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ABSTRACT Within deep space are massive molecular clouds and within these molecular clouds, stars form. In these regions of star formation, masers can occur. I studied the presence of water masers within these high mass star forming regions. This was done in order to ascertain whether or not there is a correlation between the intensity of water masers versus the star formation activity within the molecular clouds. My findings provide answers to my specific research questions and includes information on the location of the water masers I observed with the star-forming regions. These findings provide information on water masers and sets the groundwork for further research.

INTRODUCTION

Stars begin their formation within giant molecular clouds in space and inside these regions of star formation, water masers form. An astrophysical maser is defined as a source of stimulated spectral line emission (Gray 1999). These masers are naturally occurring and can be found in multiple locations throughout space, including but not limited to molecular clouds, planetary atmosphere, comets, and stellar atmospheres (Richards et al. 2020). The presence of masers in areas such as these provide a great advantage, because masers are compact and bright sources and thus they allow us to observe these regions at high angular resolution (Moscadelli et al. 2020). Angular resolution refers to the amount of detail that can be discerned in a source. In addition to this, the presence of masers in star-forming regions throughout many stages of the star-forming process allows for consistent observation of said process (Ellingsen et al. 2007).

The goal of my research was to discover whether or not there is a correlation between the intensity of water masers versus the star formation activity within these molecular clouds. Along with my

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pre-existing research goal, I had several research questions. Over the course of my work, I developed these research questions and was able to ascertain answers for them based on my findings in the literature. My questions are as follows: What are the number of observed masers that are associated with an IR source? What is the average distance between a maser and its associated source? How many of the observed masers are located within star forming regions? What are the number of observed masers within the total time frame for which we searched the literature (2006-2020)? What are the structures in which these masers are distributed in star forming regions, and what can they tell us about the process of star formation?

METHODS

A large amount of my work was done by utilizing the NASA Astrophysics Data System (NASA ADS). I used this resource to compile a list of all academic articles written about water masers that were published between 2006 and 2020. However, the years were split into two different sections, 2006-2015 and 2016-2020 and I began searching through the 2016-2020 articles first.

For each article I found, I documented key information such as author, journal in which published, year of publication, page number, and so on. After having done this for both sets of years, I started searching through each individual article for key information. I searched for and made note of any mention of key phrases such as star-forming region, extragalactic, and circumstellar envelope. I then extended my key phrases by searching for and making note of phrases like single-dish and interferometry. After having done that, I made note of the Right Ascension (RA) and Declination (Dec) of the masers mentioned within the article. The RA and Dec of an object are its coordinates in the sky (similar to longitude and latitude, respectively, on Earth).

I needed to search for infrared sources in the areas surrounding these masers, so I took my collected RA and Dec coordinates that I had found in the NASA ADS articles and entered them into the SIMBAD (Set of Identifications, Measurements and Bibliography for Astronomical Data) Astronomical Database. I then searched through the list of nearby sources that SIMBAD gave me in order to find any IR sources with the identifier MSX (Midcourse Space Experiment) or IRAC (Infrared Array Camera) and then made note of the coordinates of those sources.

Now that I had a set of coordinates for the maser and a set of coordinates for a nearby IR source, I had to complete a series of calculations to find the distance between the original maser source and the IR source in arcseconds along with the angular separation between the two points.

I returned to the SIMBAD Astronomical Database to search for other nearby sources that were observed using interferometry. After finding those sources, I searched through the associated academic articles for figures showing the locations of masers in order to ascertain the structure(s) in which these masers form.

RESULTS & DISCUSSION

Based on my search in the literature, I discovered that the field of water maser observations is a very active area. During the period 2006-2020, I found 1606 references to water maser sources in the literature; these are not listed in this paper due to space limitations, but can be made available upon request. Not all of these referred to unique maser sources, however. In many cases, the same water maser source had been observed by different observers with different objectives. For example, some observers would observe a water maser source with a single-dish over several epochs to determine the nature and frequency of the variability of the maser source. Other observers would follow up single-dish observations with an interferometric telescope to map the morphology of water masers in different regions. Still others would observe the masers to measure magnetic fields. Some observed them to figure out their motions in the plane of the sky, so they could obtain a three-dimensional velocity map of the masers.

Given the time frame of the summer project, I decided to focus on a subset of these masers to pursue my research questions. I focused on 55 maser sources that appear to have been observed most frequently. Of these, 23 are individual maser sources, and the other 32 are a collection of masers in a region. By looking in the SIMBAD Astronomical Database, I discovered that all of these were associated with a nearby IR source. I found the average distance between maser and associated IR source to be 0.2328 parsecs. I determined this by adding all the distances I had calculated and dividing them by the total number of distances. The closest distance between a maser and an IR source is 0.07378 parsecs, and the farthest distance between a maser and an IR source is 2.8 parsecs. I then searched for structures in which these masers are distributed in star forming regions. I discovered that water masers are typically arranged in two kinds of structures. They are sometimes found in disks around the protostar. More frequently, they are found in outflows launched from the protostar.

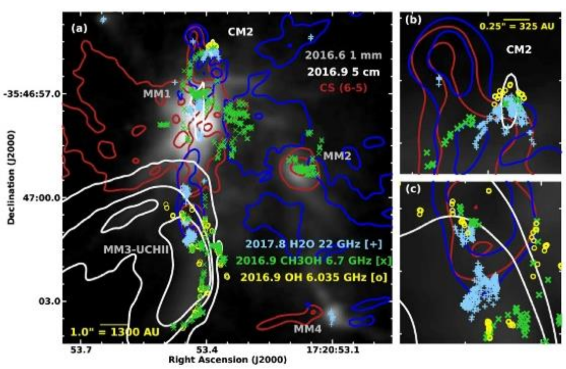

Figure 1. Panel (a) shows a section of the NGC 63341 star-forming region observed by Brogan et al. (2018). Panels (b) and (c) show the presence of water masers in the northern and southern ends of the outflow in this star-forming region.

Figure 1, taken from Brogan et al. (2018) shows forming region known as NGC 6334. Out of such an arrangement in which water masers are present in the outflow regions of the observed star individual masers and clusters of masers associated with IR sources, I discovered that a total of 15 individual masers and 12 maser clusters existed in areas near the center of the star forming region and throughout the star forming region. In addition, four individual masers and nine maser clusters were found in the outflow areas of star formation regions.

CONCLUSIONS

My research has answered several of my individual research questions; in particular, I was able to associate infrared sources with several selected masers and determine the distance between the masers and their associated infrared sources. I was also able to conclude that while some water masers are arranged in disks around the forming protostar, more often they occur in outflows in star forming regions. However, further research will need to be done to answer my primary research goal of whether there is a connection between the intensity of water masers and the star forming activity in their parent cloud. Future work should also focus on the masers that I did not get time to follow up in the SIMBAD database in order to investigate if they are also associated with IR sources. This will give us a better idea of the statistics of association of water masers and IR sources.

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