-1} 3 σ upper limit nondetection of the 4750 MHz excited-state OH emission contrasts the sole report of a ~100 mJy 5 σ positive detection in this line by Claussen & Fix (1981). If not an unrelated source in the line of sight of the 0.5′ beam of the Arecibo telescope, this suggests two possibilities.

The first is that the 4750 MHz maser emission in AU Gem has weakened substantially (by more than a factor of 10) between 1981 and 2007. The lack of other known evolved stars with 4750 MHz OH masers precludes us from commenting on the phenomenology in this transition, but it is worth noting that in a comparable time period the 6035 MHz line in NML Cyg weakened by more than a factor of 100 (Zuckerman et al. 1972; Desmurs et al. 2002 and discussed below). The second possibility is that the Claussen & Fix (1981) detection is spurious. It is based on a 5 σ spike in a single 0.6 km s^{-1} spectral channel in frequency-switched Arecibo data. It is possible that this emission arises from terrestrial interference or a bad correlator channel rather than a celestial source. The LSR velocity of this feature, 3.5 km s^{-1}, is outside the range of the dominant emission in either ground-state main line. However, it would still fall within the derived velocity range of the outer 1667 MHz OH peaks as argued in the first ($V_{\rm exp}$ = 14–15 km s^{-1}) case in § 3.1. Even though the 1612 MHz OH, H_2O, and SiO transitions have not been detected (Fix & Weisberg 1978; Nguyen-Q-Rieu et al. 1979; Olnon et al. 1980; Nyman et al. 1986), making AU Gem atypical for an (type II) OH/IR star, we could not argue a special case scenario for AU Gem as for NML Cyg outlined below. AU Gem probably just does not have a circumstellar environment thick or dusty enough to sustain 1612 MHz maser emission, and thus we think that it is unlikely to have ever had excited-state OH emission.

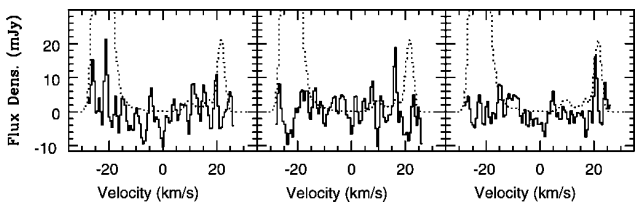

FIG. 2.—Hanning smoothed spectra of tentative 6035 MHz emission within 1″ of the position of NML Cyg. Arbitrarily scaled 1612 MHz emission from VLA archival data is shown with a dotted line for reference.

4.2. *NML Cyg*

The new nondetections of 6030 and 6035 MHz emission toward NML Cyg suggest two possibilities. Like AU Gem, this phenomenon could be a time variable or single event in the history of NML Cyg as perhaps typical for any other OH/IR object during their evolution. However, as stated before, because other searches for excited-state OH emission in circumstellar environments of a variety of evolved stars have yielded no detections, it appears that NML Cyg must somehow be special to have had 6.0 GHz excited-state OH maser emission. We reject the possibility of the original multichannel $\gg$10 σ detection by Zuckerman et al. (1972) as being spurious. The second possible explanation is that NML Cyg *indeed is special* compared to other evolved OH/IR type stars due to the interaction with its environment.

Since the discovery of emission in the ground-state OH lines in the optically obscured infrared star NML Cyg by Wilson & Barrett (1968a, 1968b), it has been extensively studied in the radio mainly in the very bright 1612 MHz satellite line of OH. The main lines at 1665 and 1667 MHz are present as well (Wilson & Barrett 1968a, 1968b; and from VLA archive data) but with typically a factor of 100 less flux than the 1612 MHz emission, whereas the 1720 MHz satellite line was reported to be undetected by Wilson & Barrett (1968a, 1968b). For comparison, in the following discussion we refer to the high-resolution (MERLIN) ground-state blueshifted 1665 MHz main-line OH and full extent 1612 MHz OH data on NML Cyg described by Diamond et al. (1984) and Etoka & Diamond (2004).

Although the asymmetric morphology in the 1612 MHz OH transition was modeled at first as a rotating disk at a position angle of about 150° toward the northwest (e.g., Masheder et al. 1974; Benson & Mutel 1979), subsequent interpretations favor a double 1612 MHz OH circumstellar shell (Diamond et al. 1984; Etoka & Diamond 2004) with the inner shell as a spherical expanding shell typical for an OH/IR star. The outer 1612 MHz OH shell only manifests itself as a curved arclike shell segment located to the northwest at about 2.3″ from the star at a velocity close to the stellar velocity, where the shell motion is predominantly tangential in the plane of the sky (Etoka & Diamond 2004, their Figs. 8 and 9). The incomplete (blueshifted emission only) 1665 MHz main-line OH image shows a similar picture, with a less prominent arc located on the sky at about 1.3″ to the northwest and between the two 1612 MHz shells (Etoka & Diamond 2004, their Fig. 7). It is noteworthy that the mass outflow is not constant; e.g., Danchi et al. (2001) deduce a 3.86 mas yr^{-1} infrared proper motion of another double shell closer (<0.3″, vs. 2.3″ for the 1612 MHz OH arc) to the star and an age difference between the two inner expanding shells of 65($\pm$14) yr.

Toward the west-northwest, NML Cyg is surrounded by an H II region (Habing et al. 1982), originating from the ionization of outflowing material from NML Cyg by the intense photoionizing radiation field of the nearby Cyg OB2 association (Morris & Jura 1983). It is in particular interesting to note that Habing et al. (1982) overlay their H II observations on the red Palomar Sky Atlas *E* plate and identify a near-linear feature at about 30″–35″ west-northwest from NML Cyg. Habing et al. (1982) suggest that this depicts Hα emission, which we in turn recognize as a tracer for shocked material. Recent *Hubble Space Telescope* observations by Schuster et al. (2006) of the dust immediately surrounding NML Cyg outlines the dissociation surface generated by this radiation field, oriented in the same direction as the H II region and the 1612 MHz OH arc (but with 0.25″ extent at a much smaller scale). We find it plausible that a bow shock–like front causes the OH molecules and dust toward the direction of the Cyg OB2 association to pile up, building up sufficient OH (column) density. The increased absorption of stellar radiation by the enhanced density of dust will radiatively pump the 1612 MHz maser, causing a partial shell or arc to appear at a line-of-sight velocity near the stellar velocity (Etoka & Diamond 2004).

We note that 1720 MHz satellite OH masers generally are seen in high-density shocks, as is Hα emission. However, recent calculations (Wardle 2007) show that excited-state OH might be observable at even higher densities. The variation in mass loss of NML Cyg may cause the northwest side pileup to occasionally be shocked and temporarily have increased density due to shells impacting on the near-stationary material. It could have been that Zuckerman et al. (1972) observed NML Cyg during such an impact event. Since then, the shock likely has dissipated and the densities have fallen. If the 65 yr between the shells found by Danchi et al. (2001) is typical, currently we are observing halfway between the impact of two shells, predicting another impact around the years 2030–2040. We speculate that while the excited-state emission is now gone, ground-state 1720 MHz OH emission may be detectable if the pumping is predominantly collisional. Observations of the 1720 MHz transition at greater sensitivity ($\ll$1 Jy) than that obtained by Wilson & Barrett (1968a, 1968b) are required to test this hypothesis.

Future discussions of maser pumping models should therefore not be distracted by these two cases of reported excited-state emission in circumstellar environments of late-type stars anymore. Instead, current models seem sufficient to explain the pumping of masers in circumstellar shells of evolved stars as part of their normal structure and evolution.

5. SUMMARY

Although a temporary event in AU Gem causing 4750 MHz excited-state OH emission cannot be excluded, we conclude that it is probable that the original report by Claussen & Fix (1981) regards an unfortunate spurious detection and is not 4750 MHz excited-state OH maser emission in the circumstellar environment of AU Gem.

The reported 6035 MHz excited-state OH emission by Zuckerman et al. (1972) in NML Cyg cannot be spurious and can be explained as originating from the special temporary conditions arising from a shock between the high-mass outflow of NML Cyg and the intense ionizing UV radiation field of the nearby Cyg OB2 association. Although it is clear that the 6035 MHz emission in NML Cyg has weakened substantially, it is unclear whether the excited-state OH emission is still present at very low levels due to a lack of sensitivity in this early stage of the VLA to EVLA transition. We suggest that the excited-state OH transitions in NML Cyg be reobserved with higher sensitivity when there are more EVLA antennas with this capability. We also recommend that the 1720 MHz OH transition be observed as a tracer of a possible shock in the environment of NML Cyg.

The transition from the VLA to the EVLA is well underway and already now offers great opportunities to observe at frequencies previously unavailable to the VLA user community.

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Facilities: VLA(EVLA)

REFERENCES

Baudry, A. 1974, A&A, 32, 191
Benson, J. M., & Mutel, R. L. 1979, ApJ, 233, 119
Boboltz, D. A., & Marvel, K. B. 2000, ApJ, 545, L149
Bowers, P. F., Johnston, K. J., & Spencer, J. H. 1983, ApJ, 274, 733
Bujarrabal, V., Guibert, J., Nguyen-Q-Rieu, & Omont, A. 1980, A&A, 84, 311
Claussen, M. J., & Fix, J. D. 1981, ApJ, 250, L77
Danchi, W. C., Green, W. H., Hale, D. D. S., McElroy, K., Monnier, J. D., Tuthill, P. G., & Townes, C. H. 2001, ApJ, 555, 405
Desmurs, J.-F., Baudry, A., Sivagnanam, P., & Henkel, C. 2002, A&A, 394, 975
Diamond, P. J., Norris, R. P., & Booth, R. S. 1984, MNRAS, 207, 611
Elitzur, M., Goldreich, P., & Scoville, N. 1976, ApJ, 205, 384
Engels, D. 1979, A&AS, 36, 337
Etoka, S., & Diamond, P. 2004, MNRAS, 348, 34
Fish, V. L., Zschaechner, L. K., Sjouwerman, L. O., Pihlström, Y. M., & Claussen, M. J. 2006, ApJ, 653, L45
Fix, J. D., & Weisberg, J. M. 1978, ApJ, 220, 836
Gray, M. D., Howe, D. A., & Lewis, B. M. 2005, MNRAS, 364, 783
Greisen, E. W. 2003, in Information Handling in Astronomy, ed. A. Heck (Dordrecht: Kluwer), 109
Habing, H. J. 1996, Astron. Astrophys. Rev., 7, 97
Habing, H. J., Goss, W. M., & Winnberg, A. 1982, A&A, 108, 412
He, J. H., & Chen, P. S. 2004, NewA, 9, 545
He, J. H., Szczerba, R., Chen, P. S., & Sobolev, A. M. 2005, A&A, 434, 201
Herbig, G. H. 1974, ApJ, 189, 75
Herman, J., & Habing, H. J. 1985, A&AS, 59, 523
Jewell, P. R., Schenewerk, M. S., & Snyder, L. E. 1985, ApJ, 295, 183
Masheder, M. R. W., Booth, R. S., & Davies, R. D. 1974, MNRAS, 166, 561
Mckinnon, M., & Perley, R., eds. 2001, The VLA Expansion Project (Socorro: NRAO), http://www.aoc.nrao.edu/evla/pbook.shtml
Morris, M., & Jura, M. 1983, ApJ, 267, 179
Neufeld, D. A., Feuchtgruber, H., Harwit, M., & Melnick, G. J. 1999, ApJ, 517, L147
Nguyen-Q-Rieu, Laury-Micoulaut, C., Winnberg, A., & Schultz, G. V. 1979, A&A, 75, 351
Nyman, L.-Å., Johansson, L. E. B., & Booth, R. S. 1986, A&A, 160, 352
Olnon, F. M., Winnberg, A., Matthews, H. E., & Schultz, G. V. 1980, A&AS, 42, 119
Rickard, L. J., Zuckerman, B., & Palmer, P. 1975, ApJ, 200, 6
Schuster, M. T., Humphreys, R. M., & Marengo, M. 2006, AJ, 131, 603
Sylvester, R. J., et al. 1997, MNRAS, 291, L42
Thacker, D. L., Wilson, W. J., & Barrett, A. H. 1970, ApJ, 161, L191
Ulvestad, J. S., Perley, R. A., McKinnon, M. M., Owen, F. N., Dewdney, P. E., & Rodriguez, L. F. 2006, BAAS, 38, 135
van Genderen, A. M., van Leeuwen, F., & Brand, J. 1982, A&AS, 47, 591
Wardle, M. 2007, in IAU Symp. 242, Astrophysical Masers and Their Environments, ed. J. Chapman & W. Baan (Cambridge: Cambridge Univ. Press), in press (astro-ph/0703508)
Wilson, W. J., & Barrett, A. H. 1968a, AJ, 73, 209
———. 1968b, Science, 161, 778
Zhou, Z.-P. 1981, Chinese Astron. Astrophys., 5, 139
Zuckerman, B., Yen, J. L., Gottlieb, C. A., & Palmer, P. 1972, ApJ, 177, 59