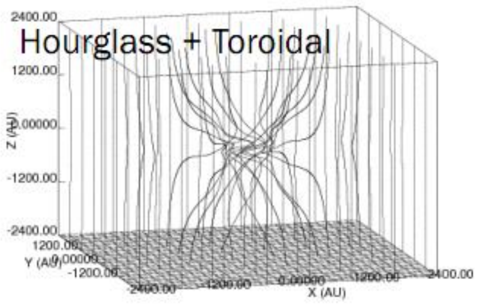
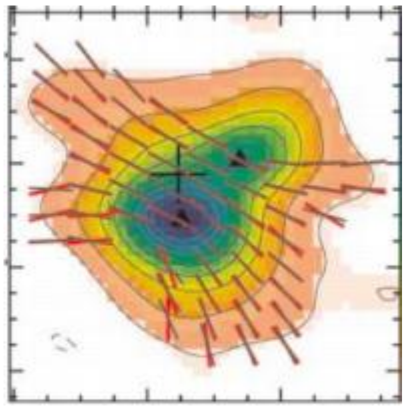
Introduction

Interstellar magnetic field is believed to play a vital role during gravitational collapse of molecular cloud cores in YSO formation theory. The key is to understand how the magnetic field drives the bipolar outflow, which takes out the extra angular momentum. Thus, it is of great importance to study the detail structure of magnetic field. In my work, I mainly focus on getting magnetic field structure from scales comparable to the core size to scales small enough to resolve the two binary class 0 sources and finding polarization signals systematically by investigating the visibility data.

Theory

There are two major questions needed to be answered in the theory of star formation. One is to understand what mechanics support the gravitational collapse in molecular clouds. The other is how to transfer excess angular momentum from a developing star. One of the most possible candidates is magnetic field, which supports the cloud from its own gravity and drive bipolar outflow to get rid of excess angular momentum. Though the exact interplay of magnetic field in YSO formation under the swept of turbulence is not known, there are a few MHD simulations show that under certain assumptions, they can generate results similar to observations. The simulated model generated a roughly hourglass magnetic field shape. The observation on NGC1333 IRAS4A is the typical type to date that match the hourglass shape. The left figure below shows a MHD simulation that shows hourglass and toroidal magnetic field component and the right figure below shows the hour-glass field observation on IRAS4A by Girart et al.



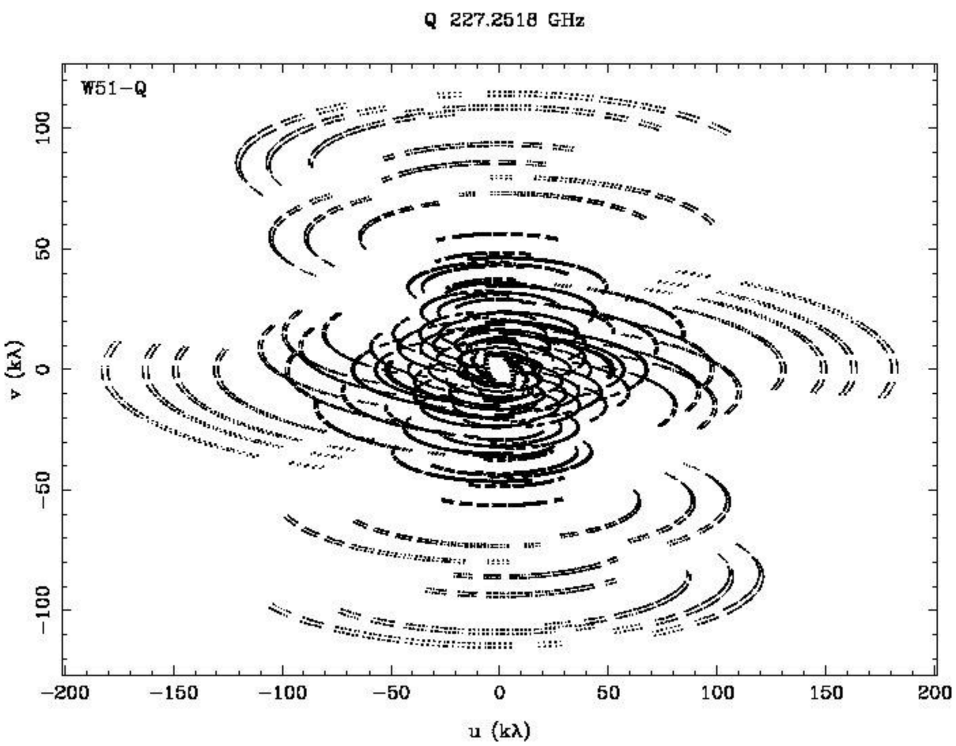


The observation is done by dust polarization. It is the most common way to detect magnetic field. The dust grains are aligned perpendicular to local magnetic field in molecular cloud, so for emission spectrum in this case, the emission light would have linear polarization along the dust grain, that is, perpendicular to the magnetic field. Combining the information of polarization magnitude, polarization percentage and polarization angle, the method can give a indication for local magnetic field direction and strength. However, the method only can show directions on the plane of the sky and cannot give us the exact power of the field strength.

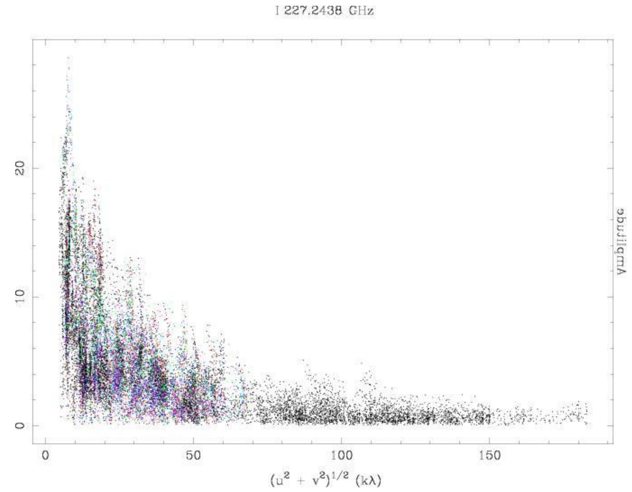
The IRAS4A observation is a wonderful match to the theory. Many observations of the other sources don't show clear hourglass shape and that the detail structure such as toroidal field are not detected. Also, the dust polarization signals are integrated in the line of sight, so not only can't we get the 3D structure, some small structure signals are averaged out and hard to show. Thus, in order to get the whole picture of magnetic field structure, we need to inspect polarization maps at different scales and find a systematic way to find small scale polarization signals. My data are two reduced BIMA data each contains 26 tracks on W51 and DR21OH. The spectrums are both smoothed, so only continuum component available. I will show the different scale mapping of magnetic field in the following sections.

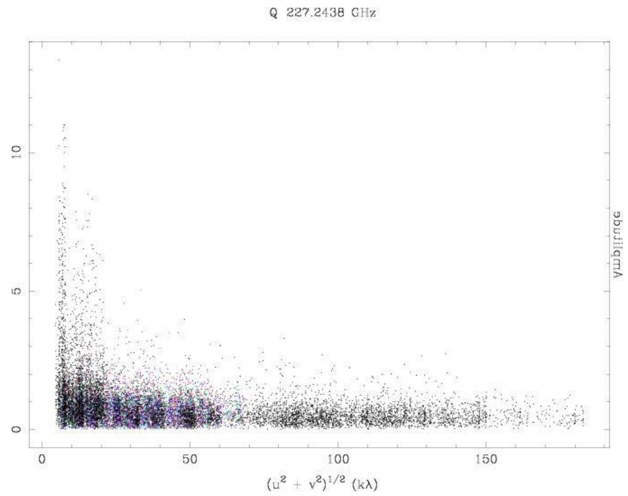
Method

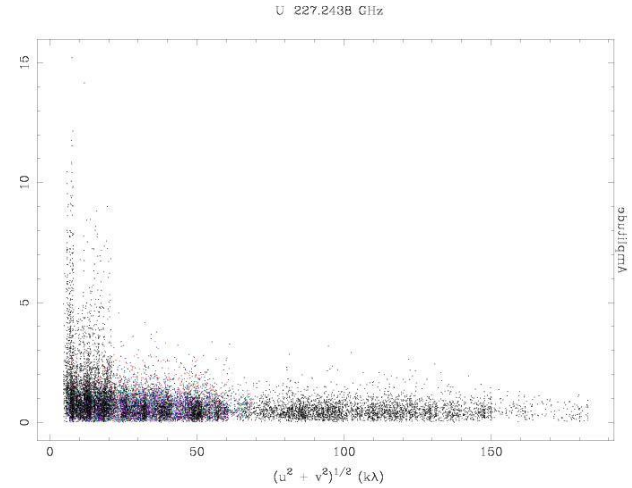
The dust polarization maps are constructed by I, Q, U maps. I correspond to total continuum intensity while Q and U store linear polarization information. The common way to map the magnetic field is simply invert the whole visibility data hoping to level up signal to noise ratio. However, sometimes the small structure polarization would not shown because it is averaged in the line of sight. One way to separate the small scale structure is to do mapping at different uv-distance. The figure below is the Q sampling function (UV coverage) of W51 data.



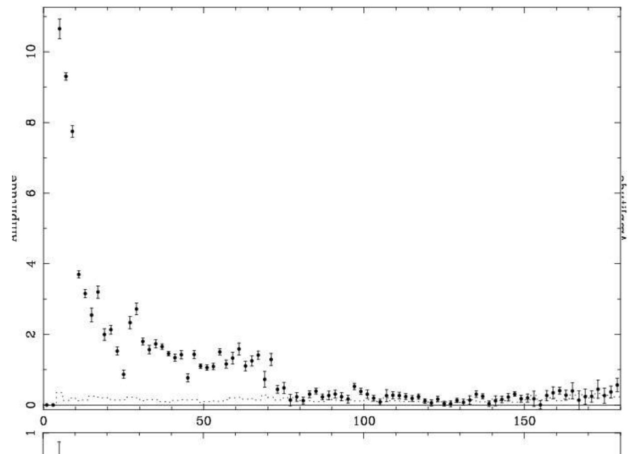
In the upper figure, each pair of curved line correspond to one baseline projected on to the sky plane. The longer baselines are curved lines with longer uv-distance ($\sqrt{u^2+v^2}$) which means higher resolution visibilities and provide more detail structures. On the contrary, short baselines give larger scale signals. The three figures below shows I, Q, U visibilities of W51. The y-axis is amplitude and the x-axis is uv-distance.

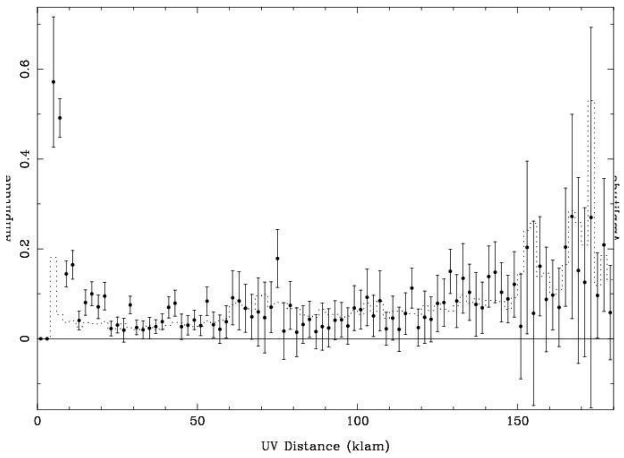


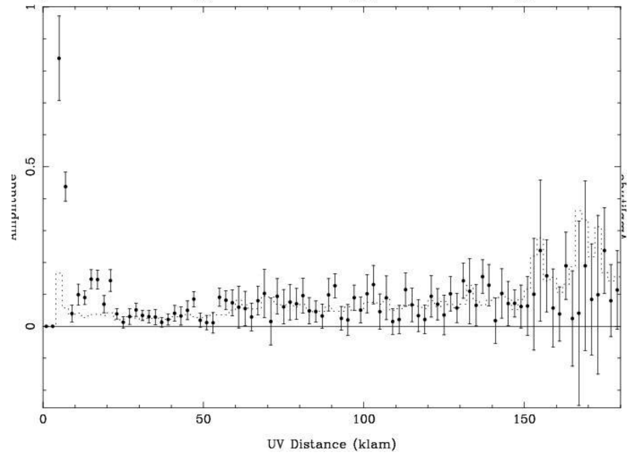




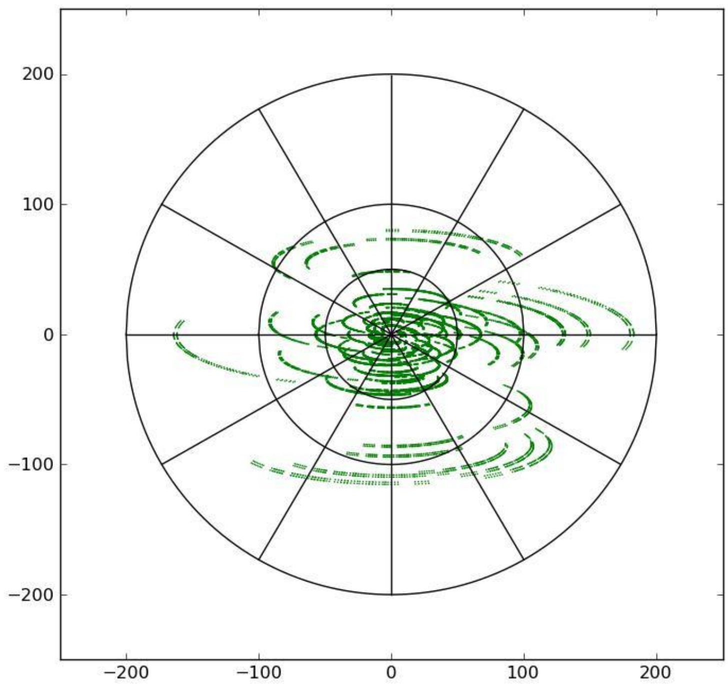
The amplitude of all three fade as the uv-distance gets higher. This is common that most of the signals lie in the larger scale which covers the small structure from us. The next three figure below shows averaged uv-distance in 2 kλ to amplitude. The dotted lines are the estimated noise level and the black dots are the integrated amplitude with uncertainties.





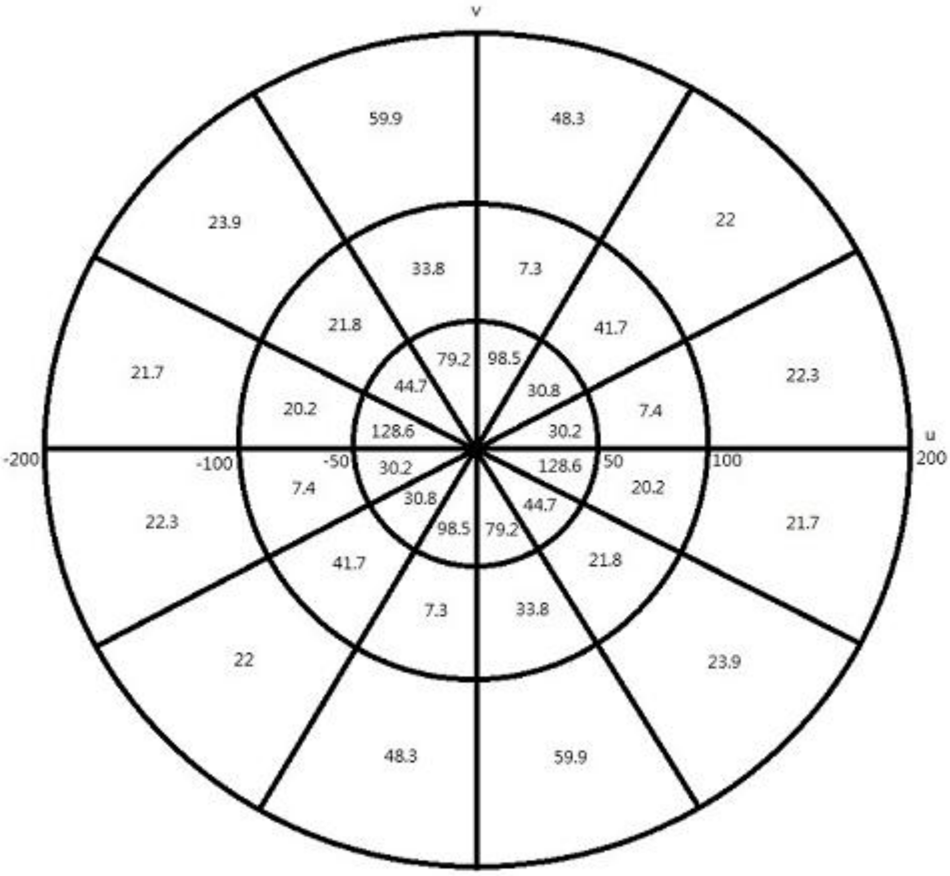


For I map(upper left), there is strong detection under 70 kλ that the visibility is much higher than the noise level. The Q map(upper right) and U map(left) show most of the polarization detections are under 20 kλ. At larger uv-distance, the noise level for Q, U is elevated and the uncertainty is larger, so it is hard to say if there is any polarization signal lying inside these scales. It is possible that even there are polarization signals in smaller scales, the above diagram wouldn't show obvious uplift of detection because the figure only shows averaged visibility. Each black dot shows the averaged value of the polarization detected signals with the other undetected data points at the similar scale (2 kλ interval). One possible method to identify polarization signals at visibility is to cut the uvcoverage with polar coordinate and see which region gives higher average amplitude. As shown in the figure below, the data points are separated into three scales (0~50 kλ, 50~100 kλ, 100~200 kλ) and 12 angle intervals (30 degree each). This gives us 36 regions. Note that the green points only show each symmetric baseline pair as one point, so the whole sampling function points should be twice as much and is point symmetric along the original point.



The mapping is done by invert Fourier transforming the visibility data (green points). So the higher uv-distance corresponds to higher spacial frequency which means smaller scale structures. The different angles on the uv plane means different spacial wave direction. Combining (u, v), amplitude(signal strength) and phase(wave shift), this gives us total mapping information.

Result



The upper figure shows the average visibility amplitude in each region. The unit is in mJy. The values are symmetric along the original point. Different regions, though lie in the same scale, may have largely different value. For example, the inner regions (0~50 kλ) range from 30mJy to 128mJy. The higher regions may indicate polarization signals embedded inside. Frankly speaking, larger scale regions give higher average values, but there are still small scale regions exhibit values over 50mJy. The average amplitude values are done simply by complex number averaging, as shown by the equations below.

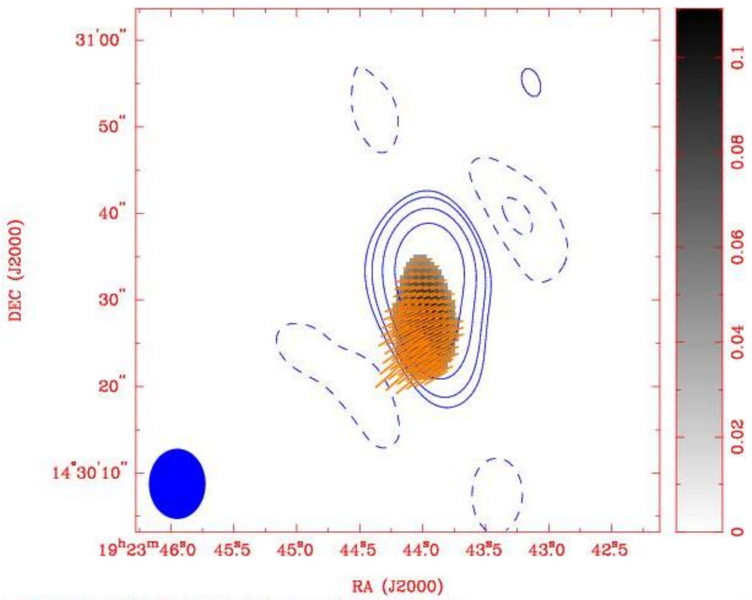
$$\bar{A}e^{i\bar{\theta}} = \frac{\sum A\cos\theta}{n} - i\frac{\sum A\sin\theta}{n} = a - bi$$

$$\bar{\theta} = \tan^{-1}\left(\frac{b}{a}\right) \qquad \bar{A} = \frac{a}{\cos\left(\bar{\theta}\right)} = \frac{b}{\sin\left(\bar{\theta}\right)}$$

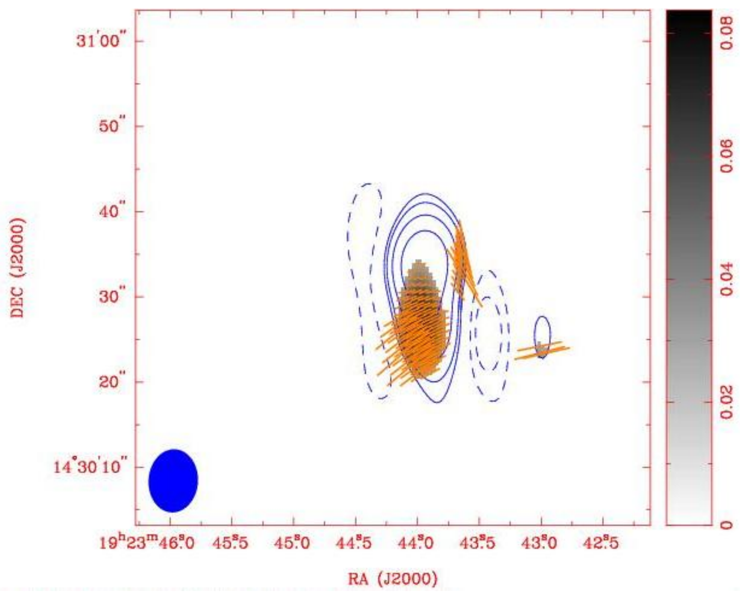
The different scale mapping of magnetic field will be shown below. Containing mapping of W51 with scales from 0~23 kλ, 10~23 kλ, 23~70 kλ and 70~110 kλ, and DR21OH from 0~22 kλ, 10~40 kλ and 22~60 kλ.

W51:

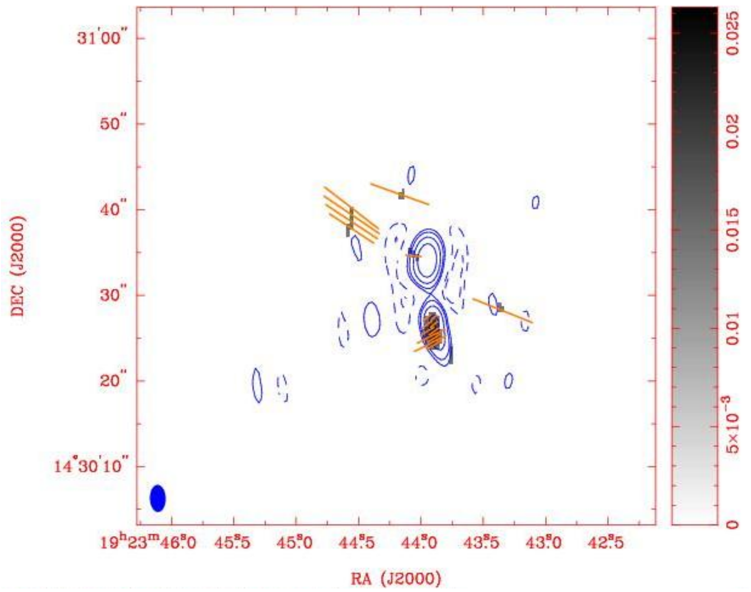
1. 0~23 kλ:



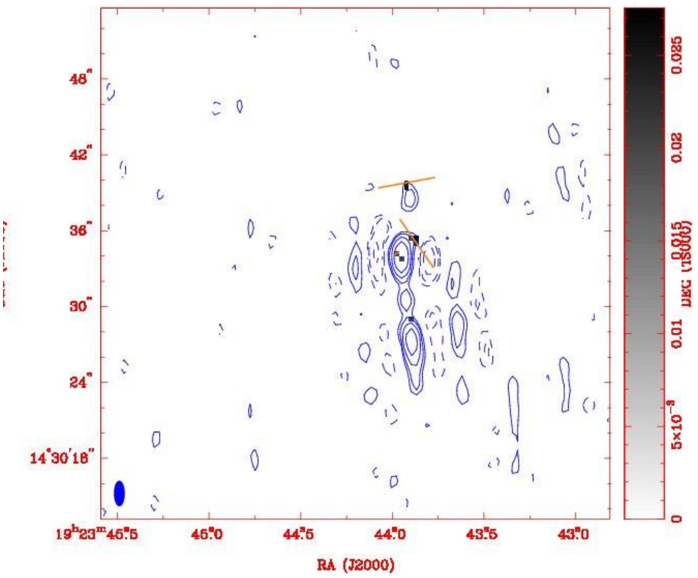
2. 10~23 kλ:



3. 23~70 kλ:



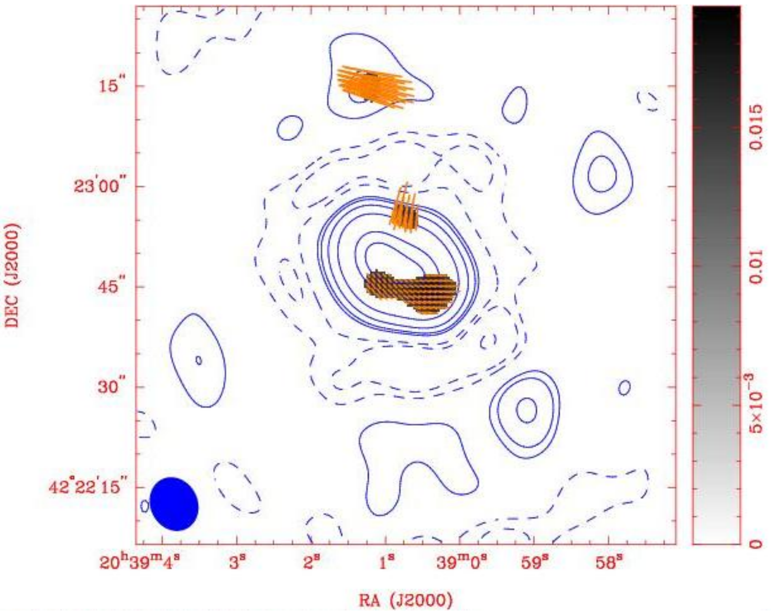
4. 70~110 kλ:



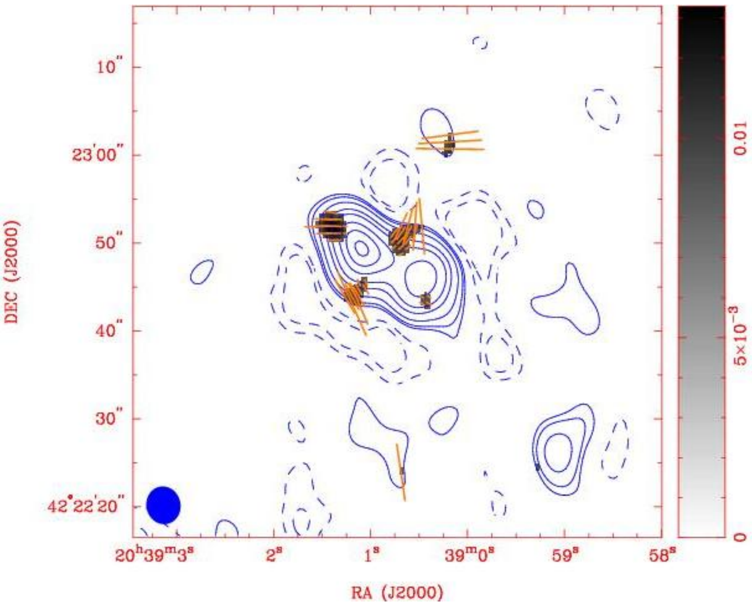
Comparing with the beam, the large scale structure (0~23 kλ) couldn't resolve the two components inside the core while the smaller scale structure do show clear two components. The orange lines is polarization angle rotating 90 degree which represents magnetic field direction. The length of the line means polarization fraction ($^{magP}\!/_{magI}$) and the grey scale means polarization magnitude ($magP$). The main magnetic field lies in the southeast side of the core and is slightly bent as entering the core. The 10~23 kλ map shows magnetic field at the northwest side of the core roughly perpendicular to the main magnetic field. This smaller field is not shown in the first map. The blank stripe between the northwest magnetic field component and the southeast main field may indicate that there is a turn in magnetic field direction in the region. At smaller scales (over 23 kλ), there are not much detection. However, there are still some weird polarization signals at the edge of the core which the larger scale maps didn't show. These signals need further investigation.

<u>DR21OH:</u>

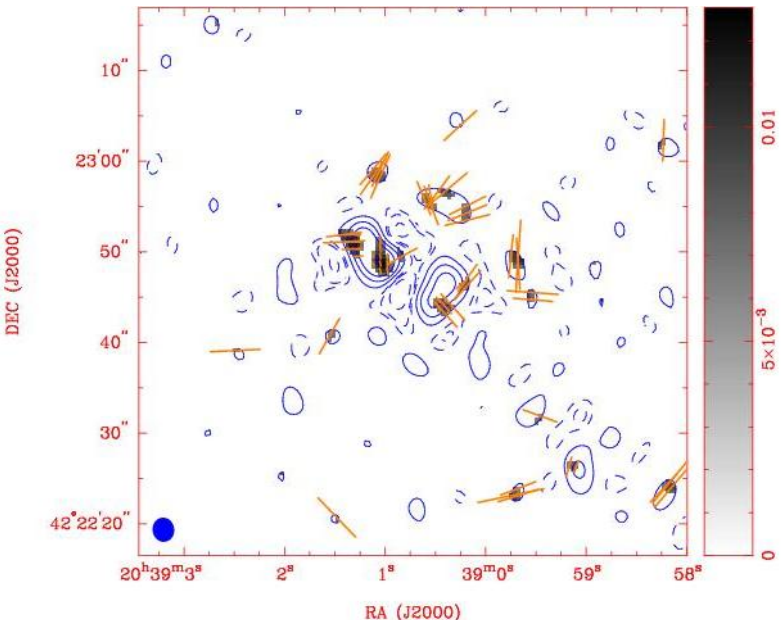
1. 0~22 kλ:



2. 10~40 kλ:



3. 22~60 kλ:



The large scale map couldn't resolve the two sources while smaller scales (2nd and 3rd map) can. The extended main field shown in the 1st map lies at the southern part of the core and is also changing direction slowly from east to west. The blank region at the center of the core may indicate the turn of field direction toward the northern part of the more compact field. Note that there is a weird strong polarization detection lie outside the northern part of the core. This strong polarization detection is not shown in other scales which make this detection more suspicious. At the smaller scales, the magnetic field does not show obvious trend. The 3rd map shows that there is not a single strong field but several weak fields perpendicular to each other. This may be toroidal field component but we cannot be sure from this weak detection and also the trend is not that obvious.

Summary

My work primary lies on finding different scale polarization signals by investigating visibility data and mapping of magnetic field of different scales. To invent a way to systematically identify polarization signals at visibility, I need to cut the uv-distance into smaller ranges. For example, like 10 kλ. This enables me to identify the higher average amplitude with more precision. However, with the different scale mapping I showed previously, the magnetic field strength and direction changes dramatically at different scales. This tells us that there is different field structure at smaller scales which is still not identified. It needs further investigation to show that the method really can identify polarization signals at specific scales. The final goal is to construct the overall structure of magnetic field and understand its influence to the core structure or the mechanics of the outflow.