Star Formation in clouds and cores: what does polarization hint us?

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Cores are dense gas precursors to individual stellar systems. Understanding their polarization properties is important as the polarized thermal radiation from dust grains are an important tool for studying the magnetic fields within the star-forming region. In general polarization levels tend to be low, perhaps indicating that the dust grains are not well aligned in cores and that most of the polarized radiation observed towards these cores is from the less dense gas envelopes in the surrounding cloud. In this project, I will not only show how the polarization varies between the cores and their surrounding background but also explore the various physical properties of these cores and discuss their formation process in Giant Molecular Clouds. Using the different starless, pre-stellar, and proto-stellar cores and their respective locations from the "derived cores" catalog of the Herschel Gould Belt Survey I have extracted the stokes parameter maps and polarization intensities using the Planck 353 GHz polarization data toward the Taurus molecular cloud. By stacking the polarization maps, I investigate whether the polarization intensity is higher for the cores when compared to each other as well as its surrounding background. Stacking also helps to improve the S/N thereby helping us extract a more detailed structure of the source. The results of my analysis show that cores are infact more polarized than their surrounding envelope cloud.

I. INTRODUCTION

Our galaxy is producing stars at a rate of between 1 and 4 solar masses per year. In contrast to elliptical galaxies, which are mostly empty of star formation, spiral galaxies continue to generate stars due to their molecular gas reservoirs, which provide the fuel for future stars. The discs of spiral galaxies are made up of both stars and gas. This is where the gas condenses into molecular clouds, which are cold, dense molecular regions where new stars emerge. The vast majority of stars are formed in huge molecular clouds, also known as giant molecular clouds (GMCs).

Giant molecular clouds have the following Physical properties :

- Temperature(T) : 10-30 K
- n_H : 10^3 to $10^6 cm^{-3}$
- Volume Filling Factor : 0.0001
- Cooling by fine CI structure lines, CO emission
- Usually self-gravitating
- Observed with : CO,CI,OH,NH3,CH,CS,HCO+

In this project, we will look closely at the Taurus Molecular Cloud (TMC) which is the nearest star-forming GMC at about 140 pc away. This proximity will help to resolve the individual cores better down to a 0.1 pc scale. Taurus also has a less clumpy nature as compared to other GMCs like Perseus, which allows to isolate the cores and extract the properties of their envelopes easily. Finally, the less inclination of the magnetic fields also improves the measurements of the polarization parameters.

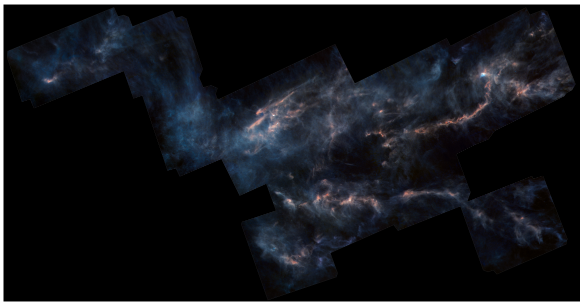

FIG. 1: The Taurus Molecular Cloud located about 140 pc away is the closes active star forming region to us, credits:ESA Herschel

Our basic model of star formation begins with a molecular cloud that collapses due to its gravitational pull. There are two primary forces at work in this scenario: gravity's inward pull and outward gas pressure. The cloud begins to fragment when gravity triumphs, which it will if the cloud is large enough. Stars form when the cloud reaches a high enough density.

This critical mass above which gravity starts to dominate is called the Jeans mass.

$$M_J = \frac{4\pi}{3}\rho\lambda_J^3 = (\frac{10k_bT}{3(\gamma-1)\mu m_H G})^{3/2}(\frac{3}{4\pi\rho})^{1/2} \quad (1)$$

Where λ_j is the critical jeans length, k_b is the Boltzmann's constant, γ is the ratio of specific heats of gas(

eg. γ is $\frac{5}{3}$ for monoatomic gas), μ is the mean molecular weight($\mu = 1$ for pure neutral hydrogen gas), ρ is the density of the gas and T is the temperature of the gas. Hence, the Jeans mass is the mass contained in a volume with a radius of Jean's length.

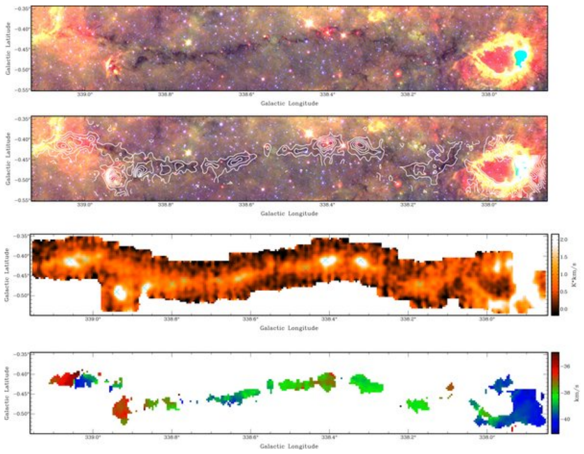

FIG. 2: [5]Fragmentation of the filaments in the Nessie Nebula. Once the cores reaches its critical Jean's Mass they start to fragment just like beads on a string.

Mestel (1965a,b) [1] argued that magnetic fields play an important role in star formation. He noted that an average region of the interstellar medium (ISM) with a stellar quantity of mass cannot simply collapse to stellar densities due to the presence of too much angular momentum. Magnetic fields, he claimed, are likely to be important in eliminating that angular momentum. He also pointed out that the average region of interstellar medium holding a stellar-mass contains too much magnetic flux to collapse to stellar densities. As a result, the magnetic field must strike a balance between allowing angular momentum to be removed while also escaping from the collapsing material. Magnetic fields thread star-forming molecular clouds, which are presumably inherited from the galactic-scale interstellar medium from which they formed. However, the importance of the magnetic field in the early stages of star formation is still not completely clear.

Since the elongated grains are generally recognized to have a preferential orientation with their longer axes perpendicular to the local magnetic field, the polarised thermal emission from dust grains at infrared/sub-mm wavelengths has been considered a reliable tracer of plane-of-sky magnetic field morphology in dense star-forming clouds. These polarized thermal emissions help us to map out the magnetic field in the star-forming cores allowing us to probe into the complex structures which finally shape the Initial mass function. Dense cloud cores gravitationally collapse in GMC to form stars. To acquire insight into the initial conditions and stages of the star formation process, researchers are studying and defining the features of dense cores.

In recent years, there has been substantial progress in our observational understanding of low-mass dense cores, and four main groups of cores can now be recognized within neighboring molecular clouds, which may indicate an evolutionary sequence: starless cores, prestellar cores, candidate prestellar cores, and protostellar cores. Starless cores are presumably temporary concentrations of molecular gas and dust without embedded young stellar objects (YSOs), as shown in tracers like C18O, NH3, or dust extinction, but without evidence of infall. Candidate prestellar cores are more-denser than starless cores and show signs of a central heating source or a YSO (young stellar object). Prestellar cores are also starless (M* = 0), but they are a denser, more centrally concentrated population of self-gravitating cores that are unlikely to be transitory. They're most commonly found in (sub) millimeter dust continuum emission and dense molecular gas tracers like NH3. Finally, the protostellar cores have a young accreting protostar embedded in them. They form when candidate prestellar cores undergo a collapse. Understanding these stages will give us a clear picture of the role of the magnetic field in star formation down to the smallest scales.

II. GIANT MOLECULAR CLOUDS AND FILAMENTS

The principal ingredients of the cold, dense clouds in the interstellar medium are dust and gas, primarily in the form of hydrogen molecules. The largest of these molecular clouds, known as Giant Molecular Clouds, have temperatures of roughly 10-30 Kelvin, density of up to 102-103 particles/cm3, masses of a few to over a million solar masses, and diameters of 20 to 200 parsecs. Star formation occurs mainly within molecular clouds, which are found largely in the discs of spiral galaxies and the active areas of irregular galaxies, according to observations. We can't see molecular clouds directly in visible light since they're cold and black. However, they emit longer millimeter-wavelength radiation that is untouched by the interstellar medium. Molecules can only rotate and vibrate at specified speeds, just like electrons in an atom can only exist at specific energy levels and must absorb or release energy when they transition from one energy level to another. When a molecule changes its rotational state, energy must be absorbed or emitted, with the minuscule energy difference corresponding to millimeter wavelengths.

One issue is that, although being the most abundant

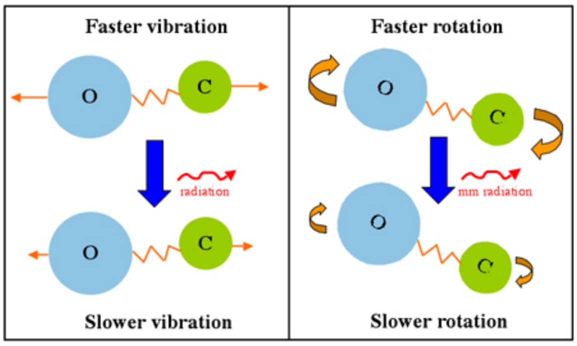

FIG. 3: Molecules can emit radiation by changing either their rotational or vibrational states. A change in the rotational state of the CO molecule results in a photon emitted at millimeter wavelengths.

component in molecular clouds, molecular hydrogen is extremely difficult to detect. One reason for this is that the strength of spectral lines from molecules is proportional to their asymmetry. The spectral lines of the hydrogen molecule are exceedingly faint since it is fully symmetric (it contains two hydrogen atoms). It takes a significant amount of energy (500 K approx.) to change its rotational state. This is particularly difficult in a cloud whose maximum temperature doesn't exceed 30 K.

Carbon monoxide molecule (CO) in particular has shown to be quite useful in detecting these GMCs. It has been determined that for every CO molecule, there are around 10,000 hydrogen molecules, implying that molecular hydrogen can be traced by the CO molecule's emission. This is the most common method for locating molecular clouds.

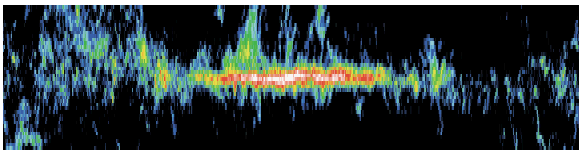

FIG. 4: [2] A CO map of the Milky Way shows that the molecular clouds are primarily located in the galactic disk.

Dense structures in GMC are found in 0.1 pc scales.

This cartoon by Pohkrel et el 2018 gives a better perspective into the multiscale nature of GMCs which can be 10s of pc across. As you go down in distance from cloud to actual disks and stars(100AU) you encounter denser structures. Filamentary structures are a common feature in the ISM, especially found in Giant Molecular Clouds. This is a result of the continuous injection of turbulence in high-density regions. The interplay between gravity and turbulence is what finally causes these long filamentary structures. It is very important for us

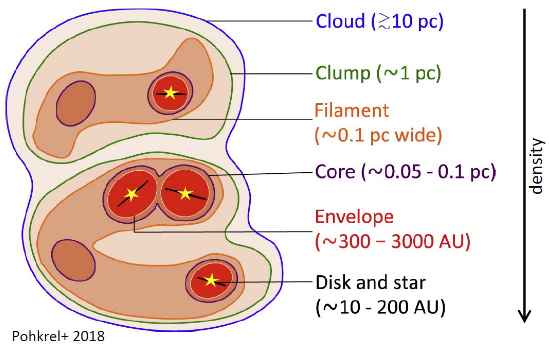

FIG. 5: [8] Cartoon showing the multiscale structure of GMCs

to study and characterize the size and shape of these filaments as they represent a very crucial phase in the early stages of star formation. Mainly prestellar and protostellar cores are found to be embedded in these filaments once they reach a certain critical mass length and start fragmenting. Filaments are typically described as hydrostatic cylinders that fragment when subjected to linear perturbations. Other environmental factors, such as turbulence, accretion, or magnetic fields, can induce additional fragmentation modes, according to some studies (Andre et al. 2017). Once these hydrostatic isothermal cylinders reach a certain critical mass length,

$$M_{crit,L} = \frac{2c_s^2}{G} \tag{2}$$

They start to fragment just like beads on a string. Fragmentation occurs at the Jeans Length,

$$\lambda_j = \sqrt{\frac{\pi c_s^2}{G\rho}} \tag{3}$$

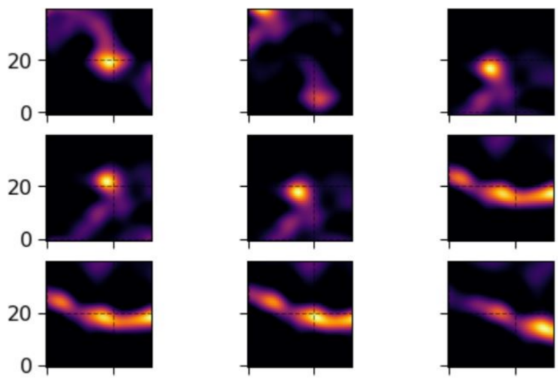

FIG. 6: Dense Cores existing in filaments, Taurus Molecular Cloud

III. DATA USED AND METHODOLOGY

The 353 GHz all-sky Planck map was used for the Taurus molecular cloud (Longitude: 174 deg Latitude:13.45deg). The location of the respective cores (starless, candidate prestellar, prestellar, and protostars) have been taken from the Herschel Gould Belt Survey. Herschel's survey also provided the column density and dust temperature maps.

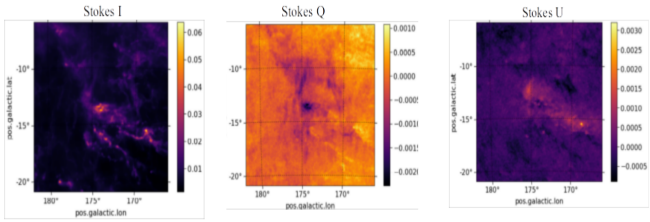

FIG. 7: The Planck 353GHz Polarization Map

Using the locations of the cores, I extracted the respective column density and dust temperatures of the cores, which helped in the analysis of the core properties. For the analysis, AstroPy was used, which helped me to convert from the respective coordinate system and extract the parameters from the maps.

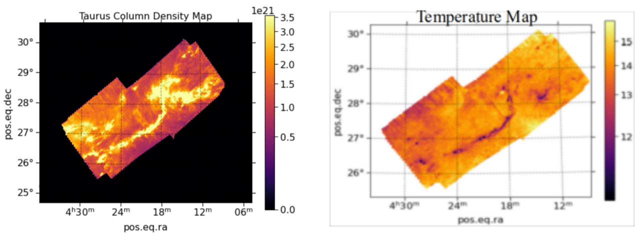

FIG. 8: Herschel Gould Belt Survey dust temperature and column density data of the Taurus Molecular Cloud

The Planck maps provided the polarization data as I, Q, and U maps of the respective region. With the knowledge of the core type and location, I was able to recreate the polarized maps of these cores and extract the relevant properties like degree of linear polarization, polarization intensity, and polarization fraction to name a few. Since these cores do not have a well-defined boundary and the resolution of Planck is not high(5 arc mins) enough to resolve them well, it gets extremely difficult to segregate and study the individual cores from their surrounding clouds. This is a problem as we want to observe and study how the polarization would vary between the cores and their surrounding envelope.

To address this, I am using stacking analysis which is a commonly used technique for studying faint sub-mm galaxies. Using cutout-2D function of AstroPy I made a huge list of individual cores centered around 30 X 30 pixels. After which I stacked these individual images, applied a high pass filter to get rid of all the unwanted structures, and finally took a mean to get my maps.

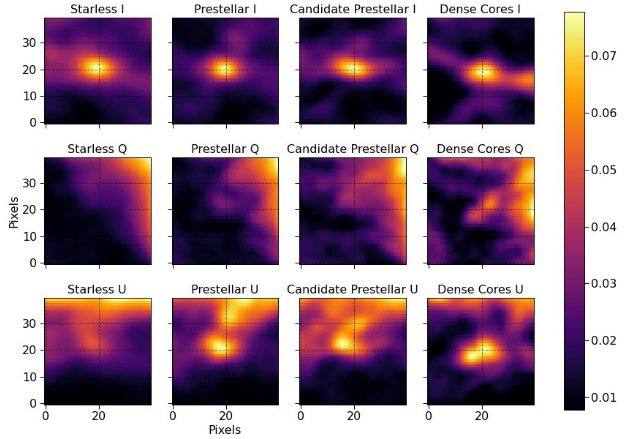

FIG. 9: Stacked mean I,Q and U Maps. This shows detailed structure of the various types of cores and their surrounding envelopes.

IV. TYPES OF CORES

A. Starless Cores

The simplest star-forming settings are starless cores in surrounding clouds. They do not have a central heating source or an embedded YSO(young stellar object) They collapse and generate individual stars (or binaries) in almost complete isolation, with little apparent impact from the surrounding cloud or prior star generations. Starless cores are good sites to study the still unknown mechanism by which interstellar matter collapses and creates gravitationally bound self-luminous objects. The starless cores of the Taurus molecular cloud have the following mean properties :

- Mass: 0.0325 M_{sun}
- Radius: 0.0235 pc
- Temperature: 12 K
- Column Density : $0.9339 * 10^{21} cm^{-2}$

When we find a starless core, we're looking at a system that will most likely collapse into a star. As a result, starless cores provide a snapshot of the early phases of star formation, as well as the early stages of the process if they have already begun to collapse. As a result, deducing these requirements from observations is of tremendous interest.

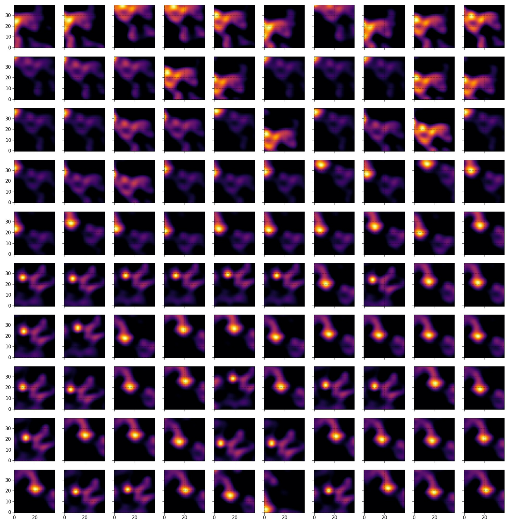

FIG. 10: A sample 100 starless cores of the Taurus Molecular cloud.

Understanding the evolution of these cores is important. The molecular freeze theory has proven to be crucial in helping us develop better evolutionary models of these starless cores and their contraction. At the density and temperatures found in starless cores, molecular freeze-out is a progressive and irreversible process. Under these conditions, every molecule that collides with a dust grain sticks to its surface and does not evaporate thermally (cosmic ray-induced evaporation seems not efficient enough to reverse the process, Hasegawa Herbst 1993). As a result, the amount of freeze-out in a given parcel of gas increases over time, and it should be able to transform the amount of freeze-out into an estimate of the contraction age in principle. In a contracting core, molecular freeze isn't the only process that accelerates with time. Since the formation of some molecules, such as NH3 and N2H+, is dependent on the slow formation of N2, they can be used as indicators of core evolution (the formation of N2H+ is aided by CO depletion).

B. Candidate Prestellar Cores

Simply put candidate prestellar cores are also starless cores but have a higher column density. The Atacama Compact Array (ACA) using its short-spacing baseline peered into the innermost part of molecular clouds showing us the first-ever evidence of such candidate prestellar cores. These cores are usually associated with low-mass star formation or brown dwarfs. The candidate prestellar cores of the Taurus molecular cloud have the following mean properties :

- Mass: 0.1407 M_{sun}
- Radius: 0.020 pc
- Temperature: 13.5 K
- Column Density : $5.28 * 10^{21} cm^{-2}$

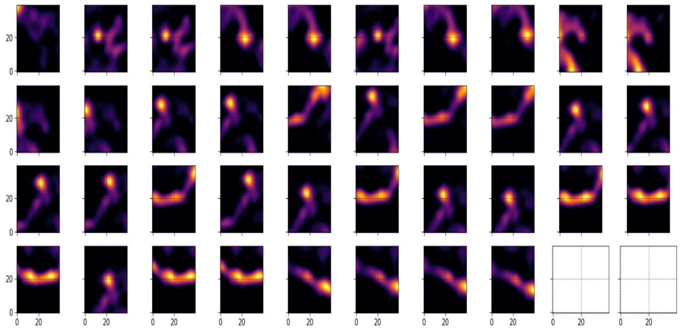

FIG. 11: A sample of candidate prestellar cores of the Taurus Molecular cloud.

The dynamical age of these cores is estimated to be around 104 years. These cores show certain substructures before self-gravity finally controls their fate. It is however not evident whether these substructures harbor on to form any YSO.

C. Prestellar Cores

Prestellar cores are a self-gravitating, denser, and more centrally concentrated population of a core that contains a trace of a central heating source or YSO (young stellar object). These cores are usually observed in (sub)millimeter dust continuum emission and dense molecular gas tracers like NH3 or N2H+, which show evidence of infall movement. Although all prestellar cores are starless in concept, only a small percentage of starless cores mature into prestellar cores; the remainder is probably "failed" cores that disperse and never create stars.

Extensive surveys such as the 3-deg2 SCUBA 850 um survey show that prestellar cores found in localized subregions within molecular clouds occupy only a small fraction of their volume. Cluster-forming clumps associated with embedded near-IR clusters frequently correlate to these localized active sub-regions. The prestellar cores

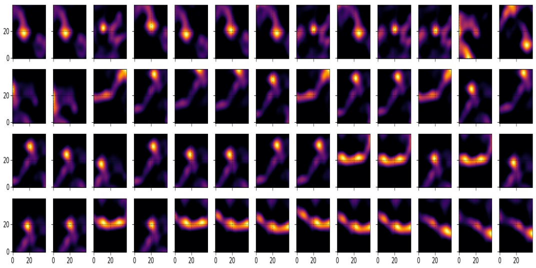

FIG. 12: A sample of prestellar cores of the Taurus Molecular cloud.

of the Taurus molecular cloud have the following mean properties :

- Mass: 0.4847 M_{sun}
- Radius: 0.0218 pc
- Temperature: 14 K
- Column Density : $12.10 * 10^{21} cm^{-2}$

Since the mean densities of prestellar cores are essentially uncorrelated with their masses, the dynamical timescale has no systematic dependence on mass. Consider a weighted core mass function in which each core is allocated a weight equal to:

$$\frac{< t_{ff} >}{t_{ff}} = \frac{\rho^{-1/2}}{< \rho^{-1/2} >} \quad (4)$$

(rather than 1), where t_{ff} is the average free-fall time of the sampled cores. If the lifetime of each core is proportionate to its free-fall period, such a weighting allows the CMF's inherent shape to be recovered. The mechanisms that cause prestellar cores to develop and evolve in molecular clouds are currently the subject of intense theoretical dispute. Self-gravity is undeniably important, and it has even been suggested that dense cores might form as a result of simply gravitational fragmentation. Along with gravity magnetic fields and turbulence also play an important role. The role of supersonic turbulence in supporting clouds on large scales and generating density fluctuations on small scales has seriously challenged the classical picture of slow, quasi-static prestellar core formation by ambipolar diffusion in magnetically supported clouds.

Isolated prestellar core density profiles are pretty well understood. Two approaches used are:

- Mapping the optically thin (sub)millimeter continuum emission from the cold-core dust.
- Mapping the same cold-core dust in absorption against the background infrared emission (originating from warm cloud dust or remote stars).

Prestellar cores are extremely crucial in understanding the protostellar/dense cores which definitively contain a central heating source.

D. Protostellar/Dense Cores

The protostellar phase of a core is when it undergoes a subsequent collapse, resulting in the creation of a young stellar object, which is commonly observed due to infrared emission from heated dust surrounding the young protostar. Young stars emit outflows as well, making them important tracers of star formation activity. As internal support, like thermal or magnetic pressure, is overcome by self-gravity, prestellar cores undergo a collapse forming a protostellar/dense core with a YSO. The protostellar/dense cores of the Taurus molecular cloud have the following mean properties :

- Mass: 0.053 M_{sun}
- Radius: 0.01 pc
- Temperature: 14 20 K
- Column Density : $15.25 * 10^{21} cm^{-2}$

These cores exists in dense filamentary structures. They closely follow Larson's scaling relation. Furthermore [3] generalized this by noticing that the Larson ratio $L = \sigma_v / R^{0.5}$, for galactic GMCs depends on the mass column density $\Sigma = \mu m_H N$ as,

$$L = \Sigma^{0.5} \quad (5)$$

instead of being constant , as would be required by Larson's velocity dispersion-size relation and/or by strong supersonic turbulence. Thus it was suggested that these dense cores are driven by self-gravity which consists of highly chaotic in fall motion due to the presence of turbulence.

V. PHYSICAL PROPERTIES OF THE CORES AND HOW DO THEY VARY

A. Cores are critical Bonnor-Ebert spheres

The early setup of star formation is determined by the physical circumstances present in prestellar cores, namely gravitationally bound concentrations of molecular gas.

Prestellar cores aren't always spherical, but a Bonnor-Ebert (BE) sphere, which is an isothermal gas sphere in hydrostatic equilibrium, has been discovered to successfully simulate multiple prestellar cores. For a given mass, there is a critical size and external pressure before the collapse, given by

$$R_{crit} = 0.41\frac{GM}{c_s^2} \tag{6}$$

$$P_{crit} = 1.4\frac{c_s^2}{G^3M^2} \tag{7}$$

where P_{crit} is the pressure at the edge of the cloud
Thus,

$$M_{BE} \propto R_{BE} \tag{8}$$

For the Taurus Molecular cloud, we can see,

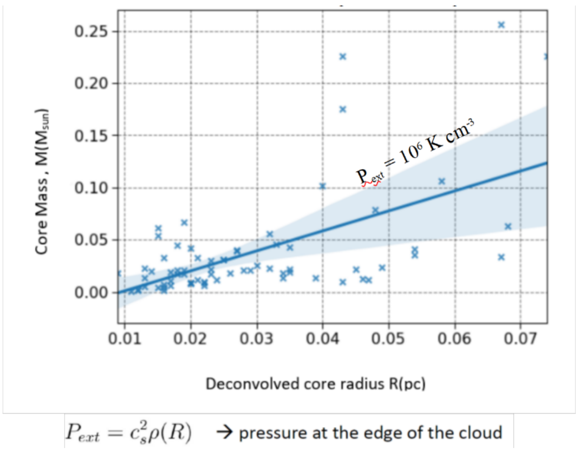

FIG. 13: Core mass vs core radius at a given external pressure, clearly showing the Bonnor-Ebert criterion $M_{BE} \propto R_{BE}$

The critical Bonnor-Ebert mass is used as a proxy for viral mass for cores to define their boundedness. [7] highlighted that dense cores can be categorized as prestellar if they are both starless and self-gravitating.

The virial mass ratio given by

$$\alpha_{vir} = \frac{M_{vir}}{M_{obsv}} \tag{9}$$

where M_{vir} is the virial mass ,

$$M_{vir} = \frac{3R_{core}\sigma_{tot}^2}{G} \tag{10}$$

for a spherical density $\rho \propto r^{-2}$ and σ_{tot} is the total contribution from thermal and non-thermal velocity dispersion of the core.

B. Core temperature, mass, and column density

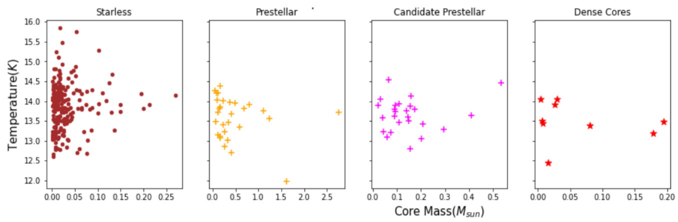

FIG. 14: Core mass vs core temperature, Taurus Molecular Cloud

At comparatively lower temperatures the central mass of these cores increases over time (due to collapse) before finally, they become dense enough to heat up again. Even slight variations in the temperature can trigger thermal support thus preventing the gravitational collapse.

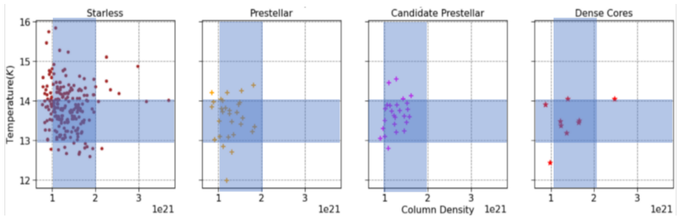

FIG. 15: Core column density vs core temperature, Taurus Molecular Cloud

The cores occupy only a specific range of :

- Column density: $(1-2)*10^{21}cm^{-2}$
- Temperature: (13-14) K
- Upon performing a linear regression of the starless and prestellar cores with mean column densities $\leq 2*10^{21}cm^{-2}$, cores beyond this threshold of column density are uncorrelated with the temperature.
- Cores under this mean column density show a relation of $T = 3.5log10N_{H2} + 86.0$.

VI. POLARIZATION AND MAGNETIC FIELDS IN STAR-FORMING CORES

A. Stokes Parameters and what does it signify

The Stokes parameters are commonly used to describe polarised light. Consider a plane electromagnetic wave propagating in the z-direction that is nearly monochromatic; nearly monochromatic means that the frequency components are closely dispersed around the mean frequency omega0. At a particular point in space, the components of the wave's electric field vector can be expressed as,

$$E_x = a_x(t)\cos[\omega_o t - \theta_x(t)] \tag{11}$$

and,

$$E_y = a_y(t)\cos[\omega_o t - \theta_y(t)] \tag{12}$$

Since the wave is nearly monochromatic we can be sure that the amplitudes a_x and a_y and the phase angles θ_x and θ_y will vary slowly to the inverse frequency of the wave. If there is some correlation between the two components in the above equation then the wave can be considered polarized. The Stokes parameters can be defined as the time average of ,

$$I \equiv \langle a_x^2 \rangle + \langle a_y^2 \rangle \tag{13}$$

$$Q \equiv \langle a_x^2 \rangle - \langle a_y^2 \rangle \tag{14}$$

$$U \equiv \langle 2a_x a_y \cos(\theta_x - \theta_y) \rangle \tag{15}$$

$$U \equiv \langle 2a_x a_y \sin(\theta_x - \theta_y) \rangle \tag{16}$$

In comparison to the wave's inverse frequency, the averages are spread out over a longer period. For blackbody radiation, the parameter I represent the intensity of the radiation, which is always positive and equal to the temperature. The remaining three factors describe the wave's polarization state and can be either positive or negative. $Q = U = V = 0$ describes unpolarized radiation, also known as "natural light." The parameters I and V are physical observables that are independent of the coordinate system, whereas Q and U are dependent on the x and y axes' orientation. If a particular wave is defined by the parameters Q and U for a certain coordinate system orientation, it is simple to check that the same wave is now described by the parameters Q and U after rotating the x-y plane through an angle ϕ.

$$Q^{'} = Q\cos 2\phi + U\sin 2\phi \tag{17}$$

$$U^{'} = -Q\sin 2\phi + U\cos 2\phi \tag{18}$$

In this project the Planck 353 GHz polarization maps have been used, which come with the Stokes I, Q, and U parameters. This allows us to reconstruct the maps of the cores in all three parameters and also extract more meaningful parameters like degree of linear polarization, polarized intensity, and polarized percentage. Where,

- The degree of linear polarization describes quantitatively the partial linear polarization of the light beam. It spans the range from 0 (unpolarized light) to 1 (totally linearly polarized light).
- Polarization Percentage is the ratio of polarized Intensity of light (P) with its total Intensity (I)

Essentially all these quantities will help us evaluate the variation in polarization at the cores and near their envelopes, which will help us to answer if cores are at all more polarized than their surrounding cloud. This will in turn help us explain the magnetic field pattern near these cores.

B. Role of Magnetic Field

The magnetic field is an important component in the creation of both high mass and low mass stars. However, the importance of the magnetic field in the early stages of star formation is still not completely clear. The ambient magnetic field can govern (or prevent) the collapse and fragmentation of star-forming clouds since even weakly ionized star-forming material is connected to it. The polarization at millimeter and submillimeter wavelengths is dominated by polarized thermal dust emission, where the dust grains are oriented relative to the magnetic field, from the kiloparsec scale of molecular clouds down to the inner few hundred au immediately surrounding nascent stars. This dust polarization, as well as the polarization of spectral-line emission, has been the subject of interferometric studies. Mapping the morphology of magnetic fields in low- and high-mass star-forming regions is therefore critical to better understand how magnetic fields affect the star-formation process at early times, and how the field's role changes as a function of spatial scale, source environment, and source mass in relation to other dynamical effects (e.g., turbulence, rotation, thermal and radiation pressure, and gravitational collapse). Magnetic fields in low- and high-mass star-forming regions have been studied at a variety of spatial scales over the last fifty years, ranging from the $>$ 100 pc scale of molecular clouds to the 1 pc scale of clumps, to the 0.1 pc scale of dense cores, and finally to the 1000–100 au scale of protostellar envelopes surrounding forming protostellar systems.

A strong, well-ordered magnetic field offers outward pressure support for infalling material in models of magnetically regulated protostellar collapse. This is because

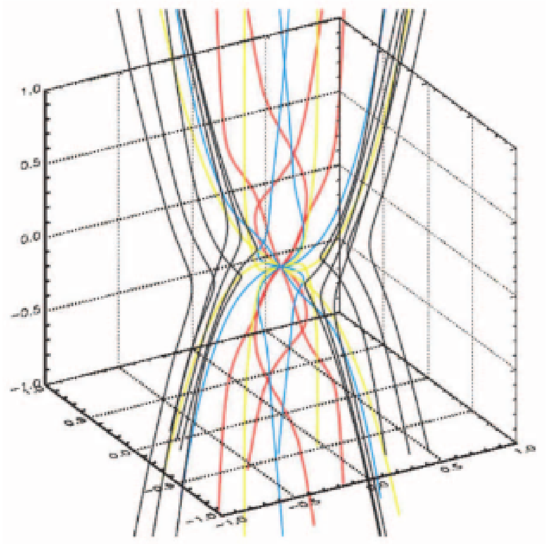

FIG. 16: Hour glass magnetic field in collapsing magnetized star forming cores [9]

the field is coupled (or "frozen") to the weakly ionized gas's small fraction of charged particles. In non-turbulent models, however, the non-ideal MHD effect of ambipolar diffusion allows neutral material (which makes up the majority of the star-forming core) to slowly slip past magnetic field lines, removing magnetic flux and eventually allowing collapse to occur once the mass-to-flux ratio exceeds the critical value.

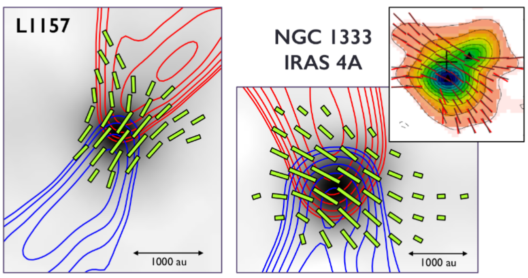

FIG. 17: Observations of hourglass-shaped magnetic field configurations in NGC-1333 [4]

C. Polarization dust emission as Magnetic Field Tracer

In general polarization levels tend to be low, perhaps indicating that the dust grains are not well aligned in cores and that most of the polarized radiation observed towards these cores is from the less dense gas envelopes in the surrounding cloud.

1. *Grain Alignment*

To cause polarization, the grains must line up. A dust grain in interstellar space will initially rotate around a random axis (and wobble). However, it needs to align its rotation with one of its principal axes (so it has a fixed projection).

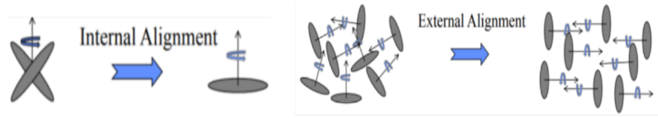

FIG. 18: Cartoon illustrating the grain alignment.

Unpaired spins in a rotating body yield magnetization. If the grain material has unpaired spins (paramagnetic, e.g. silicates) it can minimize energy while keeping angular momentum fixed by trading rotation for spin-flips thus causing magnetization. This is known as the Barnett effect (inverse of the Einstein-De Haas effect). The Einstein-De Haas effect is observed in the lab as torques on the equipment when applying a magnetic field to a paramagnetic sample. If on the other hand there are no unpaired spins (diamagnetic, e.g. carbon grains) there is no magnetization. The RAT(radiative torque alignment)[6] model is the leading candidate to explain grain alignment. As an irregular grain gets exposed to an anisotropic radiation field with $<$2a it gets spun up by the differential torques from the LHC and RHC components of the light. For a paramagnetic material, the Barnett effect gives the grain a magnetic moment which causes it to precess around the magnetic field lines. The grain then causes the grain's angular momentum to align with the B-field. The alignment efficiency and size distribution will vary with radiation field intensity. For deep star-less cores, there will be a depth beyond which no alignment takes place. Also, the alignment will depend on the angle between the magnetic and radiation field anisotropy. HII formation enhances grain alignment.

2. *Polarized dust emission*

The principal tracer of the magnetic field in star-forming areas at (sub)millimeter wavelengths is polarised thermal emission from dust grains. The long axes of oblong interstellar medium (ISM) dust grains with diameters of 100 m are positioned perpendicular to magnetic field lines in most cases. The "radiative torque" (RAT) mechanism, in which an anisotropic radiation field (e.g., the external UV field in the ISM, or the radiation from a deeply buried protostar) forces grains to align relative to the magnetic field, is currently considered as the best means to achieve this alignment. Magnetically aligned dust grains emit thermal radiation that is polarised perpendicular to the magnetic field at the physical scales of star-forming clouds, cores, and envelopes (i.e., scales 100 au).

3. Polarized molecular line emission

Another tracer of the magnetic field in star-forming areas is the polarisation of molecular-line emission. Magnetic fields affect molecular and atomic lines, causing their spectral levels to break into magnetic sub-levels. The Goldreich-Kylafis (G-K) effect occurs when an anisotropy in the radiation and/or velocity field results in a population of magnetic sub-levels that are not in local thermodynamic equilibrium (LTE) for some molecules. When the spectral line emission has an optical depth of 1, the ratio of the collision rate to the radiative transition rate (i.e., the spontaneous emission rate) is 1, and the gradient in the radiation and/or velocity field is considerable, polarisation from the G-K effect is most easily seen. The effect is strongest in simple molecules with the lowest rotational transitions, such as CO, CS, HCN, SiO, or HCO+. The G-K effect produces spectral-line polarisation that can be parallel or perpendicular to the magnetic field. Polarization from the G-K effect eventually traces the plane-of-sky magnetic field orientation with an ambiguity of 90^o due to the different optical depths of the parallel and perpendicularly polarised components in different positions on the sky.

VII. POLARIZATION: RESULTS AND DISCUSSION

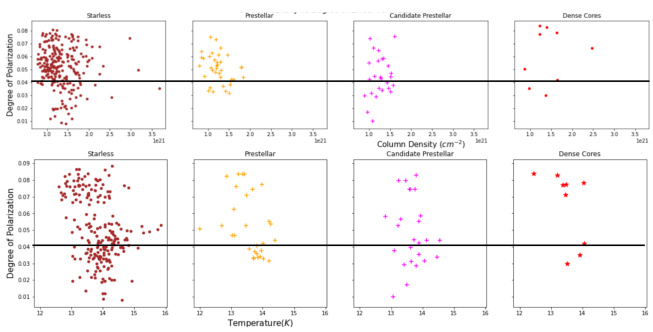

FIG. 19: Top panel showing the degree of linear polarization vs column density, bottom panel showing degree of linear polarization vs temperature. The solid black lines represent the average degree of polarization of the cloud.

These figures show that the average degree of polarization of these cores is higher than that of the cloud.

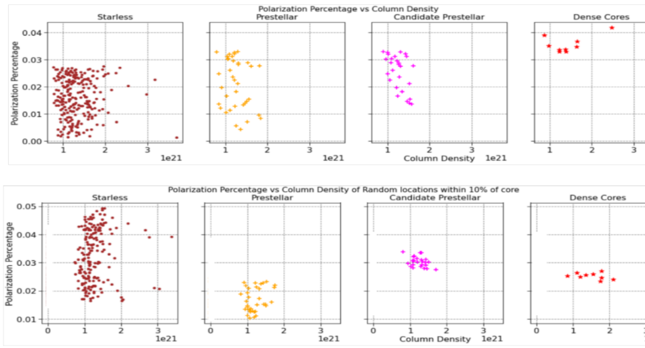

FIG. 20: Top panel showing polarization percentage vs column density for the actual cores, bottom panel showing polarization percentage vs column density for locations adjacent to the core(within 10%).

This plot shows us that overall cores show a higher polarization percentage as compared to the surrounding envelope. It also shows that out of all the cores, protostellar/dense cores show the highest polarization percentage. This indicates that dust grains are aligned strongly to the magnetic field.

These stacked polarized intensity maps of the cores also convey a similar picture,

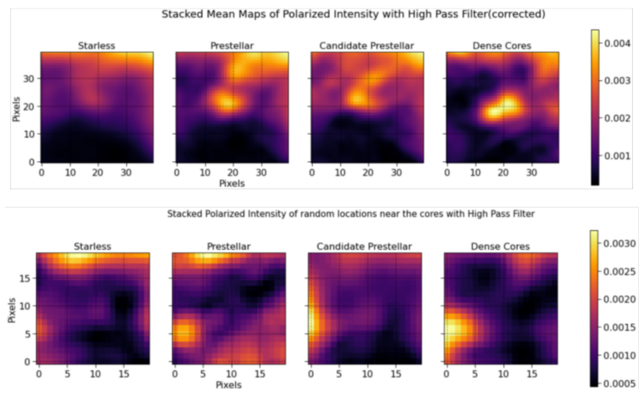

FIG. 21: Top panel showing polarized intensity for the actual cores, bottom panel showing polarized intensity for locations adjacent to the core(within 10%).

Clearly, the cores show a higher polarized intensity as compared to the surrounding envelope.

The radial profile of the polarized intensity map also shows us that as we move away from the core the polarized intensity drops off.

VIII. FINAL THOUGHTS AND FUTURE WORK

Overall through this analysis we can clearly see that cores are more polarized than their surrounding envelope. Subsequently, protostellar/dense cores show the maximum polarization as compared to starless cores. THis goes on to show that the dust grains in these cores are well aligned with the magnetic field. The final aim of this project is to be able to carry out this analysis with the higher resolution TolTEC Fields in Filaments Survey, which will start observing later this year. The 5" FWHM resolution TolTEC maps will allow to study the polarization properties of cores out to much larger distances. A higher resolution will help us to resolve these individual cores with unprecedented details.

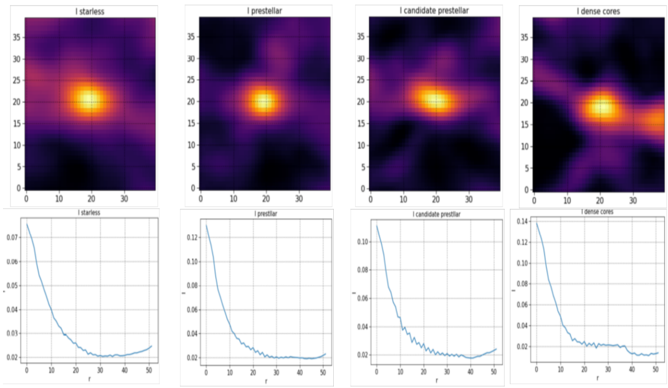

FIG. 22: Top panel showing polarized intensity for the actual cores, bottom panel showing the respective radial profile of the polarized intensity of the cores.(within 10%).

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