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Magnetic Field Analysis for Star Forming Region W3 (OH)

Josh Modica
Department of Physics

ABSTRACT Direct measurement of magnetic field strengths is only possible through the so-called Zeeman effect that causes an observable splitting in spectral lines. The star-forming region W3 (OH) contains several water masers, which are used for measuring the Zeeman effect. Matlab routines were created to fit Gaussian profiles in order to determine center velocity, intensity, and line width of each maser. The magnetic field was then determined through another Matlab routine that calculated the Stokes V profile, which was equal to the derivative of the Gaussian profiles.

INTRODUCTION AND METHODOLOGY
Stars form when clouds of hydrogen gas in our Galaxy collapse inward due to gravity. As the star (called a “protostar” at this stage) forming in the center of such a cloud gathers material from its surrounding natal cloud, it also spews out large amounts of material in the form of outflows. It is along these outflows, at the interface of material shocked by the outflow and the ambient hydrogen gas of the cloud, that water masers are formed. Masers are like the lasers encountered in day-to-day situations, except that they operate at microwave wavelengths (Mouschovias 1987). This proposal relates to the measurement of the magnetic field in a star forming cloud with these water masers, specifically in the star-forming region W3 (OH). Getting a sense of the role of the magnetic field in the star forming process is one of the most important tasks in modern astrophysics. Therefore, observations of magnetic fields in star forming regions are important (Crutcher 1977). However, such observations are difficult.

Historically, the spectral lines used to measure magnetic fields have been the lines of atomic hydrogen and the hydroxyl (OH) radical, but both probe only the lower density envelopes of star forming clouds (Sarma 2002). Moreover, the spatial resolution achievable for these lines with existing telescopes (where resolution implies the ability to study detail in an object) is rather coarse. About ten years ago, Sarma (Sarma 2002) demonstrated that water masers could be used to probe the magnetic field in star forming regions at very high spatial resolution. They are good for observing the Zeeman effect because they are very intense and compact. Their compactness means we can observe regions of star formation at very high spatial resolution.

The star-forming region W3 (OH) has been found to contain a number of water masers, which can be used to measure the Zeeman effect, and thereby the magnetic field. However, several of these masers are located very close together in the sky (i.e., within the resolution of the telescope; in other words, the telescope can’t tell them apart). Fortunately, their velocities are different, so their spectral lines show up as shown in Figure 1. In the
instance shown in this figure, five masers are detected as seen by the five peaks in the plot. The plot shows the intensity of the maser (JY/BEAM) along the y-axis and the associated velocities (Km/s) along the x-axis. However, while the spread in velocities at least reveals the presence of the masers, the velocities are so closely spaced that more analysis was required in order to figure out the characteristics of these masers - characteristics such as the center velocities, intensities, and velocity line widths of the masers. In order to resolve this issue, routines were written in Matlab, MAGFIT and GausFitMC, to not only fit Gaussian profiles to the detected masers but to also determine magnetic field strengths of the detected masers. The GausFitMC program was used to fit profiles to all detected masers in the W3 (OH) region that have profiles like those shown in Figure 1. MAGFIT was then written to generate the derivatives of these fitted profiles, and fit them to a so-called Stokes V profile, which is necessary for determining the magnetic field. The Stokes V profile is generated by subtracting the right and left circular polarizations in the observed spectral line and contains information on the magnetic field strength. In this way, the magnetic field traced by each maser can be measured, and a map of the magnetic field in the W3 (OH) region obtained at very high spatial resolution.

RESULTS

Initial magnetic field strengths were calculated from data provided by Steve Merriman (unpublished work towards Steve’s thesis research). The MAGFIT program was initially implemented for calculating the associated velocity leakage, which are impurities in detection that cause higher levels of polarization. These values were needed in order to compute the magnetic field strength. After an initial run through the program, a new leakage corrected velocity profile is created. The MAGFIT program is then rerun with the new corrected velocities using the leakage corrected profile in order to compute the magnetic field strength. Figure 2a-2f shows a sample program run through completion.

The MAGFIT program first prompts user inputs for the data file, the leakage correction value, and the channel spacing. The correction value is set in the program to equal 0 or 1 with each value prompting the program to read in a different data set. For the correction value 1, MAGFIT retrieves the initial dataset and computes the leakage correction value as seen in 2a and 2b. A new velocity profile is created from the second GUI, Graphical User Interface, which also plots the corrected velocity for inspection and physical interpretation. The program is then rerun with the corrected velocity profile and calculates the magnetic field strength. This is the variable A in the final output. In 2f the calculated value of B=0 shows the program correctly used the velocity corrected data and assures an accurate field strength calculation.

For all profiles inspected, the program proved very useful. There were no instances tested in which the program did not work properly. This program was able to operate with multiple masers such as the one provided in Figure 1.

Modifying a previously existing Matlab routine, we created the Gaussian fitting routine using a least-squares fit. The new routine, named GausFitMC1-5, adjusted maser intensity, VLSR (local standard of rest), and line width for each maser. The final number parameter 1-5 dictates the amount of possible masers detected from an initial plot created by the first GUI prompt in GausFitMC. Figures 3a and 3b provide an example of an initial plot for a given data set, and the corresponding results after the fit had been performed.

The routine is designed to handle the Gaussian fitting of one to five peaks. Beyond a five-peak profile, the fitting routine is deemed excessive, since the fit can be calculated with essentially any profile since the amount of free parameters is exceedingly high. The parameters of the fit are provided by the user upon inspection of the initial plot and can be adjusted in order to provide the best fit possible. The user inputs a predicted value for the
line width, center velocity, and intensity and the program fits the data to the Gaussian model.

The program provided exceptionally accurate results. Issues were found to exist when the center velocity was significantly small. Such examples are presented in Figures 4a and 4b. For this example, the data set provided center velocities on the order of 10^{-4} \text{ km/s} causing a significant breakdown in the performance of the Matlab routine.

The initial plot shows a very jagged collection of peaks over an even shorter interval that limits the ability of achieving an elegant Gaussian fit. The program does, however, fit a line to the presented data, even though the residuals for this example show a large discrepancy in the accuracy of the fit. For these types of plots, the routine could not provide accurate, conclusive results.

CONCLUSION

The routines MAGFIT and GausFitMC, created for the research into magnetic field strengths within the star-forming region W3 (OH), provided accurate and reliable results for nearly every task assigned. GausFitMC, in most cases, handled multiple peak data sets as well as single peak sets. The MAGFIT routine was found to be able to handle all types of data and provide a general magnetic field strength corrected for any velocity leakage. Both MAGFIT and GausFitMC were successfully used to analyze data recorded for W3 (OH) to aid in other research collaborations by both Merriman and Sarma. Over fifty datasets were analyzed in total with many more datasets to be analyzed with MAGFIT and GausFitMC on future projects.
Microwave wavelengths

Masers are like the lasers encountered in day-to-day situations, except that they operate at the outflow and the ambient hydrogen gas of the cloud, that water masers are formed. It is along these outflows, at the interface of material shocked by material from its surrounding natal cloud, it also spews out large amounts of material in the star (called a “protostar” at this stage) forming in the center of such a cloud gathers.

Stars form when clouds of hydrogen gas in our Galaxy collapse inward due to gravity. As the observed spectral line and contains information on the magnetic field strength. In this way, the magnetic field traced by each maser can be measured, and a map of the detection. Alternatively, the Stokes V profile is generated by subtracting the right and left circular polarizations in a so-called Stokes V profile, which is necessary for determining the magnetic field.

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Results

Figure 1: Spectra of water masers toward a location in the star-forming region W3 (OH).

Figure 2a provides the initial prompt for MAGFIT. The dataset to be analyzed is identified by the Field, x-pixel, and y-pixel parameters. The leak parameter tells the program whether there needs to be a leakage correction value calculated, and the delnu parameter is the channel spacing, simply radio frequency, of the telescopes.

A plotting function that plots the new data profile created in running 2a and 2b. The Field, x-pixel and y-pixel parameters again tell the program which dataset to read in and Leak correction is the B value from 2b.

FIGURE 1

Spectra of water masers toward a location in the star-forming region W3 (OH).

FIGURE 2A

This figure provides the initial prompt for MAGFIT. The dataset to be analyzed is identified by the Field, x-pixel, and y-pixel parameters. The leak parameter tells the program whether there needs to be a leakage correction value calculated, and the delnu parameter is the channel spacing, simply radio frequency, of the telescopes.

FIGURE 2B

Displays the output from running 2a. The only current value of interest is B, which is the velocity leakage correction parameter. Sigb is the error in B. Other values given A and siga will be defined in 2f.

FIGURE 2C

A plotting function that plots the new data profile created in running 2a and 2b. The Field, x-pixel and y-pixel parameters again tell the program which dataset to read in and Leak correction is the B value from 2b.
Figure 2e is a rerun of 2a with the only change in the leakage value. This change in value tells the program to now calculate with the new leakage corrected data set.

Figure 2f is the final output of MAGFIT. A is the magnetic field strength; siga represents the error in A. Just as in 2a, we only use two of the four calculated values.

The MAGFIT program first prompts user inputs for the data file, the leakage correction value, and the channel spacing. The correction value is set in the program to equal 0 or 1 with each value prompting the program to read in a different data set. For the correction value 1, MAGFIT retrieves the initial dataset and computes the leakage correction value as seen in 2a and 2b. A new velocity profile is created from the second GUI, Graphical User Interface, which also plots the corrected velocity for inspection and physical interpretation. The program is then rerun with the corrected velocity profile.

Figure 2d shows the right and left polarization after the leakage correction. This is simply a visual aid to determine the accuracy of both the program and data. The 0 line is the center with above and below the line being right and left polarization respectively.

**FIGURE 2D**

Shows the right and left polarization after the leakage correction. This is simply a visual aid to determine the accuracy of both the program and data. The 0 line is the center with above and below the line being right and left polarization respectively.

**FIGURE 2E**

2e is a rerun of 2a with the only change in the leakage value. This change in value tells the program to now calculate with the new leakage corrected data set.

**FIGURE 2F**

2f is the final output of MAGFIT. A is the magnetic field strength; siga represents the error in A. Just as in 2a, we only use two of the four calculated values.

\[
\begin{align*}
A &= -91.3286 \\
B &= 0 \\
siga &= 2.7657 \\
sigb &= 8.0157e-05
\end{align*}
\]
MAGNETIC FIELD ANALYSIS FOR STAR FORMING REGION W3 (OH)

This calculates the magnetic field strength. This is the variable $A$ in the final output. In $2f$ the calculated value of $B=0$ shows the program correctly used the velocity corrected data and assures an accurate field strength calculation.

For all profiles inspected, the program proved very useful. There were no instances tested in which the program did not work properly. This program was able to operate with multiple masers such as the one provided in Figure 1.

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**Figure 3a**
Displays an initial plot of a 4-component maser. The y-axis is the maser intensity and the x-axis is the maser central velocity.

**Figure 3b**
Shows the completion of a fitting routine. The amount of iterations is provided to see how many free parameter adjustments where calculated by the program. The program also provides $I$ or maser intensity, $V_{\text{LSR}}$ or central velocity, and $\Delta V$ or line width of the Gaussian fit.

**Figure 4a**
Displays the initial plot for a separate data set where clearly the central velocities are significantly smaller than previous data. These values.

**Figure 4b**
Shows an inability of the routine to perform a Gaussian fit to extremely small center velocities. The plot, although converging, carries a large variation displayed in the residuals, which is the green plotted line.
REFERENCES

