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Determining Kinematics of H2O Found In Orion SrcI

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ABSTRACT

The Orion Source I protostar, located in the Orion Nebula, is a well-known object of study due to its complex kinematics and role in star formation processes. In this study, we investigate the rotational, radial, and outflow velocity components associated with the H2O content in the protostar using observational data from the Atacama Large Millimeter Array obervations. By taking position-velocity cuts through a data cube containing 33 velocity channels we were able to determine the three components. The rotational velocity was found using a cut across the major axis through the disk and returned a result of $13.65 \pm 1.02\,\mathrm{km/s}$. This is important when looking into the specific angular momentum of the system. Using parallel cuts to the major axis we were able to find the relation between the radial velocity to the vertical distance from the disk. The result was mostly constant with a value of $9\,\mathrm{km/s}$ which provides insight into the motion of Orion Source I relative to the surrounding molecular cloud. Lastly using these two combined components the velocity along the outflow is also possible to be determined and gives us a value of $45.5 \pm 10.2\,\mathrm{km/s}$. This provides a deeper understanding into the mass ejection process. The results in this paper contribute to the total knowledge of the kinematics in the protostar system. With all this information it becomes easier to find deeper understandings governing star formation and the evolution of protostellar systems throughout the universe.

1. INTRODUCTION

The Orion Kleinmann-Low region of the Orion Nebula is the closest region for observation of massive star formation sitting at a distance of 400 parsec away. Within this region there is an observed young stellar object (YSO) named Orion Source I (SrcI). The observations of this YSO show a prominent disk and perpendicular jet outflow containing several molecules.

Currently there are 4 major molecules found in the disk and outflow of Orion SrcI. NaCl is found solely in the disk accreting around the center, SiO as well as SiS are also observed to be mainly in the outflow. H2O is the last observed gas and it is found sitting in the disk and also extending into the outflow but not as far as the other molecules reach.

We follow Hirota in his 2017 paper Hirota et al. (2017) as he models Orion SrcI as cylindrical disk with the outflow working as a cone with its circular bases pointed outwards. If we observe the coordinates in cylindrical coordinates this lets us develop 3 velocity components at each position of the model. First is the radial velocity which comes from the speed at which the disk or outflow moves outwards radially from the disk. Second is a rotational velocity which would represent the motion in the ϕ direction. Finally we have the outflow velocity which comes from the movement in the z direction.

Equations 1 and 2 accounts for the inclination of the observed body. The first equation describes the line of sight velocity along the outflow while the second describes along the outflow axis. The determined inclination used in these calculations is determined by a paper by Ginsburg et al. (2018)

$$v_{los} = v_r \sin(i) + v_z \cos(i) \tag{1}$$

$$v_{los} = v_\phi \sin(i) + v_r \sin(i) + v_z \cos(i) \tag{2}$$

In this report we analyze the collected intensity data of H2O found in the protostar disk and perpendicular jet outflow in order to determine the 3 separate velocities. The information on the data file used is found in §2 and the process followed with this data can be seen in §3. Following we analyze the information in §4 before finally determining our results in §5.

2. DATA

The data for the work in this paper comes from the Atacama Large Millimeter/Sub-millimeter Array making observations at approximately 30-50 mas resolution. All image data map molecular outflow and disk of Orion

SrcI on scales of about 12-20 AU. The H2O data is in the form of a fits file and the continuum was subtracted from the data before any analysis. The data is set up in a 4-dimensional intensity array with dimensions right ascension, declination, velocity, polarization. Data is centered on the sky coordinates $(83.8^o, -5.38^o)$. There are 33 velocity channels with separation of 2 km/s giving a range of -32 km/s to 32 km/s. Lastly there is only one polarization channel which was not included in the analysis.

3. METHODOLOGY

We assume a simple shape for the structure of the protostar with a circular disk and a circular cone for the outflow on both ends. This idea is taken from Hirota in which he describes in his paper Hirota et al. (2017). In order to find these values we followed the process of taking Position-Velocity (PV) cuts through the data cube along certain lines to find best fits for the velocity at those locations.

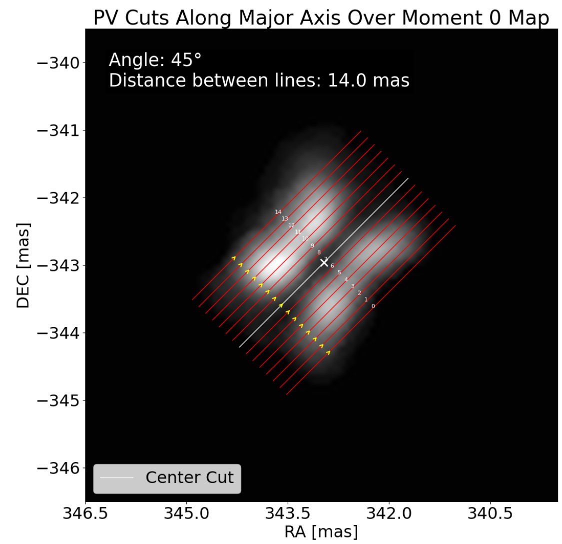
3.1. *Rotational Velocity*

By taking the following cuts along the direction of the major axis I am able to determine the rotational velocity in the disk. Figure 1 below depicts the Moment 0 map of the data with a series of PV cuts made at varied z values as well as the PV associated with the center line. By using this center PV cut we are able to plot out the 2D data and take the 2 peaks in the data. Since water in the disk is found more on the outer regions the velocities determined here should be a good estimate of the rotational velocity.

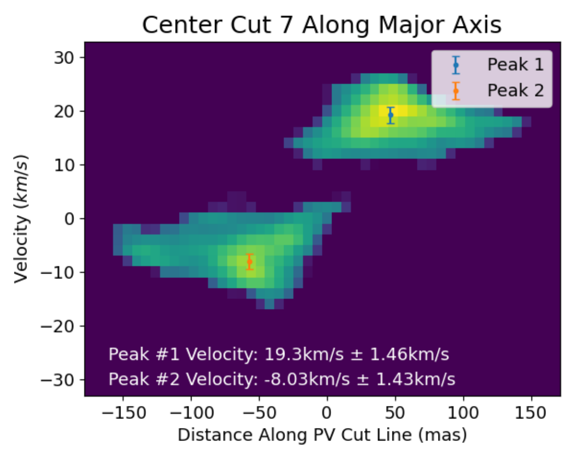
The raw peaks are not the best indication of the exact value and so we apply a weighted fit to the peak. This helps to find a more accurate result which is smoothed out. Upon applying this function, the peaks found now tell the velocity of the H2O gas found at a found distance from the center of the disk. This gives us the rotational velocities we are looking for. The average taken of the two returned values then gives us the best approximation of this value.

3.2. *Radial Velocity*

The radial velocity is next and it varies with the z distance. In order to find it we will use the same PV cuts except rotated to be perpendicular to the major axis. The lines all have a length of 350 mas and so at the 175 mas location that is where we can best determine the radial velocity as the influence of the outflow and rotational velocity impact is minimal. Figure 2 shows how the cuts were set up. To better smooth the result a slice of range 35 mas is made based at the center.



(a) PV Cuts Across Moment 0 Map



(b) Center PV Cut

Figure 1: Image (a) shows the Moment 0 map of the data with 15 PV cuts along the major axis. Each line is set 350 mas long at an angle of 45 degrees across the image. The center line indexed at 7 gives our best estimate of the rotational velocity as it is set to the position $z = 0$ AU. In (b) the 2D PV cut data for the center cut is shown. There are two distinct peaks shown and using the maxfit process the velocity and distance from the center of these peaks are found.

Section 6 Figure 5 shows an example of these slices. This is used and the peak velocity in that range is used as the velocity in the radial direction for that corresponded z distance. Using Equation 2 and ignoring the influence of the outflow we can get our velocity results for the radial direction and that is plotted in Figure 3.

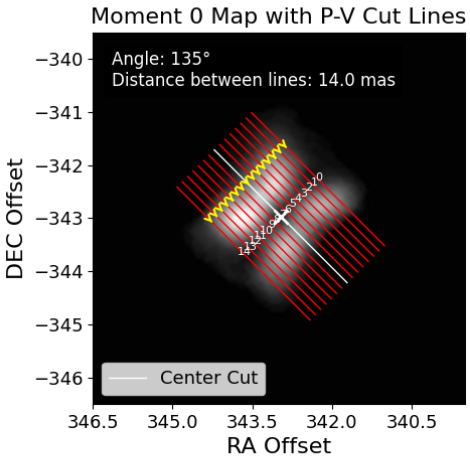


Figure 2: Moment 0 map of the data with 15 PV cuts made perpendicular to the major axis. Each line is 350 mas long with an angle of 135 degrees across the image.

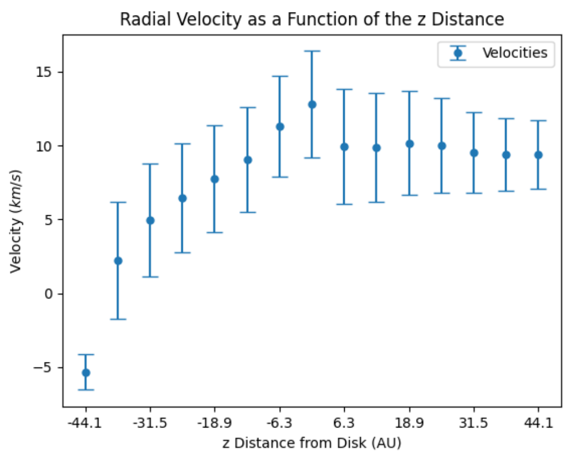


Figure 3: Above shows the correlation between the z axis and the radial velocity component of the jets. There appears to be stability around the 9km/s area especially as viewed from the positive z values.

3.3. *Outflow Velocity*

Lastly we are left with solving for the outflow velocity. In order to do that we take the PV cuts along the edge of the outflow. This is much more difficult as it is hard to determine a good positioning for these cuts to maximize the accuracy of our results. A determined edge point is found based on the Moment 0 map for both sides of each outflow and then four more cuts are made parallel to each with a separation of 7 mas. Figure 4 shows the four sets of cuts all labelled with different colours. Using these cuts again and following the same fitting process for each cut, an average is taken and that determines the line of sight for that outflow edge. Using Equation 2 with our known values for the other two components we now can determine the outflow velocity.

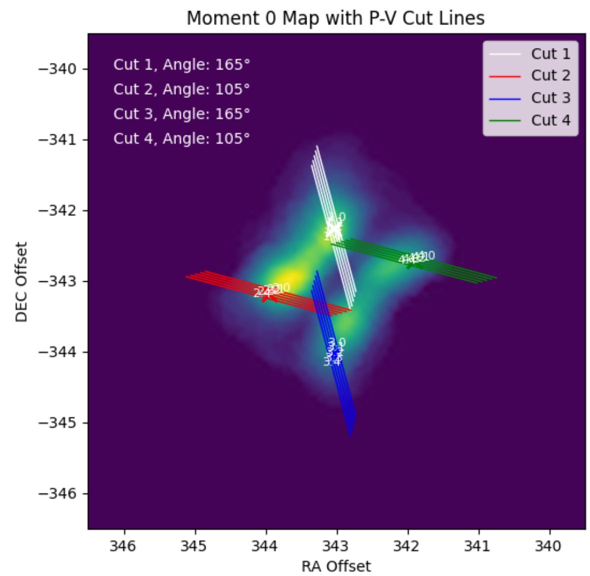


Figure 4: The above figure shows the PV cuts made along the edge of the outflow. Each of the four sides is coloured and labelled allowing us to find the velocity at each of the 4 points.

In order to determine the uncertainty in our values we started by taking the full width half max (FWHM) of each peak. This assumes the peaks are Gaussian in shape which is not true for most peaks but the difference is considered negligible in this paper. The conversion follows that the FWHM is related to the uncertainty (σ) by the relation in Equation 3.

$$\sigma = \frac{FWHM}{2\sqrt{2\ln 2}} \tag{3}$$

All work done to determine the values for the velocities is kept in a GitHub page labelled in the Appendix, Section 6. This contains all the data files used as well as all the code which developed the results. Figures and plots are also contained in the repository for comparison.

4. DATA ANALYSIS

For confirmation of the values found using our methods we compare the results to known answers of the other 3 molecules. The easiest and simplest to compare is NaCl since it is only found in the disk meaning we look at the rotation velocity in the disk. When a similar PV cut was taken for NaCl in the disk they found returned values of 18km/s on one end and -6km/s on the other. This is very similar to the values returned for water which were $19.27\,\mathrm{km/s} \pm 1.46\,\mathrm{km/s}$ and $-8.03\,\mathrm{km/s} \pm 1.43\,\mathrm{km/s}$. These rotations have one end moving away and another moving towards us. Thus taking half the difference of the two values gives us $13.65 \pm 1.02\,\mathrm{km/s}$ as our rotational speed.

Plots made for the collected data of NaCl are available in the appendix for comparison. The slight deviation in rotational speed for the H2O and NaCl can be determined as simple measurement uncertainties but it can be noted that H2O is found to be closer into the disk compared to NaCl meaning the radial distance from the center is different for the two gases. Plots from the NaCl data are added into Section 6.

Looking at the Hirota paper where he analyzes the radial velocity of $Si^{18}O$ he determines it to settle around 8-10 km/s. Following to that we check our data as visualized in Figure 3 we determine an average result of 9km/s for the radial component. However the uncertainties and error bars make determining the validity of the results difficult.

Lastly we make the comparison of the outflow velocities. Table 1 shows the results of the cuts made in Figure 4. We needed to apply Equation 1 which requires including the inclination angle. According to Ginsburg et al. (2018) the inclination is 82.5 ± 2.5^o.

Outflow Edge	**Outflow Velocity**
White Peak	$20.9\,\mathrm{km/s} \pm 14.6\,\mathrm{km/s}$
Red Peak	$63.2\,\mathrm{km/s} \pm 24.9\,\mathrm{km/s}$
Blue Peak	$48.7\,\mathrm{km/s} \pm 21.1\,\mathrm{km/s}$
Green Peak	$49.3\,\mathrm{km/s} \pm 19.3\,\mathrm{km/s}$

Table 1: The collected velocities in the z-axis of the 4 outflow edges. Refer to Figure 4 to correlate the peaks to the outflow edges.

5. DISCUSSION & CONCLUSION

When finding the radial velocities there is the noticeable trend in the negative z values. This issue arose during calculation but nothing that was done found this trend to change. This could be an implication of the fact that Orion SrcI is moving through nebula gas at fast speeds and the outflow on that end is experiencing drag through the medium. This idea is not confirmed and it is more likely that a better method of calculation could be used to give more accurate results. Since the positive z-axis returned results that matched with Hirota et al. (2017) we decided the method does represent correct velocities just loses credibility on the opposite side of the disk.

Currently there is no method for updating the inclination value and so with the accuracy we have there is wide uncertainty we cannot alter. In our calculation of the outflow velocities there is a sin / cos term which gives an error of 33% itself. If there is a way to determine a more accurate inclination angle this would help to give a better estimate of the outflow speeds. This is easier said than done and it is not expected that results are found with very powerful precision.

6. APPENDIX

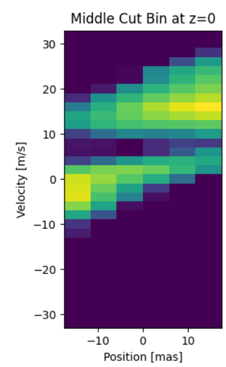


Figure 5: Sample binning strip used for finding radial velocity of the middle line strip at z=0

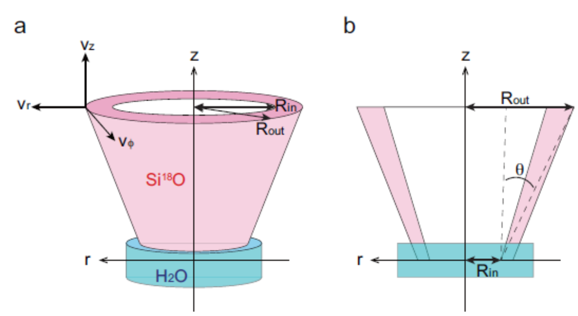


Figure 6: Hirota model of the disk and outflow. Water is found in the outer regions of the disk and also follows up the outflow as well.

REFERENCES

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