5 CENTIMETER OH MASERS AS DIAGNOSTICS OF PHYSICAL CONDITIONS IN
STAR-FORMING REGIONS

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ABSTRACT

We demonstrate that the observed characteristics of the 5 cm OH masers in star-forming regions can be explained with the same model and the same parameters as the 18 cm and the 6 cm OH masers. In our already published study of the 18 cm and the 6 cm OH masers in star-forming regions we had examined the pumping of the 5 cm masers but did not report the results we had found because of some missing collision rate coefficients, which in principle could be important. The recently published observations on the 5 cm masers of OH encourage us to report our old calculations along with some new ones that we have performed. These calculations, in agreement with the observations, reveal the main lines at 5 cm as strong masers, the 6049 MHz satellite line as a weak maser, and the 6017 MHz satellite line as never inverted for reasonable values of the parameters.

Subject headings: ISM: molecules — masers — molecular processes — radiative transfer — stars: formation

1. INTRODUCTION

The OH molecules in star-forming regions are rich in maser emission. They exhibit (a) four maser lines (at 18 cm) in the ground state \(^2\Pi_{3/2}, J = 3/2\) (e.g., Gaume & Mutel 1987; Cohen, Baart, & Jonas 1988; for reviews see Reid & Moran 1981; Cohen 1989; Elitzur 1992); (b) three maser lines (at 5 cm) in the first excited state \(^2\Pi_{3/2}, J = 5/2\) (Knowles, Caswell, & Goss 1976; Guilloteau et al. 1984; Smits 1994; Caswell & Vaile 1995; Baudry et al. 1997; Desmurs et al. 1998; Desmurs & Baudry 1998); (c) three maser lines (at 6 cm) in the next level \(^2\Pi_{1/2}, J = 1/2\) (Gardner & Martin-Pintado 1983; Gardner & Whiteoak 1983; Palmer, Gardner, & Whiteoak 1984; Gardner, Whiteoak, & Palmer 1987; Baudry et al. 1988; Baudry & Diamond 1991; Cohen, Masheder, & Walker 1991); (d) one maser line (at 2 cm) in the level \(^2\Pi_{3/2}, J = 7/2\) (Turner, Palmer, & Zuckerman 1970; Baudry et al. 1981, Baudry & Diamond 1998).

In our recently reported calculations (Pavlakis & Kylafis 1996a, hereafter Paper I; Pavlakis & Kylafis 1996b, hereafter Paper II) we explained theoretically the observed characteristics of the 18 cm and the 6 cm maser lines of OH. Naturally, we had computed also the maser emission of the 5 cm lines of OH, but we decided to not show or discuss the maser lines in the excited state \(^2\Pi_{3/2}, J = 5/2\) because this state is directly connected with the state \(^2\Pi_{1/2}, J = 7/2\), which is not included in our calculations. We urge quantum chemists to compute collision rate coefficients for as many transitions as possible "(Paper I).

Soon after our calculations were published, Baudry et al. (1997) reported an extensive study of the 5 cm maser lines of OH in star-forming regions. To our surprise, our already performed calculations explain the observed characteristics. This probably means that, for temperatures between 100 and 200 K that are thought appropriate for OH maser regions, the missing collision rate coefficients are not important for the 5 cm masers. Thus, we are encouraged to publish our results. Of course, when the missing collision rate coefficients are computed, it will be reassuring to show that they are indeed not important for the 5 cm masers.

In §2 we discuss briefly the model that we used, in §3 we present the results of the calculations, in §4 we compare our calculations with the observations and in §5 we present our conclusions.

2. MODEL

Our model is the same as that in Papers I and II. Not only this, but the values of the parameters are exactly the same. Thus, no parameters are adjusted for any qualitative or quantitative explanation of the observations.

The maser regions are modeled as cylinders of length \(l = 5 \times 10^{15}\) cm and diameter \(d = 10^{15}\) cm. The characteristic bulk velocity in the maser region is denoted by \(V\) and the assumed velocity field there is given by \(v = V/(d/2)r\hat{\rho} + (V/d)\hat{z},\) where \((\rho, z)\) are the cylindrical coordinates, and \(\hat{\rho}\) and \(\hat{z}\) are the corresponding unit vectors.

The fractional abundances of OH and ortho-H\(_2\), with respect to density of H\(_2\) molecules in the maser region are denoted by \(f_{\text{OH}}\) and \(f_{\text{ortho-H}_2}\), respectively, while the density of H\(_2\) molecules and the kinetic temperature there are denoted by \(n_{\text{H}_2}\) and \(T_{\text{H}_2}\), respectively. Finally, the brightness temperature of the maser lines is denoted by \(T_B\), the dilution factor of the far-infrared radiation field by \(W\) (see eq. [5] of Paper II), the dust optical depth parameter by \(p\) (see eq. [4] of Paper II), and the dust temperature by \(T_D\).

In addition to the exploration of the parameters used in Papers I and II, we also explore here the effects of the fractional abundance of OH.

In the figures of this paper the key is as follows: The brightness temperature of the 6049 MHz transition is shown as a solid line, that of the 6035 MHz transition by a dotted line, that of the 6017 MHz by a dashed line, and that of the 6031 MHz by a dot-dashed line.

3. CALCULATIONS AND PRESENTATION OF RESULTS

3.1 Collisions Only

For kinetic temperatures \(100 \leq T_{\text{H}_2} \leq 200\) K, which are thought to be prevailing in H\(_\Pi\)/OH maser regions, there are
several locally (i.e., thermally) overlapping lines of OH. Nevertheless, it is interesting to look at calculations, which take into account collisions only, in order to see what their effects are on the pumping of OH molecules (see also Paper I). Interestingly, we have found that for temperatures $T_{\text{H}_2} \lesssim 150$ K, which are highly likely for H II/OH regions, the effects of locally overlapping lines are insignificant on the pumping of the 5 cm maser lines and their inclusion changes the results of our calculations by less than a factor of 2. Thus, if there are no large velocity gradients in the maser regions and the external FIR field is weak, collisions alone determine the 5 cm maser emission of OH at $T_{\text{H}_2} \lesssim 150$ K.

We have found that collisions alone are unable to invert the main lines at 5 cm. For $f_{\text{ortho-}H_2} = 1$ and $f_{\text{OH}} = 10^{-5}$ only the 6049 MHz satellite line is masering for hydrogen densities $2 \times 10^2 \lesssim n_{\text{H}_2} \lesssim 7 \times 10^6$ cm$^{-3}$. The peak of the brightness temperature occurs at $n_{\text{H}_2} \sim 10^6$ cm$^{-3}$, and it is $T_{br} \sim 10^9$ K above $T_{\text{H}_2} = 100$ K (see Fig. 1 below and the discussion in the next subsection).

As $f_{\text{ortho-}H_2}$ decreases, the brightness temperature of the 6049 MHz line decreases faster than exponential. For $f_{\text{ortho-}H_2} = 0.5$ the peak of the brightness temperature is $T_{br} = 6 \times 10^6$ K, and it is at the limits of detectability. For values of $f_{\text{ortho-}H_2}$ below 0.2 the inversion disappears and no 5 cm line shows inversion.

3.2. Collisions and Local Line Overlap

The effects of collisions and local line overlap cannot be separated. It is simply a good fortune that for temperatures up to about 150 K the effects of collisions dominate those of local line overlap.

Assuming that large velocity gradients and a significant FIR radiation field are absent in the maser regions (see below for their effects), we have computed the 5 cm OH maser emission as a function of $n_{\text{H}_2}$, taking into account both collisions and local line overlap. For $T_{\text{H}_2} = 150$ K, $f_{\text{ortho-}H_2} = 1$, $f_{\text{OH}} = 10^{-5}$ and $V = 0.6$ km s$^{-1}$ (for which we do not have any nonlocally overlapping lines), we show in Figure 1 the brightness temperature $T_{br}$ of the 6049 MHz line (the only inverted OH line at 5 cm) as a function of $n_{\text{H}_2}$. This is a quite strong maser line with a peak brightness temperature $T_{br} = 6 \times 10^8$ K. As the temperature $T_{\text{H}_2}$ increases further, more and more pairs of lines overlap locally and their degree of overlap also increases. For temperatures up to 170 K, local overlap causes only quantitative (not qualitative) changes in the results. The peak brightness temperature decreases with increasing kinetic temperature and the range of densities over which inversion occurs also decreases. For $T_{\text{H}_2} = 170$ K, the peak $T_{br}$ of the 6049 MHz maser line falls to $10^7$ K, and inversion occurs for $10^2 \lesssim n_{\text{H}_2} \lesssim 10^6$ cm$^{-3}$.

Above $T_{\text{H}_2} = 170$ K, the effects of local line overlap introduce qualitative changes. The 6049 MHz line continues to weaken, while the 6035 MHz line now appears. As the temperature approaches 200 K, there are 15 pairs and one triple of locally overlapping lines. Figure 2 shows $T_{br}$ as a function of $n_{\text{H}_2}$ for $T_{\text{H}_2} = 200$ K, $f_{\text{ortho-}H_2} = 1$, $f_{\text{OH}} = 10^{-5}$ and $V = 0.6$ km s$^{-1}$. At this relatively high temperature, the peak $T_{br}$ of the 6049 MHz maser line is only $10^6$ K, while for the 6035 MHz main line, $T_{br} \sim 10^9$ K at $n_{\text{H}_2} \sim 10^7$ cm$^{-3}$.

When $f_{\text{ortho-}H_2} = 0$, no OH 5 cm maser line appears for kinetic temperatures lower than 170 K. For $T_{\text{H}_2} = 200$ K, $f_{\text{ortho-}H_2} = 0$, $f_{\text{OH}} = 10^{-5}$ and $V = 0.6$ km s$^{-1}$ the results are

![Figure 1](image1.png)

Fig. 1.—Brightness temperature $T_{br}$ as a function of density $n_{\text{H}_2}$ for $T_{\text{H}_2} = 150$ K, $f_{\text{ortho-}H_2} = 1$, $f_{\text{OH}} = 10^{-5}$, and $V = 0.6$ km s$^{-1}$. The values of the other parameters are given in § 2.

![Figure 2](image2.png)

Fig. 2.—Same as in Fig. 1, but $T_{\text{H}_2} = 200$ K.
shown in Figure 3. The peak $T_{br}$ of the 6035 MHz line is 1 order of magnitude stronger than that for $f_{\text{ortho-H}_2} = 1$, but the 6049 MHz line is absent. Thus, as with the 1720 MHz maser line (see Paper I), the 6049 MHz maser line could be a diagnostic (but see below) of the abundance of ortho-$\text{H}_2$ in maser regions.

The fractional abundance of OH in star-forming regions is probably not constant independent of density. To explore this possibility we have computed models with $f_{\text{OH}} = 10^{-6}$ (the results are not shown in a figure). No qualitative changes occur in comparison with the results for $f_{\text{OH}} = 10^{-5}$ (see Figs. 2 and 3). The 6035 MHz line is of the same intensity as in Figures 2 and 3, but it is inverted at densities a factor of 3 higher. The 6049 MHz line is reduced in intensity to the point of being unobservable. For

Increasing the characteristic velocity to $V = 2 \text{ km s}^{-1}$, but keeping the rest of the parameters the same, results in a significant reduction of the 6049 MHz line (Fig. 5). For $n_{H_2} \sim 10^8 \text{ cm}^{-3}$, the 6031 MHz main line and the 6017 MHz satellite one are inverted with high brightness temperatures. At even higher densities the 6035 MHz main line is inverted, the 6017 MHz line remains strongly inverted, while the 6031 MHz one is suppressed. A further increase of the velocity to $V = 3 \text{ km s}^{-1}$ results in the complete disappearance of the 6049 MHz line (Fig. 6).

As in the previous subsection, a significant reduction of the abundance of ortho-$\text{H}_2$ results in the disappearance of the 6049 MHz line as a maser line. This is true for $V = 1, 2, \text{ or } 3 \text{ km s}^{-1}$. As a characteristic example we show the case of $f_{\text{ortho-H}_2} = 0, f_{\text{OH}} = 10^{-5}$ and $V = 2 \text{ km s}^{-1}$ (Fig. 7). Below $n_{H_2} \sim 3 \times 10^7 \text{ cm}^{-3}$ no maser line appears.

Finally, a reduction of $f_{\text{OH}}$ by an order of magnitude has the general result of significantly reducing the brightness temperature of the 6049 MHz line ($T_{br} \lesssim 10^4 \text{ K}$), as it was also seen in the previous subsection. Furthermore, our calculations have shown that $f_{\text{OH}} = 10^{-6}$ results in destroying the inversion of all 5 cm maser lines at relatively high densities ($n_{H_2} \gtrsim 4 \times 10^7 \text{ cm}^{-3}$).

### 3.4. Effects of a FIR Radiation Field

From the calculations presented so far, it is evident that the 5 cm main lines of OH are never inverted together for densities thought prevailing in star-forming regions (i.e., $n_{H_2} \lesssim \text{few} \times 10^7 \text{ cm}^{-3}$), when a far-infrared (FIR) radiation field is absent. In this subsection we will demonstrate that a FIR radiation field is necessary to reproduce the observed
features of the 5 cm lines and their correlations with the ground state $^2\Pi_{3/2}$, $J = 3/2$ and the excited state $^2\Pi_{1/2}$, $J = 1/2$ OH masers.

For $T_{\text{H}_2} = 150$ K, $f_{\text{OH}} = 10^{-5}$, $f_{\text{ortho-H}_2} = 1$, $V = 1$ km s$^{-1}$ and dilution factor $W = 0.01$ (see Paper II), the main lines at 5 cm are inverted at low densities ($n_{\text{H}_2} \lesssim \text{few} \times 10^7$ cm$^{-3}$) when $T_d > T_{\text{H}_2}$. When $T_d < T_{\text{H}_2}$ (see Figs. 8a and 8b) the results are similar i.e., differences less than a factor of 2 in the $T_w$, to those of Figure 4, where there was no external FIR radiation field. However, when $T_d > T_{\text{H}_2}$ (see Figs. 8c and 8d), the main line at 6035 and 6031 MHz make their appearance as masers.

Increasing the strength of the FIR radiation field by taking $W = 0.1$ has dramatic effects on the 5 cm lines of OH. Figures 9a–9d show $T_w$ of the maser lines as a function of $n_{\text{H}_2}$ for $T_{\text{H}_2} = 150$ K, $f_{\text{OH}} = 10^{-5}$, $f_{\text{ortho-H}_2} = 1$, $V = 1$ km s$^{-1}$ and dilution factor $W = 0.1$. Both 5 cm main lines are masing with the 6035 MHz line stronger than the 6031 MHz one in the range of densities where both lines are inverted. The satellite line at 6049 MHz is also masing but the other satellite line at 6017 MHz is never inverted for $n_{\text{H}_2} \lesssim \text{few} \times 10^7$ cm$^{-3}$.

Remarkably, the abundance of ortho-H$_2$ causes no changes as to which 5 cm lines of OH are masers. Figures 10a–10d are made with $f_{\text{ortho-H}_2} = 0$ and the rest of the parameters the same as in Figures 9a–9d, respectively.

What has dramatic effects on the pumping of the 5 cm lines is the characteristic velocity. For $V = 2$ km s$^{-1}$ and $V = 3$ km s$^{-1}$ with the rest of the parameters the same as in Figures 9a–9d, the results are shown in Figures 11a–11d and 12a–12d, respectively. As it is clear from these figures, an increase of $V$ (i.e., increase of nonlocal overlap) causes sup-
Fig. 8—(a) Brightness temperature $T_{br}$ as a function of density $n_{hi}$ for $T_d = 150$ K, $f_{\text{ortho}} = 1$, $f_{\text{ortho}} = 10^{-4}$, $V = 1$ km $s^{-1}$, $T_d = 100$ K, $p = 1$ and $W = 0.01$. The values of the other parameters are given in § 2. (b) Same as in (a), but for $p = 2$. (c) Same as in (a), but for $T_d = 200$ K. (d) Same as in (b), but for $T_d = 200$ K.
Fig. 9.—(a) Same as in Fig. 8a, but for $W = 0.1$. (b) Same as in Fig. 8b, but for $W = 0.1$. (c) Same as in Fig. 8c, but for $W = 0.1$. (d) Same as in Fig. 8d, but for $W = 0.1$. 

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Fig. 10.—(a) Same as in Fig. 9a, but for $f_{\text{ortho-H}_2}=0$. (b) Same as in Fig. 9b, but for $f_{\text{ortho-H}_2}=0$. (c) Same as in Fig. 9c, but for $f_{\text{ortho-H}_2}=0$. (d) Same as in Fig. 9d, but for $f_{\text{ortho-H}_2}=0$. 

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Fig. 11.—(a) Same as in Fig. 9a, but for $V = 2$ km s$^{-1}$. (b) Same as in Fig. 9b, but for $V = 2$ km s$^{-1}$. (c) Same as in Fig. 9c, but for $V = 2$ km s$^{-1}$. (d) Same as in Fig. 9d, but for $V = 2$ km s$^{-1}$. 
Fig. 12. (a) Same as in Fig. 9a, but for $V = 3$ km s$^{-1}$. (b) Same as in Fig. 9b, but for $V = 3$ km s$^{-1}$. (c) Same as in Fig. 9c, but for $V = 3$ km s$^{-1}$. (d) Same as in Fig. 9d, but for $V = 3$ km s$^{-1}$. 
Fig. 13.—Same as Fig. 9c, but for $f_{\text{OH}} = 10^{-4}$

Fig. 14.—Same as Fig. 9c, but for $f_{\text{OH}} = 10^{-6}$

Fig. 15.—Same as Fig. 6c of Paper II, but for $f_{\text{OH}} = 10^{-6}$

pression of the 5 cm main lines. The 6035 MHz line is not inverted at all. The 6031 MHz either is not inverted (compare Figs. 9a and 12a) or it is much weaker (compare Figs. 9d and 12d) depending on the strength of the FIR field. The reader should notice the competition between the FIR field, which inverts the main lines (as we go from [a] to [d] in Figs. 9, 11, and 12 the FIR field increases) and the nonlocal overlap, which suppresses the inversion (as we go from Fig. 9 to Fig. 11 and then to Fig. 12 the nonlocal overlap increases).

For completeness, we take one of our cases that agrees qualitatively well with the observational data, namely the case presented in Figure 9c, and explore the effects of the abundance of OH. For $f_{\text{OH}} = 10^{-4}$ and $f_{\text{OH}} = 10^{-6}$ the results are shown in Figures 13 and 14, respectively. The abundance of OH introduces only quantitative changes. An enhanced abundance of OH increases the brightness temperature of the 6049 MHz maser line, while a reduced abundance has the opposite effect. The main lines at 6035 and 6031 MHz remain essentially unaffected.

Since the effects of the abundance of OH on the ground state $^2\Sigma_{3/2}, J = 3/2$ and the excited state $^2\Pi_{1/2}, J = 1/2$ were not investigated in Paper II, we show in Figure 15 the case of $f_{\text{OH}} = 10^{-6}$ and all the other parameters the same as in Figure 6c of Paper II.

4. COMPARISON WITH OBSERVATIONS

Since the original discovery of emission from the $^2\Pi_{3/2}, J = 5/2$ (Yen et al. 1969), many surveys were made for detection of 5 cm maser emission toward a variety of sources (Knowles et al. 1976; Guilloteau et al. 1984; Smits 1994). Caswell & Vaile (1995) surveyed for 6035 MHz
masers in 208 OH sources with peak 1665 MHz flux density greater than 0.8 Jy. Only 35 masers at 6035 MHz were detected, "a result that agrees well with our calculations."

Since these observations were made with a single dish, and the authors have not proven that any of the 1665–6035 MHz "pairs" come from the same region, these observations must be interpreted solely as a tendency of the 1665 MHz line to be inverted more easily than the 6035 MHz one. Our results qualitatively agree with this. The 1665 MHz line (see Paper II) is inverted in a much broader range of densities, velocity fields and strengths of a FIR field than the 6035 MHz line.

Let's for the rest of this section restrict to our results in the presence of a FIR field, $V < 1.5 \text{ km s}^{-1}$ and $n_{\text{H}} < 10^7 \text{ cm}^{-3}$. The 6035 MHz line is weaker than the 1665 MHz one and is inverted in a range of densities which is a subset of the range of densities over which the 1665 MHz line is inverted. As the FIR field gets stronger, this subregion becomes broader and the 6035 MHz line tends to be inverted in the same range of densities as the 1665 MHz line. By taking also into account our result that the stronger the FIR radiation field is the stronger the 1665 and 6035 MHz masers are, and assuming that both lines come from the same region, our models are in qualitative agreement with the observational result of Caswell & Vailé (1995) that the greater the peak of 1665 MHz maser intensity, the greater the detection rate of 6035 MHz masers.

An extensive search for all four maser lines in 5 cm has been made by Baudry et al. (1997) toward 265 strong FIR sources and the general observed characteristics of these 5 cm masers can be explained by our calculations. Their observations show (see also Desmurs et al. 1998) that the main-line masers at 6035 MHz, in the $^2\Pi_{3/2}$, $J = 5/2$ state of OH, are generally stronger and more common than those at 6031 MHz in H II/OH regions. Nevertheless, the 6031 MHz line is frequently observed to be masing. Strong 5 cm satellite line masers are not observed in the $J = 5/2$ state of OH. The 6017 MHz line is often found in absorption while the other satellite line at 6049 MHz is observed in weak emission which could correspond to low gain masers. Our theoretical calculations are in good qualitative agreement with these observations. The 6017 MHz line is never inverted in our calculations and the 6049 MHz line is weak in a wide range of parameters thought to be prevailing in star-forming regions.

Our calculations show that a combination of a FIR radiation field, collisions and line overlap is necessary to reproduce the general features of 6 GHz H II/OH masers. Nevertheless, simultaneous or nearly simultaneous VLBI observations at 1.6 GHz, 4.7 GHz, and 6 GHz are necessary to restrict the range of parameters for the inversion of these masers and a search of the correlation between 5 cm maser and FIR radiation field strength would be important to prove or not the importance of FIR radiation for the inversion of these masers.

5. SUMMARY AND CONCLUSIONS

We have performed a detailed, systematic study of OH maser pumping in order to attempt to invert the problem and from the OH maser observations to infer the physical conditions in H II/OH regions. This was partially accomplished in Papers I and II. With the present study of the 5 cm masers of OH the predictions of our model are

1. When strong 5 cm maser main lines are seen, a FIR radiation field must be strong there, i.e., high value of $W$ or $p$ or $T_{\text{d}}$ or a combination of them.
2. Inversion of both main lines at 5 cm requires relatively small velocity gradients. For $V \leq 1 \text{ km s}^{-1}$ and a FIR radiation field present, these lines are always seen. If these lines are seen together in the same spatial region, the 1665 MHz OH ground state main line maser will also be observed in the same region, while there is a high probability the other ground state main line maser at 1667 MHz to be observed too (see Paper II).
3. When the 6031 MHz maser line is observed in a region where there is no detection of 6035 MHz maser, the 1665 MHz ground state line is inverted in the same spatial region. This situation has a great probability to be indicative of relatively large velocity gradients ($V > 1 \text{ km s}^{-1}$).
4. When the 6049 MHz maser line is seen as a strong line (say, as strong as the 5 cm main lines are typically seen), then $f_{\text{OII}} \approx 10^{-5}$.
5. We predict that maser spots showing very strong 18 cm main lines should exhibit 5 cm maser main lines also. This may have already been seen (Caswell & Vailé 1995), but VLBI observations are needed to confirm or reject our prediction.
6. We also predict that 18 cm maser main lines with $V \approx 2 \text{ km s}^{-1}$ will not be accompanied by 5 cm maser main lines.

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REFERENCES

Baudry, A., Desmurs, J. F., Wilson, T. L., & Cohen, R. J. 1997, A&A, 325, 255
Baudry, A., & Diamond, P. J. 1991, A&A, 247, 551
—. 1998, A&A, 331, 697
Baudry, A., Diamond, P. J., Booth, R. S., Graham, D., & Walmsley, C. M. 1998, A&A, 301, 105
Baudry, A., Walmsley, C. M., Winnberg, A., & Wilson, T. L. 1981, A&A, 102, 287
Caswell, J. L., & Vailé, R. A. 1995, MNRAS, 273, 328
Cohen, R. J. 1989, Rep. Prog. Phys., 52, 881
Cohen, R. J., Baart, E. E., & Jonas, J. L. 1988, MNRAS, 231, 205
Cohen, R. J., Masheder, M., & Walker, R. N. F. 1991, MNRAS, 250, 611
Desmurs, J. F., & Baudry, A. 1998, A&A, 340, 521
Desmurs, J. F., Baudry, A., Wilson, T. L., Cohen, R. J., & Tofani, G. 1998, A&A, 334, 1085
Elitzur, M. 1992, ARA&A, 30, 75
Gardner, F. F., & Martin-Pintado, J. 1983, A&A, 121, 265
Gardner, F. F., & Whiteoak, J. B. 1983, MNRAS, 205, 297
Gardner, F. F., Whiteoak, J. B., & Palmer, P. 1987, MNRAS, 225, 469
Gaume, R. A., & Mutel, R. L. 1987, ApJS, 65, 193
Guilloteau, S., Baudry, A., Walmsley, C. M., Wilson, T. L., & Winnberg, A. 1984, A&A, 131, 45
Knowles, S. H., Caswell, J. L., & Goss, W. M. 1976, MNRAS, 175, 537
Palmer, P., Gardner, F. F., & Whiteoak, J. B. 1984, MNRAS, 211, 41P
Pavlakis, K. G., & Kylafis, N. D. 1996a, ApJ, 467, 300 (Paper I)
—. 1996b, ApJ, 467, 309 (Paper II)
Reid, M. J., & Moran, J. M. 1981, ARA&A, 19, 231
Smits, D. P. 1994, MNRAS, 269, L11
Turner, B. E., Palmer, P., & Zuckerman, B. 1970, ApJ, 160, L125
Yen, J. L., Zuckerman, B., Palmer, P., & Penfield, H. 1969, ApJ, 156, L27