



# The Role of Magnetic Fields in Shaping Molecular Clouds

Krittika Computational Astronomy Projects 2023

**Debasish Panda**

21D070021

Mentor : Tamojeet

Krittika, The Astronomy Club  
Indian Institute of Technology Bombay

# Contents

1	Introduction	2
2	Observational Probes of Magnetic Fields	3
3	The Planck Mission	4
4	Methodology	7
5	Results	13

# 1 Introduction

Molecular interstellar clouds, composed primarily of hydrogen gas and dust, play a crucial role in the formation of stars and planetary systems. Understanding the magnetic field structure within these clouds is essential for unravelling the complex processes governing star formation. This project delves into the theory of analysis of these molecular clouds and how they result in the formation of structures within the molecular cloud. We will verify the correlation between gas column density and orientation of the magnetic field in the cloud in the case of several different regions in the sky captured by the Planck mission. We will arrive at a 'Histogram of Relative Orientation' used for correlation purposes. This project is based on a paper released by the Planck collaboration back in 2015.

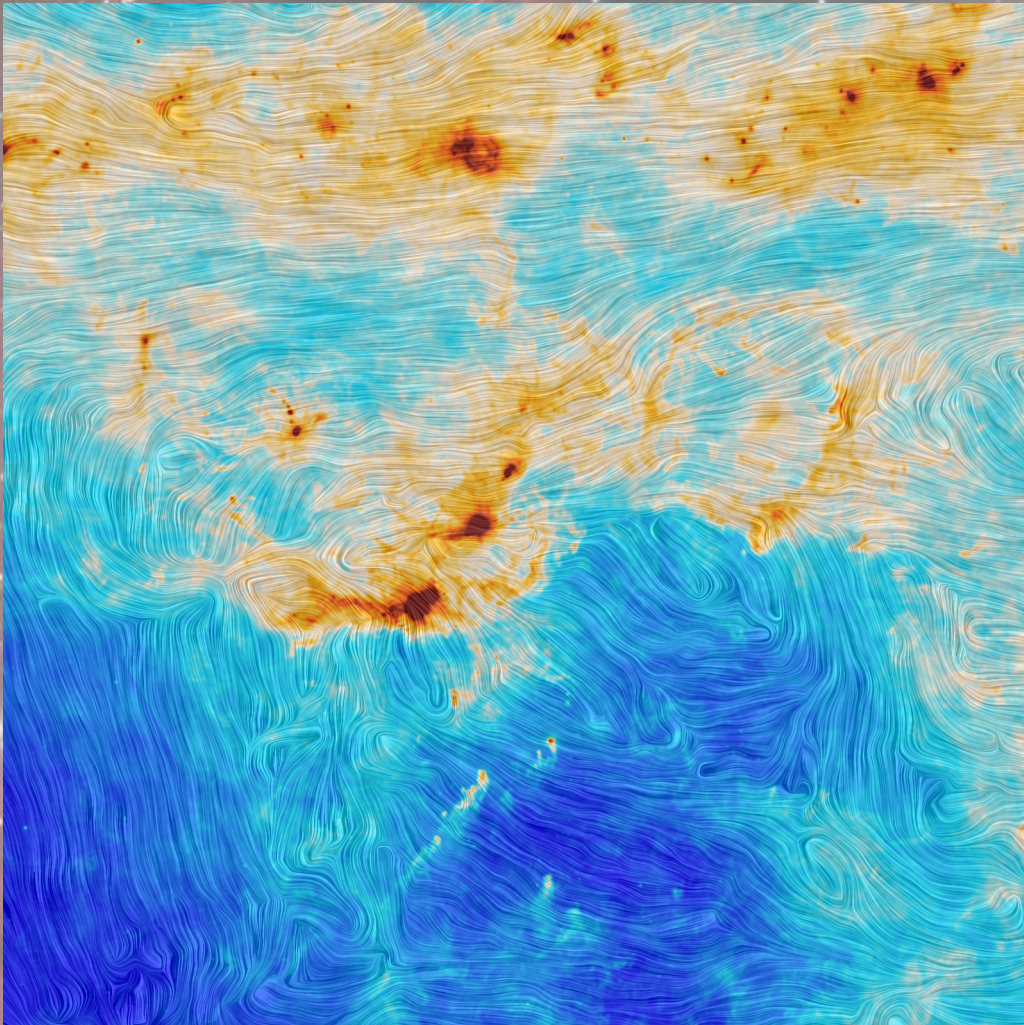


Figure 1: Magnetic field and column density measured by Planck towards the Orion MC. The colours represent column density. The “drapery” pattern, produced using the line integral convolution method, indicates the orientation of magnetic field lines, orthogonal to the orientation of the submillimetre polarization

## 2 Observational Probes of Magnetic Fields

Molecular clouds constitute a category of interstellar cloud that is dense enough to obscure visible light. This is due to the high density of dust grains in the cloud, the chemical composition of which is predominantly silicates and phosphates. A region consisting of a high density of these dust grains is rendered opaque to visible light and thus appears a dark 'blotch' against the brighter background of the Milky Way- however, the dust grains do interact with electromagnetic radiation in novel ways, and their radiation-emission curves provide important signatures that can help identify the composition of the dust particles.

There can be regions of particularly high density within the molecular clouds, called *clumps*, which can drive the process of star formation within the cloud if gravitational forces are sufficient to cause the gas and dust to collapse. In this sense, molecular clouds serve as giant incubators where gas and dust are transformed into stars. Observations have shown that the evidence of such star formation in molecular clouds is ubiquitously associated with the presence of filamentary structures. The outcomes from the observational data then suggest that filaments precede the process of star formation- first, turbulent motions of gas and dust give rise to filamentary structures; then, the densest regions of the filament contract and fragment under the influence of gravity to form clumps of star formation. Analogous to a major artery branching off to smaller arterioles, these larger filaments draw interstellar material from their surroundings through a network of smaller filaments. Although stellar formation is not limited to the region within filaments, stars that form away from dense filaments appear to constitute a smaller fraction of the stellar population, and their average mass tends to be lower than their filamentary counterparts. Observational data suggests that filamentary structures are not limited to any single galaxy or interstellar region, but there seems to be a 'top-down' order of filamentary structures throughout the observed Universe, funnelling interstellar dust and gas into increasingly denser concentrations and thus fostering stellar birth across the galaxy.

Local magnetic fields in the molecular clouds are vital in channelling the flow of interstellar medium via filaments. Observations have agreed with the theoretical model that predicts such movement of material to be directed along routes that are parallel to the direction of the local magnetic field. Thus, it appears that the magnetic field is preferentially oriented perpendicular to the densest filaments, which is in accordance with two previous observations- one, that the filaments draw matter from the interstellar medium through smaller filaments, and two, that the matter drawn as such is directed parallel to the local magnetic field. The orientation of the magnetic field changes from parallel to perpendicular with increasing density of the filaments, which is what one would expect from the previous observations, too.

Although dust grains are opaque to visible light emanating from the background (which can occasionally prove to be a nuisance in visible-light astronomy), they emit black body radiation, and more often than not, this radiation spans the electromagnetic spectrum from the microwave to the infrared region. The dust grains tend to align their longest axis along the local magnetic field (as predicted by the radiative torque (RAT) theory), so the light emitted by them is partly polarised; thus, the direction of polarisation is a direct indicator of the orientation of the local magnetic field in the vicinity [1].

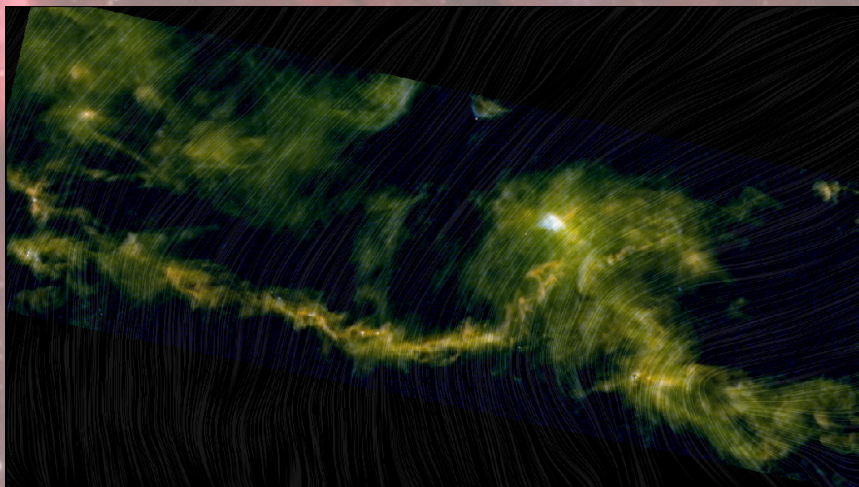


Figure 2: Taurus Molecular Cloud as viewed by Herschel and Planck. Observe the interstellar filament running from the top left to the bottom right of the image, dotted with prominent regions of star formation

### 3 The Planck Mission

Planck was a space observatory launched by the European Space Agency (ESA) to study cosmic microwave background (CMB) radiation- a relic from the Big Bang era. Planck's measurements are the most precise to date, following previous measurements by NASA's COBE (Cosmic Background Explorer) and WMAP (Wilkinson Microwave Anisotropy Probe) observatories. As compared to COBE's observations, Planck was able to map minuscule variations in the CMB, which are imprints left in the past by the 'seeds' of galaxies and galaxy clusters of the present Universe. Built at the Cannes Mandelieu Space Center by Thales Alenia Space, Planck was created as a medium-sized mission for ESA's Horizon 2000 long-term scientific program. The observatory was launched in May 2009 and reached the Earth/Sun L2 point by July 2009. By February 2010, it had successfully started a second all-sky survey. On 21 March 2013, the Planck team released its first all-sky map of the cosmic microwave background. An expanded release in February 2015 included polarization data, which we will be utilising for the project.

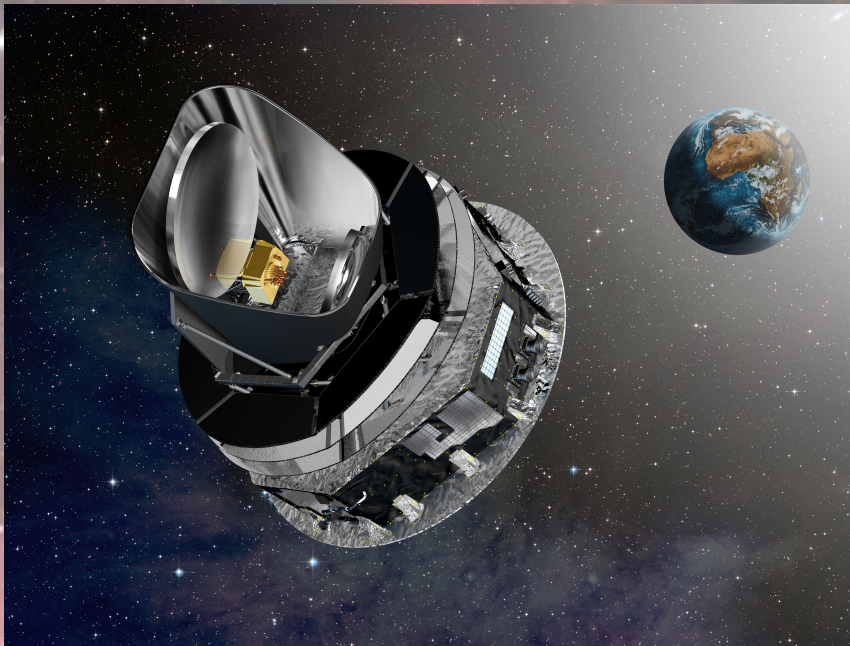


Figure 3: An artist's impression of the Planck observatory

The interstellar dust predominantly consists of amorphous silicate grains and carbonaceous (graphite) grains. The graphite grains are randomly oriented, while the silicate grains can be aligned via the RAT mechanism. These silicate grains polarise starlight passing through them, which is recorded on the intensity maps. Apart from this, dust grains heated by the starlight also emit polarised black-body radiation. These two radiation sources indicate that emission intensity is a direct measure of the gas density since interstellar dust is invariably associated with the presence of interstellar gaseous medium. Polarimeters aboard the Planck observatory record the intensity ( $I$ ) of the polarised emission, along with the Stokes' parameters  $Q$  and  $U$ , which can be used to estimate the angle of polarization [1].

[1]

---

<sup>1</sup>Visit the [Planck](#) mission website

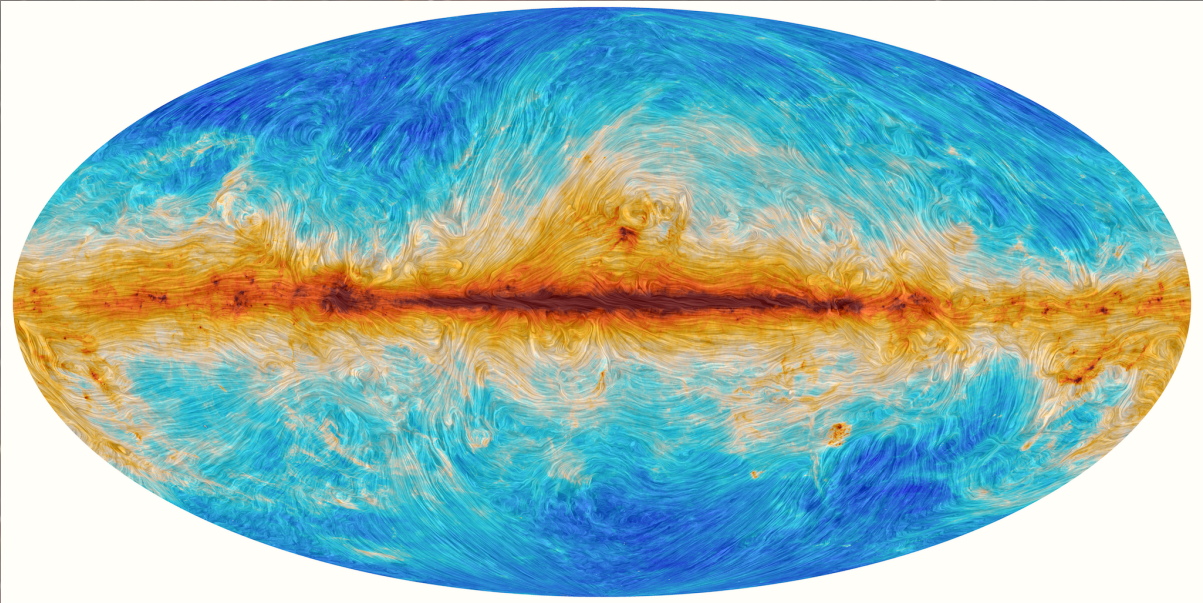


Figure 4: In this image, the colour scale represents the total intensity of dust emission, revealing the structure of interstellar clouds in the Milky Way. The texture is based on measurements of the direction of the polarised light emitted by the dust, which in turn indicates the orientation of the magnetic field.

The central dark region is our Milky Way galaxy. Sky maps give the best estimate of the intensity and polarization (Stokes'  $Q$  and  $U$  components), if available, of the signal from the sky after removal, as far as possible, of known systematic effects (mostly instrumental, but also including the solar and earth-motion dipole, Galactic starlight and the Zodiacal light). Sky maps are provided for the full Planck mission using all valid detectors in each frequency channel and also for various subsets by splitting the mission into various time ranges or subsets of the detectors in a given channel [2].

There were different types of Planck sky maps.

- **Full mission, Full channel maps:** Full channel maps are built using all the valid detectors of a frequency channel and cover either the full or the nominal mission. For HFI, the 143-8 and 545-3 bolometers are rejected entirely as they are seriously affected by RTS noise. HFI provides the  $Q$  and  $U$  components for the 100, 143, 217, and 353 GHz channels only. LFI provides the  $I$ ,  $Q$ , and  $U$  maps for all the channels. Reminder: HFI  $Q$  and  $U$  maps are corrected for bandpass leakage, but LFI  $Q$  and  $U$  maps are not.
- **Nominal mission, full channel maps:** These maps are similar to the ones above but cover the nominal mission only. They are meant primarily to be compared to the PR1 products in order to see the level of improvements in the processing. Because of this, they are produced at temperature only and have not had post-processing applied.
- **Single survey, full channel maps:** Single survey maps are built using all valid detectors of a frequency channel; they cover the different sky surveys separately. The surveys are defined as the times over which the satellite spin axis rotates but 180 degrees, which, due to the position of the detectors in the focal plane, does not cover the full sky, but a fraction between 80 and 90% depending on detector position.
- **Yearly, full channel maps:** These maps are built using the data of surveys 1+2, surveys 3+4, and so forth. They are used to study long-term systematic effects. The 70 GHz years maps are also available at Nside 2048.
- **Full mission, single detector maps:** These maps have no polarization data; they only have temperature data.

- **Half-mission, full channel maps:** For HFI, the half-mission is defined after eliminating those rings discarded for all bolometers. There are 347 such rings, many of which were during the 5th survey when the End-of-Life tests were performed. The remaining 26419 rings are divided in half (up to the odd ring) to define the two halves of the mission. This exercise is done for the full mission only. For LFI, instead of the half-mission, the following year combination has been created: Year 1+2, Year 1+3, Year 2+4, Year 3+4.
- **Full mission, detector set or detector pairs maps:** The objective here is to build independent temperature ( $I$ ) and polarization ( $Q$  and  $U$ ) maps with the two pairs of polarisation-sensitive detectors of each channel where they are available, i.e. in the 44-353 GHz channels.
- **Half-ring maps:** These maps are similar to the ones above but are built using only the first or the second half of each ring (or pointing period). The HFI provides half-ring maps for the full mission only and for the full channel, the datasets, and the single bolometers. The LFI provides half-rings maps for the channel full mission (70 GHz also at Nside 2048), for the radiometer full mission and for the horn pairs full mission.
- **The Zodiacal light correction maps:** The Zodiacal light signal depends on the location of the observer relative to the Zodiacal light bands, and thus, it is not a fixed pattern on the sky but depends on the period of observation.

We want a full mission map for our study to understand the physics behind the correlation, so maximum temporal data would be more suitable for our purposes. We would want the map to have polarization data because we need the Stokes parameters and intensities to identify magnetic fields in these cloud images. Also, we would prefer a sky map at the highest frequency, so the most suitable one is that of the 353GHz channel. In the next section, we will look at the actual code-based implementation for manipulating the data and extracting useful information from it.

## 4 Methodology

HEALPix (Hierarchical, Equal Area, and iso-Latitude Pixelation) spherical data representation format and associated healpy modules are essential for extracting and visualising the information recorded by Planck since these modules were specifically designed to handle pixelated data on sphere. HEALPix was developed to efficiently process Cosmic Microwave Background data from Cosmology experiments like BOOMERANG and WMAP, but it is now used in other branches of Astrophysics to store data from all-sky surveys. The data available to us is in the NESTED format, which must be converted into the RING format for further analysis and visualisation. The RING ordering is necessary for the Spherical Harmonics transforms; the other option is NESTED ordering, which is very efficient for map domain operations because scaling up or scaling down the maps is achieved just by multiplying and rounding pixel indices.

```

from astropy.io import fits
import healpy as hp
import numpy as np
import matplotlib.pyplot as plt

from google.colab import drive
drive.mount('/content/gdrive')
file_path = '/content/gdrive/MyDrive/Krittika_CAP/K-CAP/353GHz.fits'
map = fits.open(file_path, mode='readonly')

I = map[1].data['I_STOKES']
Q = map[1].data['Q_STOKES']
U = map[1].data['U_STOKES']
I = hp.reorder(I, inp='NESTED', out='RING')
Q = hp.reorder(Q, inp='NESTED', out='RING')
U = hp.reorder(U, inp='NESTED', out='RING')

```

Listing 1: Initial data preparation

```

NPIX = len(I)
print(NPIX)
NSIDE = 2**11 #NPIX = 12*NSIDE**2
print(NSIDE)

#Taurus: (theta, phi) = (-14.5, 172.0)
central_latitude = -14.50
central_longitude = 172.0
def deg_to_rad(angle):
    return angle*np.pi/180.0

latitude = np.radians(90.0-central_latitude)
longitude = np.radians(central_longitude)
nres = np.radians(15.0)

vertices = [hp.ang2vec(latitude - nres/2, longitude - nres/2),
            hp.ang2vec(latitude - nres/2, longitude + nres/2),
            hp.ang2vec(latitude + nres/2, longitude + nres/2),
            hp.ang2vec(latitude + nres/2, longitude - nres/2)]

ipix_poly = hp.query_polygon(nside=NSIDE, vertices=vertices)
np.savetxt('pixel_indices.csv', ipix_poly, fmt='%d', header='Pixel_Indices')

m = np.arange(NPIX)
m[ipix_poly] = m.max()
hp.mollview(m, title="Mollview image RING")

```

Listing 2: Identifying the region of interest



```

m = I
def display_pixels(sel_pix):
    pix_list = []
    onerow = list([sel_pix[0],])
    for i in range(1, len(sel_pix)):
        if sel_pix[i] == sel_pix[i-1] + 1:
            onerow.append(sel_pix[i])
        else:
            pix_list.append(onerow)
            onerow = [sel_pix[i],]
    sizex = np.max([len(j) for j in pix_list])
    sizey = len(pix_list)
    mat = np.zeros((sizey, sizex))
    for j in range(sizey):
        start_ind = int(sizex/2 + 1/2) - int(len(pix_list[j])/2 + 1/2)
        new_pix_list = pix_list[j]
        mat[j, start_ind : start_ind + len(pix_list[j])] = m[new_pix_list]
    plt.figure(figsize=(7,6))
    plt.imshow(mat, aspect='auto', vmin=0, vmax=0.1)#, cmap='coolwarm')
    plt.gca().invert_xaxis()
    #plt.contour(mat, levels = np.linspace(0,np.max(mat),5), cmap='Reds')
    #plt.title(title)
    plt.colorbar()
    plt.show()
    return mat

m = display_pixels(ipix_poly)
hdu = fits.PrimaryHDU(m)
hdu.writeto('Taurus.fits', overwrite=True)

```

Listing 3: Plotting intensity map of the Taurus MC

The dimensions of the image plotted using the data available to us as-is will usually not be 'standardised', i.e. it will be numerically difficult to deal with. In order to tackle this issue, the initial image was interpolated via cubic interpolation to a standard  $1200 \times 1200$  pixels array.

```

from scipy.interpolate import interp2d

input_map = '/content/gdrive/MyDrive/Krittika_CAP/K-CAP/Taurus.fits'
hdul = fits.open(input_map)
data = hdul[0].data

x = np.arange(data.shape[1])
y = np.arange(data.shape[0])

10 xn = np.arange(1200)
11 yn = np.arange(1200)
12
13 resize_fits = interp2d(x, y, data, kind='cubic', bounds_error=False)
14 interp_data = resize_fits(xn*len(x)/len(xn), yn*len(y)/len(yn))
15
16 header = hdul[0].header
17 hdu = fits.PrimaryHDU(interp_data, header=header)
18 hdul_interpolated = fits.HDUList([hdu])
19 hdul_interpolated.writeto('Taurus_resized.fits', overwrite=True)

```

Listing 4: Resizing the intensity map to a 1200x1200 image

```

def display_fits_image(fits_file):
    hdulist = fits.open(fits_file)
    data = hdulist[0].data
    header = hdulist[0].header
    hdulist.close()
    plt.figure(figsize=(7,6))
    plt.imshow(data, aspect='auto', vmin=0, vmax=0.05)#, cmap='coolwarm')
    plt.gca().invert_xaxis()
    plt.colorbar()
    plt.show()

output_map = 'Taurus_resized.fits'
display_fits_image(output_map)

```

Listing 5: Displaying the resized intensity map

```

x = np.arange(u.shape[1])
y = np.arange(u.shape[0])
z = np.arctan2(q,u)

xn = np.arange(1200)
yn = np.arange(1200)

resize_image = interp2d(x, y, z, kind='cubic', bounds_error=False)

im = resize_image(xn*len(x)/len(xn), yn*len(y)/len(yn))

header = hdul[0].header
hdu = fits.PrimaryHDU(im, header=header)
hdul_interpolated = fits.HDUList([hdu])

hdul_interpolated.writeto('polarization.fits', overwrite=True)
plt.figure(figsize=(7,6))
plt.imshow(im, aspect='auto', vmin=-np.pi, vmax=np.pi)
plt.gca().invert_xaxis()
plt.colorbar()
plt.show()

```

Listing 6: Resizing the polarization map

The data from the Planck mission also incorporates the Stokes' parameters  $Q$  and  $U$ , which provide us with a direct measurement of the polarization angle at each pixel. However, it is impractical to consider the data at each pixel for analytic purposes due to the noise associated with the data. Instead, the data was first convoluted with a *gaussian filter* to suppress the noise, following which we took the average of the polarization angle over squares of size  $30 \times 30$  pixels, as illustrated in the code below.

Following this, constant-intensity contour lines were plotted for the molecular cloud. Care must be taken while choosing the contours so that portions of the contour lines inside the  $30 \times 30$  squares should not curve excessively to form a 'semi-circular' structure since this can result in wrong estimation of the average slope of the contour. After obtaining the mean polarization angle and mean contour slope over all the  $30 \times 30$  squares, the histogram of relative orientations showing the distribution of relative angle between these two parameters was plotted.

The final part of the project involves establishing the correlation between intensity and angle of relative orientation. In order to do so, a scatter plot showing the distribution of average intensities over the  $30 \times 30$  squares v/s the corresponding angle of relative orientation was drawn up. Next, we average out the intensities over regions of width  $5^\circ$  (so as to suppress the noise in the data) and create a binplot to obtain the correlation between intensity and angle of relative orientation.

```

import scipy
from scipy.ndimage import gaussian_filter

length = 10
step = 30
n = 2
sm = 4

#store the averaged-over-square values of the polarization angle
num_height = 1200//step
num_width = 1200//step

hdul = fits.open('polarization.fits')
polar_data = hdul[0].data

avg_polar = np.zeros((num_height, num_width))

for i in range(num_height):
    for j in range(num_width):
        square = polar_data[i*n : (i + 1)*n, j*n : (j + 1)*n]
        avg_polar_val = np.mean(square)
        avg_polar[i, j] = avg_polar_val

#plotting the polarization vector map
hdulist = fits.open('Taurus_resized.fits')
data = hdulist[0].data
header = hdulist[0].header
hdulist.close()

plt.figure(figsize=(14,12))
convolve_im = scipy.ndimage.gaussian_filter(data, [sm,sm], mode='constant')
plt.imshow(convolve_im, aspect='auto', alpha=1.0, vmax=0.05)
a = im

for i in range(step,1200,step):
    for j in range(step,1200,step):
        ang = np.mean(a[i-int(step/n):i+int(step/n),
                        j-int(step/n):j+int(step/n)])
        x1, x2, y1, y2 = j+length*np.cos(ang), j-length*np.cos(ang),
                        i+length*np.sin(ang), i-length*np.sin(ang)
        plt.plot([x1,x2],[y1,y2], color='white', alpha=0.4)

plt.gca().invert_xaxis()
plt.colorbar()
plt.show()

```

Listing 7: Overlay of polarization vectors on the intensity map

```

1 plt.figure(figsize=(14,10))
2 image = plt.imshow(convolve_im, aspect='auto', alpha=1.0, vmin=0, vmax=0.05)
3 contour_plot = plt.contour(convolve_im, levels=7, cmap='plasma')
4 plt.gca().invert_xaxis()
5 plt.colorbar(contour_plot)
6 plt.colorbar(image)
7 plt.show()

```

Listing 8: Displaying the constant-intensity contours on the intensity map

```

avg_slopes = np.zeros((num_height, num_width))

for i in range(num_height):
    for j in range(num_width):
        region = convolve_im[i*step:(i+1)*step, j*step:(j+1)*step]

        contours = plt.contour(region, levels=7, cmap='plasma')

        slopes = []
        for collection in contours.collections:
            paths = collection.get_paths()
            for path in paths:
                x, y = path.vertices[:, 0], path.vertices[:, 1]
                slope = np.polyfit(x, y, deg=0)[0]
                slopes.append(np.arctan2(slope, 1))

        if slopes:
            avg_slope = np.mean(slopes)
            avg_slopes[i, j] = np.degrees(avg_slope)

plt.close()

angle_diff = abs(avg_slopes.flatten() - avg_polar.flatten())
plt.xlabel('Relative orientation (in  $^{\circ}$ )')
plt.ylabel('Frequency')
plt.xlim(0,90)
plt.ylim(0,300)
plt.hist(angle_diff, bins=30, color='lightblue', edgecolor='navy')
plt.grid(False)

```

Listing 9: Plotting the histogram of relative orientations

```

avg_intensity = np.zeros((num_height, num_width))

for i in range(num_height):
    for j in range(num_width):
        square = interp_data[i*n : (i + 1)*n, j*n : (j + 1)*n]
        avg_intensity_val = np.mean(square)
        avg_intensity[i, j] = avg_intensity_val

x = angle_diff
y = avg_intensity.flatten()
w = 5
midpts = np.arange(50+w/2, 90, w)
avg_y = []

for midpt in midpts:
    avg_y_val = np.mean(y[(x >= midpt-w/2) & (x < midpt+w/2)])
    avg_y.append(avg_y_val)

plt.scatter(x, y, marker='o', s=2, color='green')
plt.xlabel('Angle (in  $^{\circ}$ )')
plt.ylabel('Intensity')
plt.xlim(50,90)
plt.ylim(0,0.030)
plt.show()

```

Listing 10: Scatter plot of intensity v/s angle

```
plt.plot(midpts, avg_y, marker='o', linestyle='-', color='blue')
plt.xlabel('Angle (in  $^{\circ}$ )')
plt.ylabel('Intensity')
plt.xlim(50,90)
plt.ylim(0.0080,0.0125)
plt.show()
```

Listing 11: Binplot of intensity v/s angle

## 5 Results

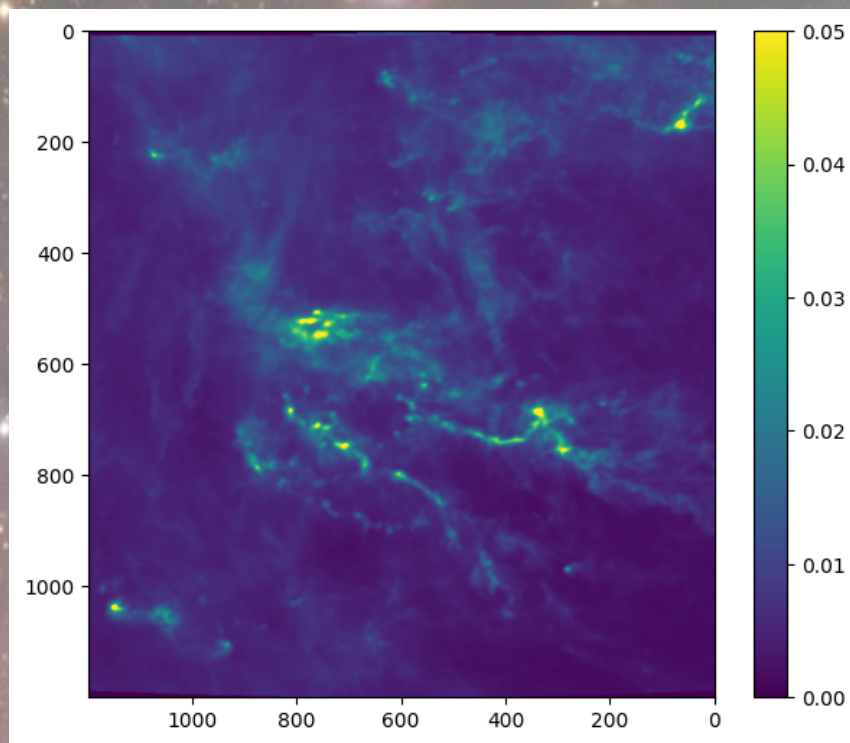


Figure 5: Intensity (or column density) map of the Taurus molecular cloud

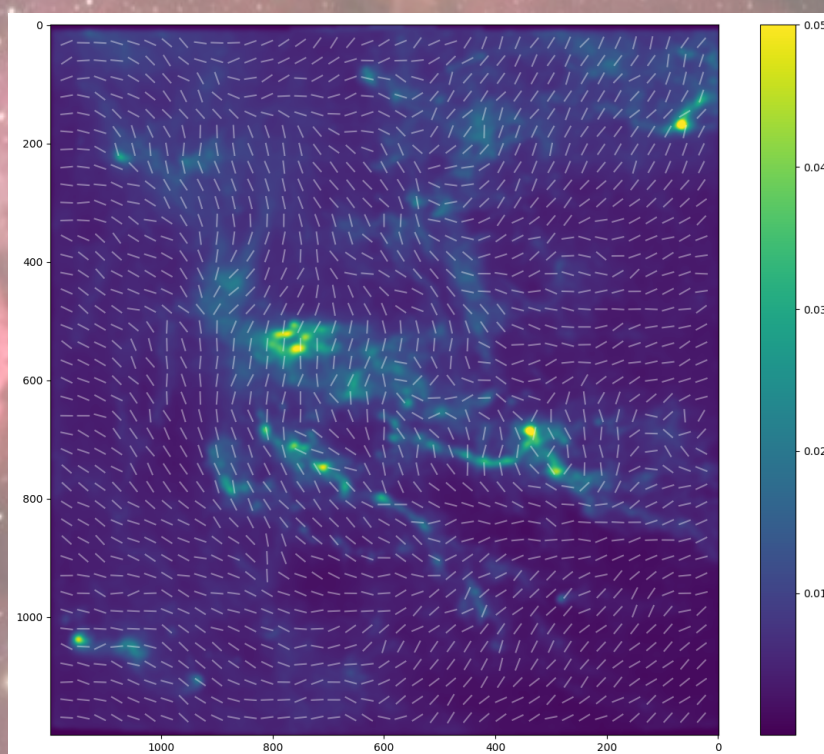


Figure 6: Polarization vectors of dust emission overlaid on the intensity (or column density) map of the Taurus molecular cloud

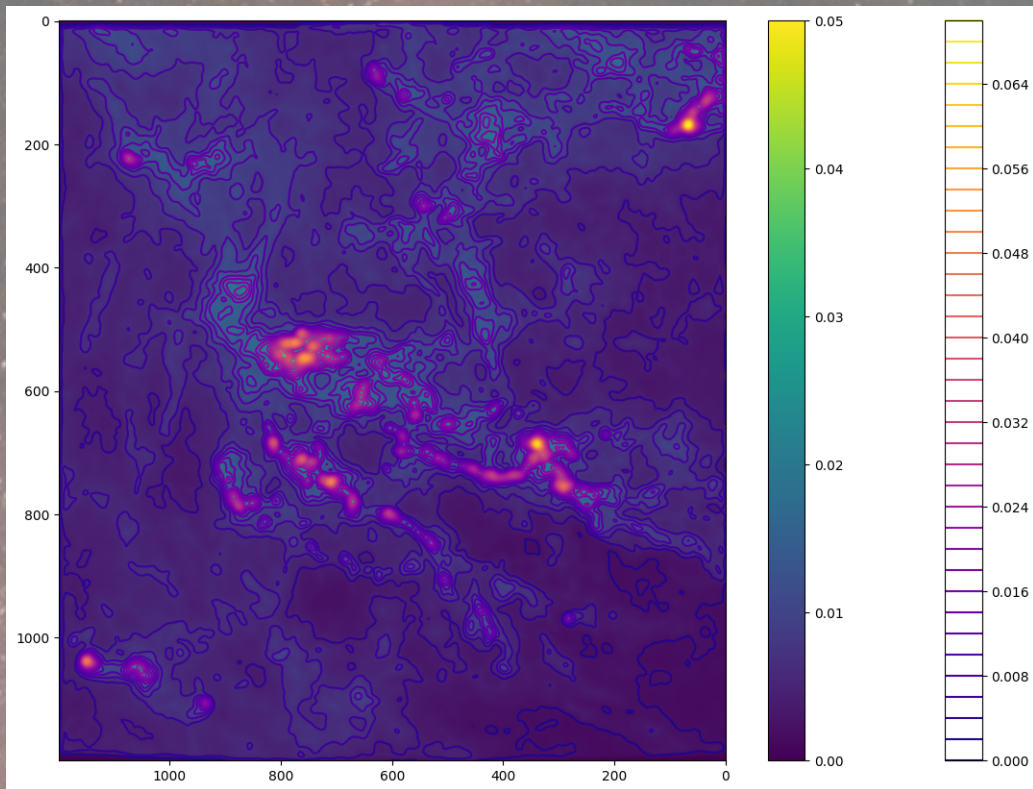


Figure 7: Constant-intensity contour lines plotted for the Taurus molecular cloud

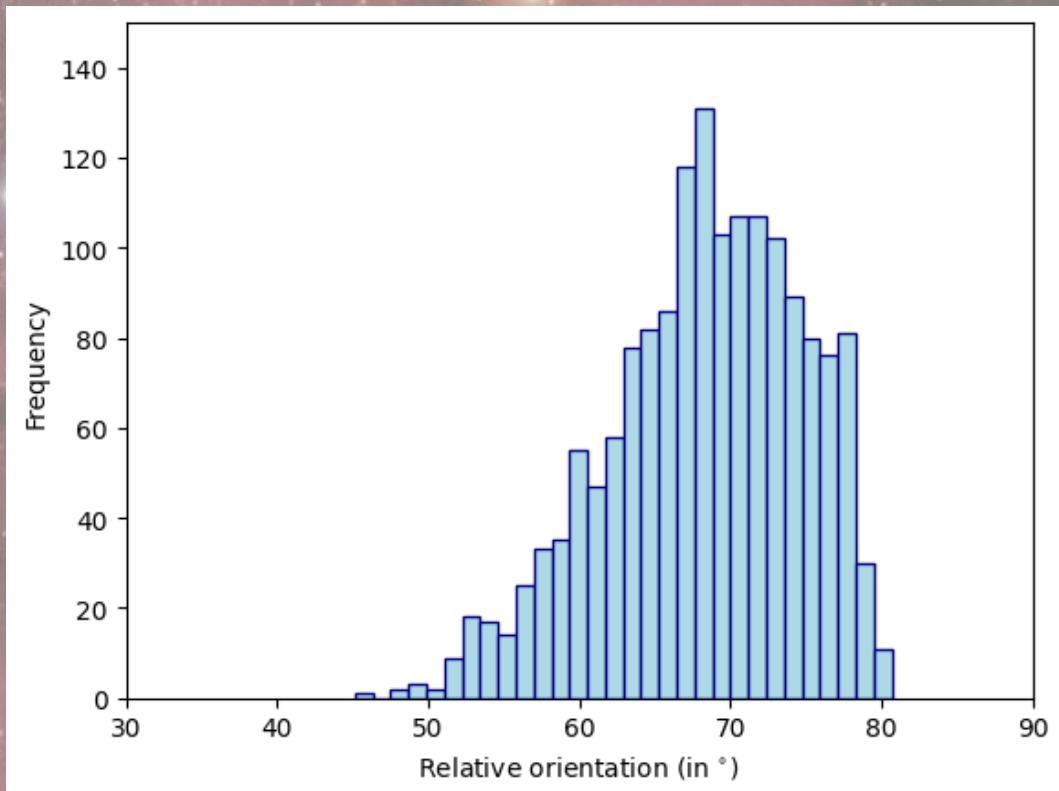


Figure 8: Histogram showing the distribution of relative orientation between the contours and average polarization angle

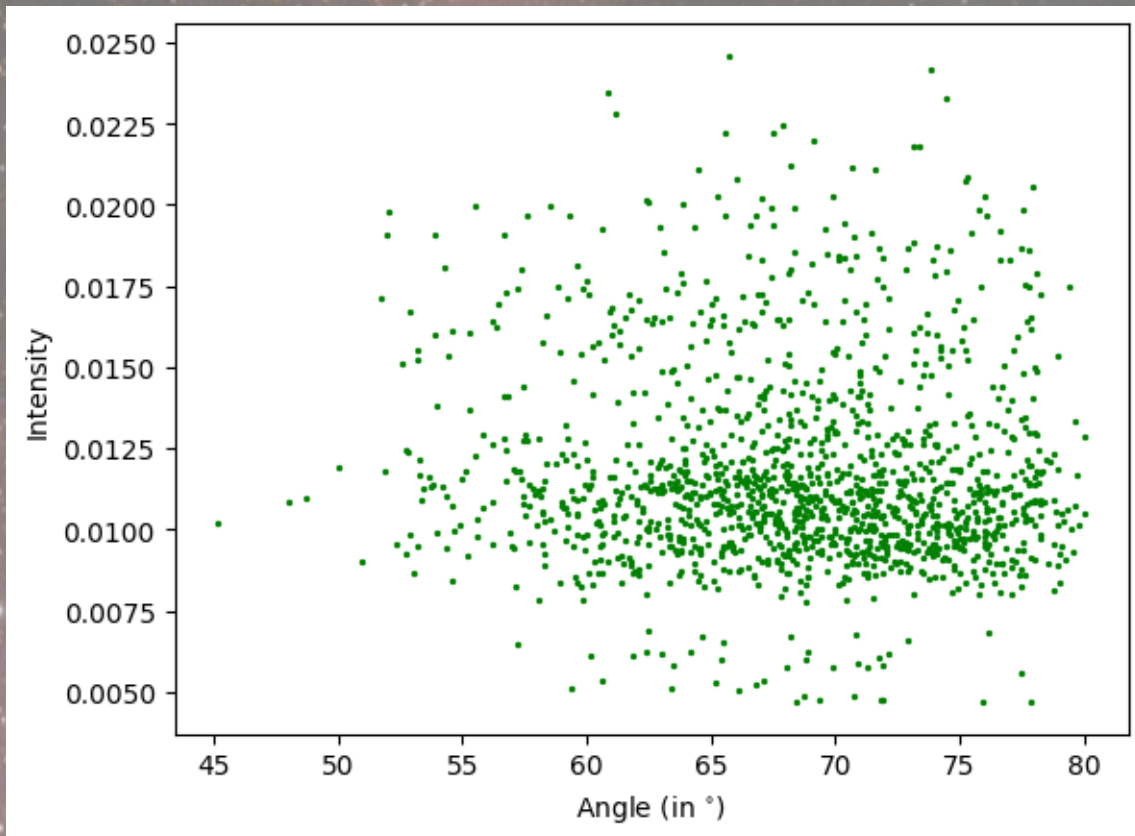


Figure 9: Scatter plot showing the distribution of intensity and angle of relative orientation

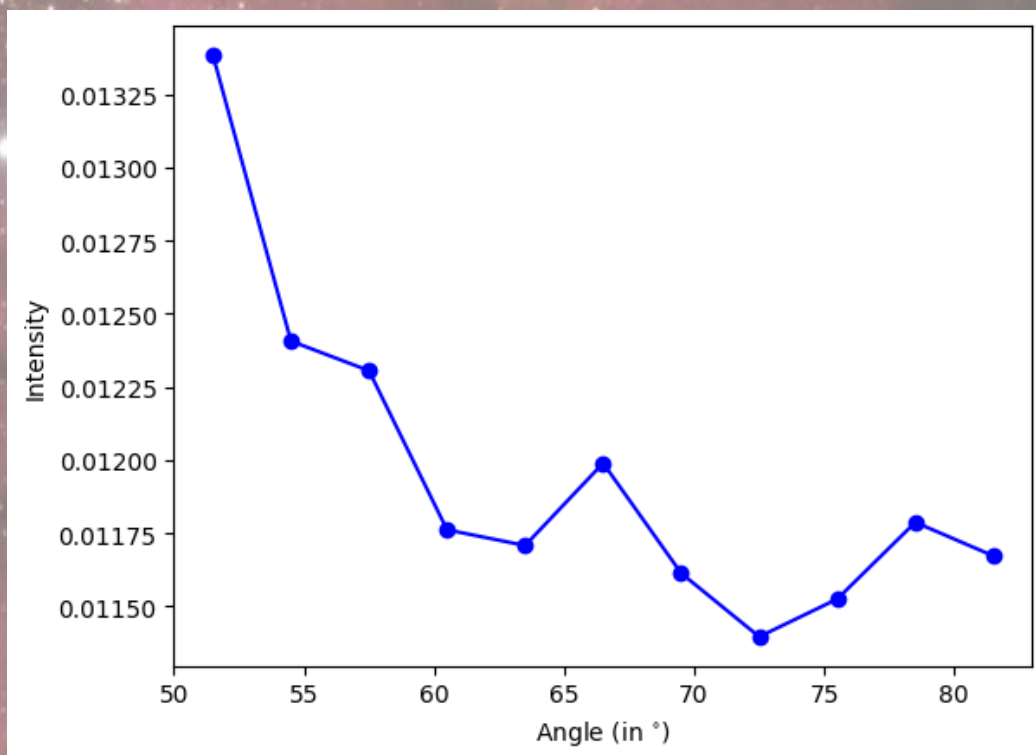


Figure 10: Binplot showing the correlation between intensity and angle of relative orientation



## References

- [1] N. L. Hyeseung Lee, Thiem Hoang and J. Cho, “Physical model of dust polarization by radiative torque alignment and disruption and implications for grain internal structures,” *The Astrophysical Journal*, p. 15, June 2020.
- [2] P. A. R. Ade, N. Aghanim, M. I. R. Alves, M. Arnaud, D. Arzoumanian, M. Ashdown, J. Aumont, C. Baccigalupi, A. J. Banday, R. B. Barreiro, N. Bartolo, E. Battaner, K. Benabed, A. Benoît, A. Benoit-Lévy, J.-P. Bernard, M. Bersanelli, P. Bielewicz, and J. J. a. Bock, “Planck intermediate results: Xxxv. probing the role of the magnetic field in the formation of structure in molecular clouds,” *Astronomy amp; Astrophysics*, vol. 586, p. A138, Feb. 2016.