ON THE IONIZATION OF LUMINOUS WMAP SOURCES IN THE GALAXY: CONSTRAINTS FROM He RECOMBINATION LINE OBSERVATIONS WITH THE GBT

D. ANISH ROSHI1,2, ADELE PLUNKETT3, VIVIANA ROSERO4, AND SRAVANI VADDI5
1 National Radio Astronomy Observatory (NRAO), Green Bank, WV 24944, USA; aroshi@nrao.edu
2 NRAO Technology Center, Charlottesville, VA 22903-4608, USA
3 Department of Astronomy, Yale University, P.O. Box 208101, New Haven CT 06520, USA; adele.plunkett@yale.edu
4 Physics Department, New Mexico Institute of Mining and Technology, 801 Leroy Place, Socorro, NM 87801, USA; viviana@nmt.edu
5 Astrophysical Sciences and Technology, Rochester Institute of Technology, NY 14623, USA; ss11249@rit.edu

Received 2011 December 18; accepted 2012 February 3; published 2012 March 21

ABSTRACT

Murray & Raham used the Wilkinson Microwave Anisotropy Probe (WMAP) free–free foreground emission map to identify diffuse ionized regions (DIRs) in the Galaxy. It has been found that the 18 most luminous WMAP sources produce more than half of the total ionizing luminosity of the Galaxy. We observed radio recombination lines (RRLs) toward the luminous WMAP source G49.75–0.45 with the Green Bank Telescope near 1.4 GHz. Hydrogen RRL is detected toward the source but no helium line is detected, implying that \( n_{\text{He}}/n_{\text{H}} < 0.024 \). This limit puts severe constraint on the ionizing spectrum. The total ionizing luminosity of G49 (\( 3.05 \times 10^{51} \text{ s}^{-1} \)) is \( \sim 2.8 \) times the luminosity of all radio \( \text{H} \text{II} \) regions within this DIR and this is generally the case for other WMAP sources. Murray & Raham propose that the additional ionization is due to massive clusters (\( \sim 7.5 \times 10^4 \text{ M}_\odot \) for G49) embedded in the WMAP sources. Such clusters should produce enough photons with energy \( \geq 24.6 \text{ eV} \) to fully ionize helium in the DIR. Our observations rule out a simple model with G49 ionized by a massive cluster. We also considered “leaky” \( \text{H} \text{II} \) region models for the ionization of the DIR, suggested by Lockman and Anantharamaiah, but these models also cannot explain our observations. We estimate that the helium ionizing photons need to be attenuated by \( \geq 10 \) times to explain the observations. If selective absorption of He ionizing photons by dust is causing this additional attenuation, then the ratio of dust absorption cross sections for He and H ionizing photons should be \( \gtrsim 6 \).

Key words: Galaxy: general – \text{H} \text{II} regions – ISM: clouds – ISM: general – ISM: structure – radio lines: ISM

1. INTRODUCTION

The existence of a diffuse ionized gas in the Galaxy is evident from a variety of observations (Hoyle & Ellis 1963; see a review by Haffner et al. 2009). This gas, referred to as the warm ionized medium (WIM), is now considered as one of the major components of the interstellar medium. The WIM has been primarily studied using optical emission lines, which indicates that it contains 90% of the ionized mass of the Galaxy (Haffner et al. 2009). These observations also indicate that the local electron density of the WIM is in the range 0.01–0.1 cm\(^{-3}\). In the inner galaxy, the optical lines suffer extinction and hence the distribution of the ionized gas has been studied in the radio frequency regime. In particular, low-frequency (\( \lesssim 2 \) GHz) radio recombination line (RRL) observations have been used to detect diffuse ionized regions (DIRs) with local density in the range 1–10 cm\(^{-3}\). In the literature, this DIR is referred to as Galactic Ridge RRL emission by Davies et al. (1972); see also Gottesman & Gordon (1970), extended low-density ionized gas by Mezger (1978), evolved \text{H} \text{II} region by Shaver (1976), \text{H} \text{II} envelopes (i.e., low-density envelopes of compact \text{H} \text{II} regions) by Lockman (1976), and Anantharamaiah (1986; see also Roshi & Anantharamaiah 2000) and more recently as extended low-density WIM by Petuchowski & Bennett (1993) and Heiles (1994). The latter authors consider the DIR as a higher density version of the WIM in the inner Galaxy, though the exact relationship between the DIR and WIM is still uncertain.

In addition to spectral lines, DIRs have been studied through radio free–free emission (e.g., Mezger 1978). More recently, Murray & Rahman (2010) used the free–free galactic foreground emission model, obtained from the Wilkinson Microwave Anisotropy Probe (WMAP) data, to study the DIR. For the WMAP measurements of cosmic microwave background emission, the galactic foreground is accurately characterized using a maximum entropy model (MEM; Bennett et al. 2003; Gold et al. 2009). The foreground is modeled as a linear combination of emission due to synchrotron, free–free, and vibrational excitation of dust with power-law frequency dependence. The MEM finally produces sky models for each of these emission processes. Since the free–free model has an angular resolution of \( \sim 1 \) deg (after smoothing), it is more sensitive to emission from DIRs compared to compact \text{H} \text{II} regions. Murray & Rahman (2010) used this free–free model to identify emission regions with 94 GHz flux density \( \gtrsim 10 \text{ Jy} \). By considering that the WMAP sources are associated with known \text{H} \text{II} regions, which are either cataloged by Russell (2003) or identified in the Midcourse Space Experiment (Price et al. 2001) or Spitzer GLIMPSE (Churchwell et al. 2006) data set, distances can be assigned. The free–free flux density, source angular size, and the distance are used to estimate the Lyman continuum (Lyc) luminosity required for ionization balance. They found that the 18 most luminous WMAP sources contribute half of the total ionizing luminosity (3.2 \( \times 10^{53} \text{ s}^{-1} \)) of the Galaxy.

Rahman & Murray (2010) studied in detail a subset of the luminous WMAP sources. The estimated Lyc luminosities of these sources are in the range \( 10^{51.5–52} \text{ s}^{-1} \). They show that the radio \text{H} \text{II} regions embedded in these WMAP sources contribute only one-half to one-third of the Lyc luminosity obtained from the WMAP emission. Murray & Rahman (2010) suggest that the additional ionization is due to embedded stellar clusters. The mass of the cluster required to produce the ionizing luminosity is \( \gtrsim 10^4 \text{ M}_\odot \). These clusters evaded detection presumably due to heavy dust obscuration in the star-forming region.

For the most widely used initial mass function (IMF; e.g., Scalo 1986; Muench et al. 2002) of the stellar content of clusters, the bulk of the ionizing photons occurs for star with
The helium line is not detected; the upper limit implies that the abundance of He, if all the He is in He+, is lower than the expected value of 0.1 from cosmic abundance. We note here that the upper limit implies that $n_{\text{He}}/n_{\text{H}} \approx 0.024$. The upper limit to helium line is determined from the spectrum shown in (c), which is obtained after subtracting Gaussian models for the carbon and X lines from the average spectrum and smoothing to 10.5 km s$^{-1}$ velocity resolution. The velocity range near 110 km s$^{-1}$ is affected by RFI.

In this paper, we present results of 1.4 GHz RRL observations toward G49.75−0.45, located within the luminous WMAP source G49 (Rahman & Murray 2010), with the National Radio Astronomy Observatory (NRAO) Green Bank Telescope (GBT). Our objective was to do a deep integration toward a single pointing in G49 (i.e., without spatial average) away from bright radio H II regions and determine $n_{\text{He}}/n_{\text{H}}$. The observations and data analysis procedure are presented in Section 2. As discussed in Section 3, we have detected hydrogen (and carbon) RRL toward G49.75−0.45, but no He line is detected. The upper limit implies that $n_{\text{He}}/n_{\text{H}} \lessapprox 0.024$. The implication of this upper limit on the spectrum of the ionizing source is discussed in Section 4. The main results of the paper are summarized in Section 5.

2. OBSERVING STRATEGY, RRL OBSERVATIONS, AND DATA REDUCTION

We selected the position G49.75−0.45, located toward the WMAP source G49 (Rahman & Murray 2010), for observations. The WMAP source G49 is located in galactic longitude away from other dense star-forming regions in the inner Galaxy and is near the outer edge of the Sagittarius–Carina arm. The star-forming complex W51 is located within this source. We selected the position in G49 (see Figure 1(a)) such that it is away from compact H II regions and hence samples the diffuse thermal gas seen by WMAP.

The RRL observations are made with the GBT. The frequency band for the observations is chosen as follows. The approximate continuum brightness temperature toward G49 at 4.785 GHz (Altenhoff et al. 1979) and 408 MHz (Haslam et al. 1982) are, respectively, $\sim 0.5$ K and $\sim 150$ K. Assuming that the emission at 408 MHz is dominated by non-thermal emission and has a spectral index of $-2.6$, the expected non-thermal contribution at 4.785 GHz is $\sim 0.25$ K. An emission measure of $\sim 1800$ pc cm$^{-6}$ for the ionized gas is estimated to produce the thermal emission of 0.25 K at 4.785 GHz. We take the electron temperature of 7000 K, same as that of the compact H II region, for this calculation (Dowens et al. 1980). For the estimated emission measure and a mean electron density of $\sim 5$ cm$^{-3}$ (Roshi & Anantharamaiah 2001), the expected signal-to-noise ratio of RRL detection peaks near 1 GHz. Taking into account Radio Frequency Interference (RFI) near 1 GHz, we decided to observe with the L-band (1.1 to 1.75 GHz) system of the GBT.

Observations were made with the GBT on 2011 July 13. The L-band receiver is a single-beam, dual-linear-polarization system. The FWHM beam width at this frequency is $\sim 9$'. The GBT spectrometer was used to simultaneously observe the 169$\alpha$, 168$\alpha$, 167$\alpha$, and 166$\alpha$ transitions of hydrogen (H), helium, and carbon from both polarizations. A bandwidth of 12.5 MHz and 8192 channels for the spectrometer were selected, which gave a spectral resolution of $\sim 1.5$ KHz ($\sim 0.3$ km s$^{-1}$). This higher spectral resolution was helpful in editing out narrowband RFI. We employed a dual-Dicke frequency switching to measure the reference spectrum. The frequency is switched by 2.5 MHz, which corresponds to $\sim 526$ km s$^{-1}$. All the spectral lines of interest fall within this velocity range. The front-end bandwidth was restricted between 1.3 and 1.45 GHz to reduce the effect of out of band RFI. The total on-source observing time was about 3.5 hr. The calibrator 3c295 was observed in the beginning for pointing, focus, and flux calibration.

The data analysis is done in GBTIDL and Matlab/Octave. Data corresponding to all the transitions and the two polarizations are examined for RFI and averaged separately in GBTIDL. The H I 21 cm line, present in the 166$\alpha$ band, was examined and
found not to affect the RRL. Online Doppler correction could be done only for the 166α transition and so the residual corrections for other transitions were done by fast Fourier transform (FFT) shift method in GBTIDL before averaging. A third-order baseline was fitted to these spectra using data points from the spectral region free of RRLs. The velocity resolution of the spectra of different transitions were then made identical by FFT re-sampling (see Roshi et al. 2005). The averaged spectra corresponding to each transition were further edited for bad spectral baseline and RFI. The spectrum corresponding to the 166α transition had narrowband RFI near the expected position of the He line and hence was edited out. The spectral baseline of the X-polarization of the 166α transition had a ripple, which was also excluded from further analysis. Narrowband RFI, which were located at frequencies far from the expected line frequencies, were edited out using a channel weighting scheme (Roshi & Anantharamaiah 2000). The edited spectra were averaged to obtain the final integrated spectrum. The effective integration time of the final spectrum is about 16.4 hr and average $T_{\text{sys}}$ is 22.6 K. The amplitude of the final spectrum is given in antenna temperature, which is obtained using the calibrated noise source in the GBTL-band receiver. To convert to main beam brightness temperature these values need to be multiplied by 1.14, since the observed source is extended and roughly fills the beam.

3. RESULT

The final spectrum obtained from the data is shown in Figure 1(b). The H and carbon RRLs are clearly detected. A line feature corresponding to an unknown transition, marked as X, is also detected. The parameters for Gaussian models of the detected lines are given in Table 1. The He line is not detected. To determine the upper limit to the He line intensity, Gaussian models for the carbon and X lines are removed from the integrated spectrum and the resultant spectrum is smoothed to $\sim 10.5$ km s$^{-1}$ velocity resolution. The smoothed spectrum is shown in Figure 1(c). The root mean square (rms) of the spectral values over the velocity range $-120$ to 0 km s$^{-1}$ is $4.4 \times 10^{-4}$ K. Since there are only 11 points for estimating the rms, we have taken the upper limit for the He line as the 99.99% confidence limit of the spectral mean (obtained using Student’s $t$-distribution), which is listed in Table 1. Using this upper limit we determine that $n_{\text{He}}/n_{\text{H}} < 0.024$. We have neglected the effect of the smaller expected thermal line width for He compared to H to obtain this ratio and have also considered that H is fully ionized in the DIR (Roshi & Anantharamaiah 2001).

4. DISCUSSION

The “Giant” H ii (GH ii) regions are located within the WMAP source G49. They are W51, W51A, and W51West, all of which are well studied in radio and infrared wavelengths (e.g., Conti & Crowther 2004). The GH ii regions are observed as compact sources in radio continuum images (see Figure 1(a)). They are located at a kinematic distance of 5.5 kpc (Russell 2003). RRL observations near 327 MHz have detected lines toward W51, which arise from the DIR since most of the compact H ii regions become optically thick at this frequency (e.g., Roshi & Anantharamaiah 2001). The LSR velocities of the 327 MHz RRLs coincide with those detected from the compact H ii regions at higher frequencies. Therefore, in this paper, we consider the distance to the WMAP source G49 as 5.5 kpc.

The total Lyc luminosity of GH ii regions after dust extinction correction is $1.1 \times 10^{51}$ s$^{-1}$ (Conti & Crowther 2004). On the other hand, the total Lyc luminosity obtained from WMAP free–free emission after dust extinction correction and using a distance of 5.5 kpc is $3.05 \times 10^{51}$ s$^{-1}$ (Murray & Rahman 2010). The larger ionizing photon requirement obtained from DIR tracers is noted earlier (e.g., Mezger 1978; McKee & Williams 1997). As suggested by Lockman (1976) and Anantharamaiah (1986), most of the Lyc photons from H ii regions may leak out to produce low-density envelopes which are observed as the DIR (see also McKee & Williams 1997). In this picture, the ionizing sources are the same star clusters embedded in the GH ii regions (Conti & Crowther 2004). The two ionizing luminosities estimated above for G49 imply that $\sim 63\%$ of the Lyc photons are leaking out of the GH ii regions. Murray & Rahman (2010) suggested another possibility that the DIR are ionized by embedded massive clusters not associated with classical radio H ii regions within the WMAP sources. Such clusters are not directly detected presumably due to high obscuration.

Here, we explore the possibility of using He RRL observations toward the G49 region to distinguish between these different possible ionization models and to constrain the spectrum of the ionizing photons. Since the ionization potential of He (24.6 eV) is greater than that of H (13.6 eV), the observed H to He line ratio can be used to constrain the ionizing spectrum. We calculate the ionizing photon from a stellar cluster using Starburst99 (Leitherer et al. 1999; Vázquez & Leitherer 2005). The mass of the cluster to get the required total Lyc photons for G49 is $\sim 7.5 \times 10^5 M_\odot$; the IMF used for this calculation is from Muench et al. (2002). In Murray & Rahman’s picture, a single cluster will have this mass. On the other hand in the Lockman (1976) and Anantharamaiah (1986) pictures the mass gets distributed to three clusters in the three GH ii regions. In either case, the ratio of He ionizing photons, $Q_{\text{He}}$ (photon energy interval 24.6–54.4 eV), to the H ionizing photons, $Q_{\text{H}}$ (number of photons emitted per second in the energy interval 13.6–24.6 eV), is $\sim 0.24$ (see Figure 2). From the ionization model of H ii region this $Q_{\text{He}}/Q_{\text{H}}$ implies that the He and H Strömgren spheres overlap (Mathis 1971) and hence the He line should have been detected. However, our observations did not detect the He line in G49.

The $n_{\text{He}}/n_{\text{H}}$ ratio obtained from high-frequency RRL observations toward compact H ii regions in G49 is $> 0.066$ (Churchwell et al. 1974; Lichten et al. 1979; Thum et al. 1980; McGee & Newton 1981; Mehringer 1994; Bell et al. 2011). The low observed $n_{\text{He}}/n_{\text{H}}$ for the DIR in G49 thus indicates that the

| Transition | $T_0$ (K) | $V_{\text{LSR}}$ (km s$^{-1}$) | $AV$ (km s$^{-1}$) |
|------------|-----------|-------------------------------|-------------------|
| H$^+$      | 0.0324(0.0003) | 60.46(0.15) | 28.95(0.35) |
| He         | 0.00074$^a$ | ... | ... |
| C$^+$      | 0.0048(0.0009) | 69.83(0.37) | 3.87(0.91) |
| C$^+$      | 0.0050(0.0012) | 64.35(0.27) | 2.18(0.64) |

Notes.

$^a$ The line parameters are obtained from the spectrum smoothed to a velocity resolution of $1.1$ km s$^{-1}$.

$^b$ See Section 3 for the determination of upper limit to He line emission.

$^c$ This transition is not identified. The listed LSR velocity of X line is with respect to hydrogen.

The effects of stochasticity on the luminosity of cluster with mass a few times $10^5 M_\odot$ will be investigated in a future publication.
He ionizing photons are eliminated on scales somewhat larger than the compact H\textsc{ii} regions. If the DIR is ionized by clusters embedded in the GH\textsc{ii} regions, as suggested by Lockman (1976) and Anantharamaiah (1986), then one possibility is that the spectrum of the photons changes while diffusing out of the H\textsc{ii} regions. However, models of “leaky H\textsc{ii} regions” show that the He ionizing photons can be significantly suppressed only for low leakage (∼15%) and for effective temperature of ionizing source < 45,000 K (Hoopes & Walterbos 2003; Wood & Mathis 2004); both these conditions are not true for G49.

Murray & Rahman (2010) identify stellar wind bubbles within WMAP sources. For G49, the dynamical timescale estimated from the expansion of these bubbles is ∼2 Myr. We investigated using Starburst99 the evolution of a 7.5 × 10\textsuperscript{3} M\odot star cluster and the change of Q_{He}/Q_{H} with its age. Figure 2 shows the result. The ratio Q_{He}/Q_{H} decreases by a factor of 3.4 by ∼2.5 Myr and then increases due to the evolution of massive stars to Wolf–Rayet (WR) stars. The surface temperatures of WR stars are > 50,000 K and hence they contribute significantly to He ionization. Note that by about 2.8 Myr or so the total Lyc flux due to the cluster drops down. As can be seen from Figure 2(b), the reduction in Q_{He}/Q_{H} at age ∼2 Myr is not sufficient to explain the observed upper limit of He line.

The observed limit to the He line can be used to obtain an upper limit on the ratio Q_{He}/Q_{H} using the He ionization model of Mathis (1971). The upper limit thus obtained for Q_{He}/Q_{H} is about 0.028, which is marked on Figure 2(b). We modified Starburst99’s massive star atmospheric model emission routines to introduce an attenuation for photons with energy ≥ 24.6 eV. These photons need to be attenuated by at least a factor of 10 relative to the current model results if the ionizing sources are star clusters with age ∼ 2.8 Myr (see Figure 2(b)).

Environments of stellar clusters and their evolution have been recently studied both theoretically (Pelupessy & Zwart 2012) and observationally (Churchwell et al. 2006). These studies show that the cluster wind is a dominant factor affecting the environment at all stages of cluster evolution. These winds can produce dust bubbles. We follow the treatment of Mezger et al. (1974; see also Panagia & Smith 1978), developed for compact H\textsc{ii} regions, to investigate whether selective absorption of He ionizing photons by dust can explain the non-detection of He RRL toward the DIR. The size of G49 is ∼70 pc, which, along with electron density (∼5 cm\textsuperscript{-3}; Roshi & Anantharamaiah 2001), gives a dust optical depth at λ = 912 Å in the range 0.25–0.8 depending on the absorption cross section at this wavelength. The dust optical depth near 0.25 cannot significantly change n_{He}/n_{H} in H\textsc{ii} regions (Sarazin 1977). Using the observed limit on n_{He}/n_{H}, Q_{He}/Q_{H} ∼ 0.24 and the above estimated dust optical depth, we find that the ratio of the dust absorption cross sections for He and H ionizing photons is ≥6. This high cross-section ratio is inconsistent with our current understanding of UV absorption properties of the dust (Draine 2003).

5. SUMMARY

RRL observations of the luminous WMAP source G49 were made at 1.4 GHz with the GBT. Hydrogen and carbon lines were detected but no helium line was observed. The upper limit to the ratio of ionized helium to hydrogen obtained is 0.024. It has been suggested that the WMAP sources are ionized by star clusters which may not be associated with the radio H\textsc{ii} regions within these sources. Using Starburst99, we found that the mass of the cluster should be ∼7.5 × 10\textsuperscript{3} M\odot to satisfy the total ionization requirement of G49. The ratio Q_{He}/Q_{H} obtained for such a cluster is ∼0.24, implying that the hydrogen and helium Strömgren spheres should overlap and hence the helium line should be detectable. The non-detection of helium line rules out the possibility that the DIR is an H\textsc{ii} region produced by such stellar clusters. We examined whether the DIR is ionized by “leaky” H\textsc{ii} regions embedded in G49, as suggested by Lockman (1976) and Anantharamaiah (1986). Models of “leaky” H\textsc{ii} regions show that the helium ionizing photons are significantly suppressed for photon leakage ≤ 15%.
and for ionizing source with effective temperature $\lesssim 45,000$ K; both of these conditions are not met for G49. We determined that photons with energy $\geq 24.6$ eV need to be attenuated by at least a factor of 10 compared to the current model results to be consistent with our observations. If selective absorption of He ionizing photons by dust is causing this additional attenuation, then the ratio of dust absorption cross sections for He and H ionizing photons should be $\gtrsim 6$.

D.A.R. thanks J. Lockman and R. Maddalena for helpful discussions during the planning stage of the GBT observations. D.A.R. also thanks Ed Churchwell and Claus Leitherer for informative discussion during the interpretation of the results. The data were taken as part of a project for the Sixth NAIC/NRAO School on Single Dish Radio Astronomy, held at NRAO, Green Bank during 2011 July. The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

Facility: GBT

REFERENCES

Altenhoff, W. J., Downes, D., Pauls, T., & Schraml, J. 1979, A&AS, 35, 23
Anantharamaiah, K. R. 1986, J. Astrophys. Astron., 7, 131
Bell, M. B., Avery, L. W., MacLeod, J. M., & Valle, J. P. 2011, Ap&SS, 333, 377
Bennett, C. L., Hill, R. S., Hinshaw, G., et al. 2003, ApJS, 148, 97
Churchwell, E., Mezger, P. G., & Huchtmeier, W. 1974, A&A, 32, 283
Churchwell, E., Povich, M. S., Allen, D., et al. 2006, ApJ, 649, 759
Conti, P. S., & Crowther, P. A. 2004, MNRRAS, 355, 899
Davies, R. D., Matthews, H. E., & Pedlar, A. 1972, Nature, 238, 101
Dowens, D., Wilson, T. L., Bieging, J., & Wink, J. 1980, A&AS, 40, 379
Draine, B. T. 2003, ARA&A, 41, 241
Gold, B., Bennett, C. L., Hill, R. S., et al. 2009, ApJS, 180, 265
Gottesman, S. T., & Gordon, M. A. 1970, ApJ, 162, L93
Haffner, L. M., Detmmer, R.-J., Beckman, J. E., et al. 2009, Rev. Mod. Phys., 81, 969
Haslam, C. G. T., Salter, C. J., Stoffel, H., & Wilson, W. E. 1982, A&AS, 47, 1
Heiles, C. 1994, ApJ, 436, 720
Heiles, C., Koo, B.-C., Levenson, N. A., & Reach, W. T. 1996, ApJ, 462, 326
Hoopes, C. G., & Walterbos, R. A. M. 2003, ApJ, 586, 902
Hoyle, F., & Ellis, G. R. A. 1963, Aust. J. Phys., 16, 1
Leitherer, C., Schaerer, D., Goldader, J. D., et al. 1999, ApJS, 123, 3
Lichten, S. M., Rodriguez, L. F., & Chaisson, E. J. 1979, ApJ, 229, 524
Lockman, F. J. 1976, ApJ, 209, 429
Mathis, J. S. 1971, ApJ, 167, 261
McGee, R. X., & Newton, L. M. 1981, MNRAS, 196, 889
McKee, C. F., & Williams, J. P. 1997, ApJ, 476, 144
Mehringer, D. M. 1994, ApJS, 91, 713
Mezger, P. G. 1978, A&A, 70, 565
Mezger, P. G., Smith, L. F., & Churchwell, E. 1974, A&A, 32, 269
Muench, A. A., Lada, E. A., Lada, C. J., & Alves, J. 2002, ApJ, 573, 366
Murray, N., & Rahman, M. 2010, ApJ, 709, 424
Panagia, N., & Smith, L. F. 1978, A&A, 62, 277
Pelupessy, F. I., & Zwart, S. P. 2012, MNRAS, 420, 1503
Petuchowski, S. J., & Bennett, C. L. 1993, ApJ, 405, 591
Price, S. D., Egan, M. P., Carey, S. J., Mizuno, D. R., & Kuchar, T. A. 2001, AJ, 121, 2819
Rahman, M., & Murray, N. 2010, ApJ, 719, 1104
Reynolds, R. J., & Tufte, S. L. 1995, ApJ, 439, L17
Roshi, D. A., & Anantharamaiah, K. R. 2000, ApJ, 535, 231
Roshi, D. A., & Anantharamaiah, K. R. 2001, ApJ, 557, 226
Roshi, D. A., Balser, D. S., Bania, T. M., Goos, W. M., & De Pree, C. G. 2005, ApJ, 625, 181
Russel, D. 2003, A&A, 397, 133
Scalo, J. M. 1986, Fundam. Cosm. Phys., 11, 1
Shaver, P. A. 1976, A&A, 49, 1
Thum, C., Mezger, P. G., & Pankonin, V. 1980, A&A, 87, 269
Vázquez, G. A., & Leitherer, C. 2005, ApJ, 621, 695
Wood, K., & Mathis, J. S. 2004, MNRAS, 353, 1126