Multi-epoch observations of methanol masers in DR21(OH)

Nycole Wenner, Mentor: Dr. Emmanuel Momjian, Academic Advisor: Dr. Anuj Sarma

September 1, 2020

Abstract

Class I methanol masers in star forming regions are generally found in outflows. There, shocks provide the collisional pumping that causes the population inversion necessary for maser action. We present an investigation of the intensities of Class I methanol masers toward the high mass star forming region DR21(OH). Our study uses data from three epochs, the first (2001) from the literature, and the other two (2012 and 2017) observed by the mentor and academic advisor listed in this report. This report is a summary of the work completed in summer 2020 under the NRAO summer student program. The work consisted mainly of searching for masers in the 2017 data, fitting Gaussians to these masers using the AIPS task XGAUS, and then comparing to the data from 2001 and 2012. A total of 56 maser spots were found in the 2017 data, with center velocities ranging between -8.5 to +2.5 km s^{-1}. Of interest is that the strongest maser in 2001 becomes the second strongest maser in 2012, whereas the second strongest maser in 2001 becomes the strongest maser in 2012. This shift is substantiated by the 2017 observations. Finally, an additional maser discovered in the 2012 undergoes a 55% drop in brightness between 2012 and 2017; this maser is found 0.5” north of the strongest maser (from 2012) in the field. Future work will examine the reasons for the shift in intensities between the 2001 and 2012 data, accompanied by the appearance of the maser discovered in 2012 near the strongest maser.

Contents

1 Introduction

1.1 What is a Maser?

MASER stands for Microwave Amplification of the Stimulated Emission of Radiation. Charles Townes and his research team at Columbia University made the first maser out of ammonia gas in 1954 [5]. The difference between a laser and a maser is that laser wavelengths are in the visible part of the spectrum (the L stands for Light), and Maser wavelengths are microwave or longer.

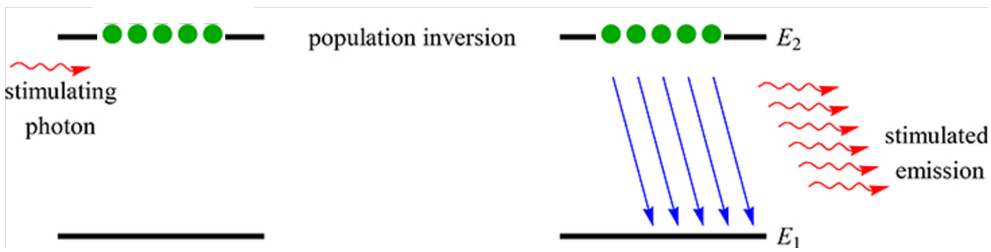

Figure 1: Population inversion in a maser transition. The majority of molecules are in the higher excited state then are knocked to the lower one by incoming photons. When this happens, they release identical photons, resulting in maser transmission.

Light is emitted from a molecule when a photon is released from a molecule falling from a higher energy state to a lower energy state. The amount of photons released depends upon how many molecules are populating the higher energy state in comparison to the lower energy state. Usually in a 2-state system of molecules, the majority of molecules populate the lower energy state rather than the higher energy state. The reason for this distribution is because the lower energy state requires less energy (or is the lowest energy in the case of the ground state), and thus, it doesn't require as much energy to keep it populated.

A maser is formed when molecules are pumped into a state of population inversion where the majority of the molecules within a particular maser transition are in the higher energy state of the transition rather than the lower as is seen in Figure 1. Population inversion allows for the stimulated emission of radiation; when a photon at the specific frequency of the maser transition enters, it interacts with one of the higher energy molecules and causes it to fall to the lower energy level, producing a second identical photon. These photons then interact with more molecules, releasing more identical photons along the pathlength of the maser, producing maser emission. Maser light is monochromatic since they are tied to a specific energy transition in a molecule.

1.2 Astronomical Masers

Though the scientists first created masers on earth in the 1950's, masers are also found to occur in nature in varying astronomical environments. The first astronomical maser was discovered in 1963 [13], and since then, masers have been found in star forming regions, galactic nuclei, supernova remnants, and late stage stars [11]. A few examples of masers found in star forming regions are H_2O, OH, and CH_3OH masers [11]. For the purpose of this paper, I will focus on CH_3OH masers.

There are two different types of CH_3OH masers: Class I and Class II. Class II CH_3OH masers are radiatively pumped, and they are typically found close to their protostellar host [8]. Class I CH_3OH are collisionally pumped; thus, in star forming regions, they are typically formed in outflows of their protostellar host [7]. Since they are formed in outflows, they tend to be further offset from their protostellar host than Class II CH_3OH masers and are distributed on scales of 0.1 to 1 pc [8].

1.3 Maser Variability

Variability in the context of a maser refers to the change of the maser's peak intensity over a given timescale. Some masers are known to exhibit variability, such as H_2O masers [3] which are highly variable on timescales of days, but they can also vary on timescales of months and years [2]. However, they aren't the only type of maser found to be variable. Class II CH_3OH are also found to vary on the timescales of days to months [4].

1.3.1 Are Class I Methanol Masers Variable?

It was originally argued based on sparse single dish observations (low angular resolution) that Class I CH_3OH masers would not vary [9]. Although references to variability of Class I methanol masers exist in the literature, there appear to be no dedicated variability studies on Class I CH_3OH masers. For instance, observations taken in 2012 by Momjian and Sarma [10] suggested changes in the intensity of the 44 GHz Class I CH_3OH masers in DR21(OH) compared to data taken by Araya et al. [1] in 2001.

My project over the summer was to look at the variations in 44 GHz Class I methanol masers in the star-forming region DR21(OH). To do this, I examined data from 2001, 2012, and 2017 observations.

1.4 DR21(OH)

DR21(OH) is a Star forming region that is located 1.5 kpc away [12]. The region itself is Part of the larger Cygnus-X molecular cloud complex [10]. The region is embedded within a filament like structure that is 4 pc in length and stretches across the sky in the north-south direction.

DR21(OH) is a region that is very rich in Class I methanol masers. Figure 2 is a map of the 44 GHz Class I methanol masers in DR21(OH) from the 2017 observations. The figure shows how the masers are aligned in two different arc structures along the east and the west. This is in agreement with the observations presented by Araya et al. (2009). There are two sets of double arcs, one in the east, and another in the west. The masers found in the eastern arcs have more blueshifted center velocities than those found in the western arcs. There are a total of 56 maser spots found in the 2017 observations.

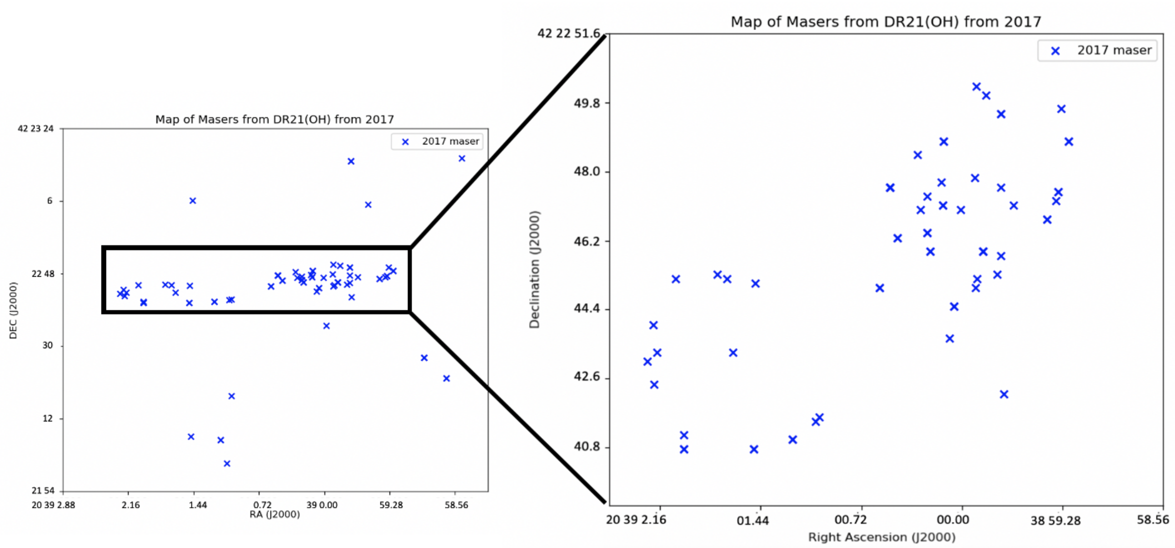

Figure 2: Map of 44 GHz Class I CH_3OH masers in DR21(OH) from 2017 observations. The masers are observed to be arranged in a dual arc structure orientated along the east-west direction.

2 Observations

The observations were taken by Sarma and Momjian in 2017, and the parameters of the observations can be found in Table 1. Some important things to note about the different observations are that all of the observations were taken in the VLA-C configuration, with an average angular resolution of 0.6". The typical rms noise is about 5 mJy for the 2001 data and about 10 mJy for the 2012 and 2017 data.

Most of the summer was spent finding all the masers in the field and fitting Gaussian's to them. Multiple sweeps were done to account for all the masers in the field. The first sweep was to find the strong masers (> 1 Jy b^{-1}) and compare their locations to those found in previous observations to get an idea of how the field compares to previous observations. After the maser locations were compared to the previous observations, a second sweep was conducted to catch the low intensity masers. The masers were fitted using the task XGAUS in AIPS, and the fits were determined by qualitatively assessing the residuals.

Table 1: Parameters for VLA Observation

Parameter	Value
Date	2017 May 24
Configuration	C
R.A. of field center (J2000)	20^h 39^m 00.8^s
Dec. of field center (J2000)	42^o 22' 47.00"
Total bandwith (MHz)	4.0
No. of Channels	1024
Channel spacing (km s^{-1})	0.0266
Approx. time on source	81 min
Rest frequency (GHz)	44.069488
FWHM of synthesized beam	0.58" $\times$ 0.55"
	P.A. = -65.88^o
Line rms noise (mJy beam^{-1})	14

Notes:
The line rms was measured from the Stokes I image cube using maser line free channels.

3 Results and Discussion

3.1 2017 observations

A total of 56 maser spots are found in the 2017 data set. Of the 56 maser spots found, 30 are in the western outflow and 15 are found in the eastern outflow; the remaining 11 are found within 30" north and south of the outflows. The center velocities of observed masers range between -8.5 to +2.5 km s^{-1}, with 37 falling in the range of -3.0 to +1.0 km s^{-1}. The average linewidth (FWHM) of observed masers is 0.469 km s^{-1}, where 0.193 km s^{-1} is the narrowest and 1.587 km s^{-1} is the widest. The intensities of the masers range from 0.08 to 278 Jy b^{-1}, with the majority falling below 10 Jy b^{-1}.

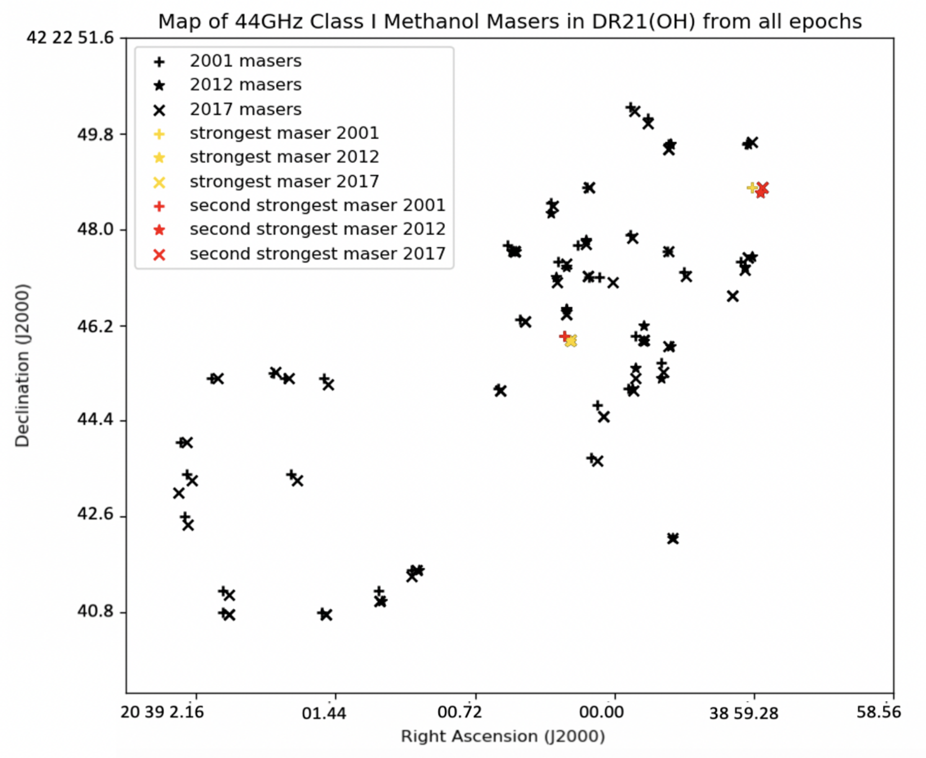

Figure 3: Map of 44 GHz Class I CH_3OH masers in DR21(OH) from all observations. The highlighted masers are color coded so that yellow represents the strongest maser in each epoch, while red represents the second strongest maser in each epoch. The crosses represent the masers from the 2001 data, the stars represent the masers from the 2012 data, and the x's represent the masers from the 2017 data.

When comparing the 2017 data to the other two epochs, 48 of the 49 masers from the 2001 observations are found, as well as all 24 of the 2012 masers. There are 2 potentially new masers found as well.

3.2 2001 vs 2012 Epoch

Between the 2001 and 2012, the two strongest masers in the field flipped in strength. What is meant by that is that the strengths of the two strongest masers in the field changed in a way that switched which was the strongest maser. The original location for the strongest maser in 2001 was the outer western arc as is seen in Figure 3. The second strongest maser was located in the western inner arc about 10" away. This is congruent with observations taken prior to 2001 by Kurtz et al. (2004) [6].

However, in 2012, the opposite is true: the strongest maser now resides in the inner arc while the second strongest maser is located in the outer arc. This is where the observations come in; the strongest maser in the 2017 data also resides in the same place as the strongest maser in 2012 as does the second strongest maser in 2017. What this shows is that the change is not only real, but something must be occurring in order for this change to happen.

Due to the low velocity resolution of the 2001 data, I had to apply velocity smoothing to the 2012 data in order to compare the two. What I found after smoothing is that Maser 1 is 7.7 times brighter in 2012 than in it was in 2001, and that Maser 2 is 1.6 times brighter in 2012 than in it was in 2001, which is evident in the flip I showed previously.

3.3 2012 vs 2017 Epoch

The 2012 and 2017 data had the same velocity resolution and angular resolution, so I can compare their values directly. Maser 1 is 323 Jy in 2012 and 278 Jy in 2017, which is about a 14% dip in brightness. On the other hand, Maser 2 is 219 Jy in 2012 and 198 Jy in 2017, which is a 10% dip in brightness. So what we're seeing between 2001 and 2012 is a change in which maser is the strongest, and what we see between 2012 and 2017 is that the change in 2012 is real, and that the two strongest masers appear to have a slight dip in their overall brightness.

The change in strength coincided with the appearance of an 8 Jy maser in 2012 that wasn't present in 2001. The reason that I'm pointing out this new maser is because it is a very strong maser to have appeared, and it decreases in intensity by 55% between 2012 and 2017. Overall, 18 masers vary in Intensity by greater than 10% from 2012 to 2017. Of those 18, 13 decrease by between 10 and 40% in brightness, 3 increase by 11%, 27% and 51% respectively, which indicates that we are not seeing a systematic shift that would occur due to calibration errors. Lastly, 2 maser decreases by 55% and 65%, which is by more than half their original brightness.

In Figure 4 the maser map of DR21(OH) and I've marked the locations of strongest and second strongest masers in 2017 so that you can see where they are in relation to the new maser that was detected in 2012. This new maser is about half an arcsecond north of the strongest maser in 2012. It's detection happening in conjunction with the sudden increase in intensities of the strongest maser most likely isn't coincidental. It also drops in intensity between the 2012 and 2017 observations by 55%, which suggests that it could be highly variable; it's appearance is most likely tied to the significant increase in the strongest maser in 2012.

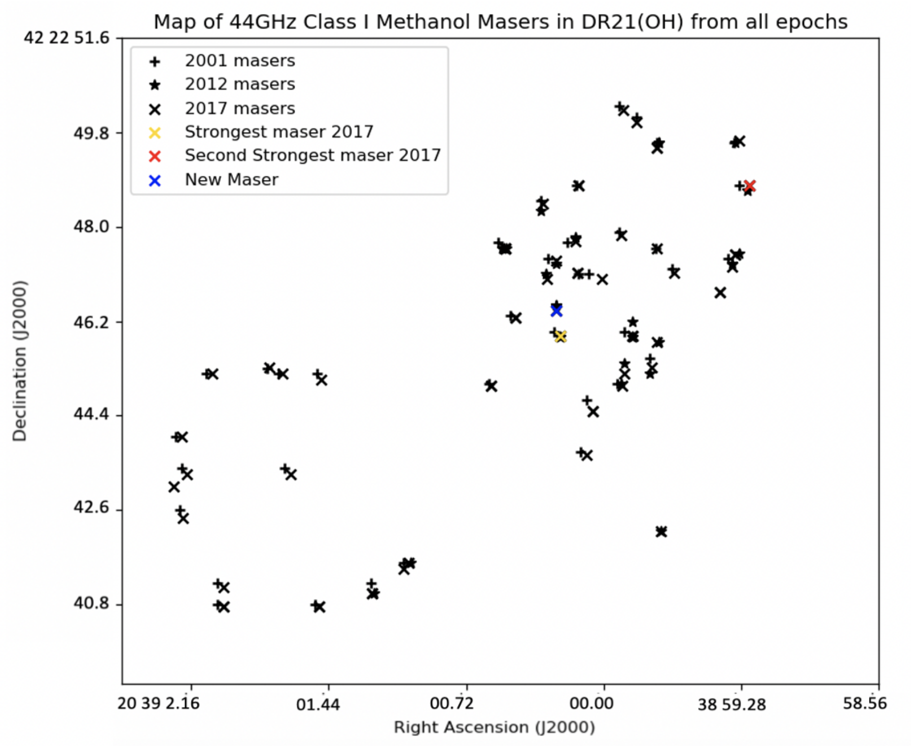

Figure 4: Map of 44 GHz Class I CH_3OH masers in DR21(OH) from all observations. The crosses represent the masers from the 2001 data, the stars represent the masers from the 2012 data, and the x's represent the masers from the 2017 data. The highlighted masers are color coded so that yellow represents the strongest maser in 2017 while red represents the second strongest maser in 2017. The blue maser is the new 8 Jy maser that appears in 2012 and decreases in brightness by 55% between 2012 and 2017.

Acknowledgements

I would like to gratefully acknowledge a Summer Student Research Grant from the NRAO.

References

[1] Esteban D. Araya et al. "Radio continuum and methanol observations of DR21(OH)". In: *Astrophysical Journal* 698.2 (June 2009), pp. 1321–1329. ISSN: 15384357. DOI: 10.1088/0004-637X/698/2/1321.

[2] M. Felli et al. "Water maser variability over 20 years in a large sample of star-forming regions: the complete database". In: *Astronomy and Astrophysics* 476.1 (Oct. 2007), pp. 373–664. DOI: 10.1051/0004-6361:20077804. URL: http://arxiv.org/abs/0710.0790.

[3] B. Sestokas Filho and E. Scalies Jr. "Long term variability of southern hemisphere water masers". In: *Astronomy and Astrophysics Supplement Series* 88 (1991), pp. 177–187.

[4] S. Goedhart et al. "Short-period variability in the Class II methanol maser source G12.89+0.49 (IRAS 18089-1732)". In: *Monthly Notices of the Royal Astronomical Society* 398.2 (Sept. 2009), pp. 995–1010. ISSN: 00358711. DOI: 10.1111/j.1365-2966.2009.15176.x.

[5] J P Gordon et al. "The Maser New Type of Microwave Amplifer, Frequency Standard, and Spectrometer". In: *Physical Review* 99.4 (1955), pp. 1264–1274.

[6] Stan Kurtz et al. "A CATALOG OF CH 3 OH 7 0-6 1 A + MASER SOURCES IN MASSIVE STAR-FORMING REGIONS". In: *The Astrophysical Journal Supplement Series* 155 (2004), 149–165.

[7] S. Leurini, K. M. Menten, and C. M. Walmsley. "Physical characteristics of bright Class I methanol masers". In: *Astronomy and Astrophysics* 592 (2016), pp. 1–22. ISSN: 14320746. DOI: 10.1051/0004-6361/201527974.

[8] Tiege P. McCarthy et al. "The relationship between Class I and Class II methanol masers at high angular resolution". In: *Monthly Notices of the Royal Astronomical Society* 477.1 (May 2018), 507–524. URL: http://arxiv.org/abs/1803.01962https://doi.org/10.1093/mnras/sty694.

[9] K. M. Menten et al. "Methanol in the Orion region. II. The 25 GHz masers revisited." In: *Astronomy and Astrophysics* 198 (1988), pp. 267–273. URL: https://ui.adsabs.harvard.edu/abs/1988A&A...198..267M.

[10] E. Momjian and A. P. Sarma. "THE ZEEMAN EFFECT IN THE 44 GHZ CLASS I METHANOL MASER LINE TOWARD DR21(OH)". In: *The Astrophysical Journal* 834.2 (Jan. 2017), p. 168. ISSN: 1538-4357. DOI: 10.3847/1538-4357/834/2/168.

[11] M Oshe Elitzur. "ASTRONOMICAL MASERS". In: *Annu. ReV. Astron. Astrophys* 30 (1992), pp. 75–112. URL: www.annualreviews.org.

[12] K. L.J. Rygl et al. "Parallaxes and proper motions of interstellar masers toward the Cygnus X star-forming complex: I. Membership of the Cygnus X region". In: *Astronomy and Astrophysics* 539 (2012). ISSN: 00046361. DOI: 10.1051/0004-6361/201118211.

[13] Harold Weaver et al. "Observations of a Strong Unidentified Microwave Line and of Emission from the OH Molecule". In: *Nature* 208.5005 (1965), pp. 29–31. DOI: 10.1038/208029a0.