Magnetic fields in turbulent molecular clouds

We are investigating the effects of the magnetic field in the Polaris molecular cloud, depending on data obtained through polarimetry at the Beauty and the Beast Polarimeter at the University of Montreal, Canada.
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Chapter 1

An Introduction to the Interstellar Medium

1.1 Molecular Clouds

A molecular cloud is a dense cloud of interstellar gas in which molecules have formed in appreciable abundance. They are relatively cold dense clouds, with densities ranging from $10^{-6}$ to over $10^6$ molecules per cm$^3$ at temperatures around 10 - 100K, consisting primarily of molecular hydrogen (H$_2$) gas. Not directly observable under the natural conditions of a cloud, other simple molecules such as carbon monoxide (CO), with strong emission lines in the centimetre to sub-millimetre wavelengths of the EM spectra, can be used to determine the properties of such clouds.

Molecular clouds are classed into 3 main categories, depending on their properties - Giant Molecular Clouds (GMC’s), Molecular Clouds and High Latitude Diffuse Molecular Clouds (Infrared Cirrus).

Giant Molecular Clouds (GMC’s), with mass $10^4 - 10^6 \, M_\odot$ of densities, $n_{H_2}$, ranging between $10^2$ and $10^8$ cm$^{-3}$ at the most within the cloud, at temperatures 10-50 K, contain most of the molecular mass of the ISM. Spanning distances of tens of parsecs, they are some of the largest inhabitants of galaxies, often taking up large fractions of the night sky covering parts of constellations in the process, hence earning their names, e.g. Orion Molecular Cloud covers part of Orion. Star formation sites are dense cores ($>10^4 \, cm^{-3}$) which can be traced with ammonia, surrounded by filaments, sheets, bubbles and irregular clumps. They usually last for 10-100 million years before dissipating due to heat and stellar winds from newly formed stars within them.

Isolated, gravitationally bound small molecular clouds, consisting of H$_2$, carbon oxides, helium, dust, with a mass less than $100 \, M_\odot$ about a light year across, are often known as Bok Globules, usually found within HII regions and sometimes embedded within warm regions. Star formation sites in these clouds, are typically molecular cores, similar to that of GMCs, which result in the formation of double or multiple star systems. The density and structures of these cold regions, still remain a mystery, and is an area of research being followed.

High Latitude Diffuse Molecular Clouds, also known as Infrared Cirrus, were first detected by the IRAS at a wavelength of 12-100 microns. Diffuse filamentary clouds (30 cm$^{-3}$), visible at high galactic latitudes, are believed to be formed due to dust grains in cool diffuse atomic hydrogen clouds warmed by UV light from nearby stars.

Molecular clouds, being self gravitating magnetized turbulent compressible fluids, have complex internal structures - clumps and filaments of matter of varying densities all mixed together. Small individual clumps have supersonic internal motions at velocities, approximately several kms per second, the source suspected to be outflows from young stars during their primary stages of evolution. Magnetic fields which thread molecular clouds may play an important role in the longevity of turbulent motions and may support clouds against gravitational collapse.
1.1.1 The Polaris molecular cloud

At a fairly crude approximation of 150 pc away from Earth, obtained by observing the reddening of starlight, the Polaris Molecular Cloud is a cloud devoid of any star formation happening this present instant. There happen to be a few dense cores, however, no signs of collapse anytime soon are detected. This indeed makes it a perfect candidate to study the preliminary conditions that eventually lead to dense core formation since, it is very turbulent and all the pressure exhibited will only be caused due to the turbulence or magnetic field lines. The Polaris Cloud was first detected in HI as a spur of gas that appears to rise more than 30° out of the Galactic Plane. This region is an area rich in IRAS cirrus emission (Low et al. 1984) and is sometimes known as the Polaris Cirrus Cloud. On the large scale this cloud appears to merge with the Cepheus Flare cloud (see Fig. ??, and both clouds extend to high Galactic latitude. It was mapped in CO by Heithausen & Thaddeus (1990) at a resolution of 0.5°. One of the denser regions in the cloud is known as molecular cloud 123.5+24.9, or MCLD 123.5+24.9 (e.g. Falgarone et al. 1998), which was mapped at high spatial resolutions with the IRAM-30m telescope by Hily-Blant & Falgarone (2009). It has recently been observed by Ward-Thompson et al 2010, with the Herschel satellite. Several dense cores were unveiled, but these observations confirm the non–star-forming nature of this cloud. With a total mass estimated to be $\approx 2200 \, M_\odot$, the Polaris Cloud is, like most high-latitude cirrus, not gravitationally bound.
1.2 Interstellar matter

Being the reservoir from which new stars are born in the Universe, interstellar matter is of fundamental importance in understanding both the processes leading to the formation of stars, planetary systems, including the solar system, and ultimately the origin of life in the universe.

Although seemingly empty to the naked eye, photographs from even low-powered telescopes provide striking and visually beautiful images of the existence of matter between stars. Detections of radiation, which carry information, of gas near hot stars and spectroscopy measurements, as a result of transitions caused by energy absorption or emission between different energy levels within atoms, ions and molecules, further assert this prediction. Gravitational effects within the galaxy give indirect evidence for the existence of interstellar matter and allow us to deduce an upper limit to the interstellar density.

The multiphasic medium, ionized or neutral being either hot, warm or cold, is filled with non uniform, clumped gases of mean density, $n_H$, approximated to be $10^6 m^{-3}$, consisting of mainly hydrogen and very small percentages of other atoms such as helium, carbon, nitrogen and oxygen with other elements being even less abundant (McKee & Ostriker 1977). In pressure equilibrium are:

1. **Hot Ionized Gas**: Occupies most of space with $n \approx 10^3 m^{-3}$, $T_{kin} \approx 10^6 K$. Probable origin is overlapping old supernova remnants.

2. **Cold Neutral Gas**: Occupies smaller volume fraction providing most mass in the form of “clouds” with $n_H \approx 10^7 m^{-3}$, $T_{kin} \approx 30 – 100 K$. Characteristic length scale is approximatly parsecs. May contain simple molecules such as CO.

   Interface between the hot and cold regions:

3. **Warm Ionized Medium**: Ionization factor, $X \approx 0.7$, Outerskin. $n_H \approx 10^5 m^{-3}$, $T_{kin} \approx 800 K$.

4. **Warm Neutral Medium**: $X \approx 0.7$. Maintained by X-rays and cosmic rays. $n_H \approx 10^6 m^{-3}$, $T_{kin} \approx 8000 K$

Not in pressure equilibrium are:

5. **Dense Molecular Clouds**: $n_H \approx 10^9 – 10^{13} m^{-3}$, $T_{kin} \approx 10 – 50 K$. Extensive molecular formation. Sites of star formation. Typical length scales are approxilately parsecs.

6. **Photoionized (HII) regions**: Overpressured.

Mixed with the gas are the dust grains, with interstellar absorption and reddening, Solid state spectral features, reflection nebulae and element depletion providing evidence for the presence of such grains. Dust grains are distributed throughout the ISM at a ratio of 1 for every $10^{12} n$ atoms, of sizes $\approx 10^{-2}$ nm, with their size distribution characterized by $n(r) \propto r^{-3.5}$.

As well as gas and dust, the whole of the ISM is bathed in the universal cosmic microwave background (CMB) and by cosmic rays, comprised of very high energy electrons and protons.

1.2.1 The gas phase

1.2.2 The solid phase: Interstellar Dust Grains

Dust grains play a central role in the astrophysics of the ISM, from the thermodynamics and chemistry of the gas to the dynamics of star formation.

Evidence of Grains

The existence of interstellar dust was first inferred from obscuration, a property called "extinction", of starlight, often known as reddening because of the tendency for extinction to be greater in the blue than in the red. This property is measured in terms of an extinction coefficient, $\alpha$, such that the intensity $I_0$ of a star is reduced to

$$I = I_0 \exp \left(-\int_0^L \alpha \, dl\right)$$  \hspace{1cm} (1.1)
after passage through a distance $L$ of the ISM.

Extinction is most reliably determined using the pair method - comparing spectrophotometry of two stars of the same spectral class, one which has little material between it and us and the other behind a gas cloud. Comparison of the two spectra and their intensities, together with the assumption that the dust extinction goes to zero at very long wavelength, allows one to determine the extinction

$$A_{\lambda} = 2.5 \log_{10} \left( \frac{F_{\lambda}^0}{F_{\lambda}} \right)$$

as a function of wavelength, $\lambda$ which is comparable to the diameter of the dust grain, where $F_{\lambda}$ is the observed flux and $F_{\lambda}^0$ is the flux in the absence of extinction. The pair method has been used to measure extinction curves for many sightlines, in many cases over a range of wavelengths extending from the near-IR to the vacuum UV.

Observations of light from background stars, which encounter dust, show that visible light is often linearly polarized (see subsection on Polarization) by at least a few percent, with the amount of observed polarization seemingly proportional to the amount of extinction. If this mechanism occurs in the ISM, the conclusions obtained are that grains of isotropic behaviour are elongated with some degree of alignment between them, causing radiation with electric vectors parallel to the longer axes of the grains to be more heavily extinguished than vectors parallel to the shorter ones and polarization occurs.

Another main evidence for the presence of these dust grains, is that the observable universe is filled with diffuse light, not directed from any particular source, whose natural origin is in the scattering of starlight by interstellar grains and not in any other physical process, which contain information on the grain properties, mainly the “albedo” (or reflectivity) and the ‘phase factor’ describing whether grains scatter light preferentially forwards or backwards.

Other evidences include the relative decrease in abundances of elements in other stars, similar to that of the sun, in comparison to the sun, which can be explained by the formation of refractory solids (heat-stable and persistent) among those with high depletions, and unidentified spectral lines in the visible region of the spectrum, such as the wide absorption at 443 nm, and absorptions in the infrared support the existence of interstellar dust grains.

Formation of Interstellar Grains

Dust is primarily formed in the shells around stars in the red-giant and asymptotic giant branch (AGB) phases of their evolution (outflowing gas from cool stars), but some small fraction is also formed in the circumstellar shells around supergiants, novae, planetary nebulae (PNe), WC stars and in the ejecta of supernovae (SNe types Ia and II).

The material cools as it moves away from the star, but the densities (approximately $10^{19}$ m$^{-3}$) and temperatures ($10^3$ K) are so high compared to interstellar clouds that atoms can arrange themselves into most stable molecules at that temperature, where it is possible that the partial pressure of the molecule may exceed the vapour pressure of its solid form. As the temperature drops further, the gas becomes supersaturated in the molecules and corundum particles may nucleate (formation into a nucleus) and settle out. As solid absorbing particles, they experience a radiation pressure due to the stellar flux, and may be blown clear into the interstellar medium. On entering the ISM, through the effects of stellar winds, dust formed in circumstellar regions is subject to processing in the ISM. This processing may include erosion, fragmentation and destruction in SN-generated shock waves, which also provide the kinetic energy that is responsible for the turbulent diffusion of dust and the maintenance of turbulent motions in the ISM, grain growth via mantle accretion and coagulation in quiescent clouds, and fragmentation/coagulation in turbulent interstellar clouds. Once grains have moved away from their formation sources, they may grow further by the accretion of molecules from the gas. However, the timescale for this will be unacceptably long unless the gas density, $n$, is high in the order of $\geq 10^9$ m$^{-3}$.

Properties of Grains

The nature of the particles forming is sensitive to the cosmic abundance of the particles and the stability of the individual molecules at those temperatures. For Example, at temperatures of 1000-2000 K the molecule CO is
stable, and most of the C and O atoms are tied up in this form. If O atoms are in excess, then we expect such oxides as Al$_2$O$_3$ to form, whereas when there is an excess of carbon, solid grains of carbon, possibly graphite, are expected to form.

<table>
<thead>
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<th>composition</th>
<th>nature</th>
<th>evidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>'aromatic' carbons</td>
<td>small heat capacity,</td>
<td>depletion of carbon, extinction,</td>
</tr>
<tr>
<td>(hydrogenated)</td>
<td>stochastically heated,</td>
<td>'aromatic' emission bands</td>
</tr>
<tr>
<td>carbonaceous</td>
<td>amorphous grains</td>
<td>depletion of carbon, extinction,</td>
</tr>
<tr>
<td>(hydrogenated)</td>
<td>(not in mantles)</td>
<td>unpolarized aliphatic C–H band</td>
</tr>
<tr>
<td>silicate/metal oxide</td>
<td>amorphous, aspherical, magnetic inclusions</td>
<td>Si, Mg and Fe depletions, extinction,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Si–O bands at 10 and 20 μm,</td>
</tr>
<tr>
<td></td>
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<td>optical and IR polarization</td>
</tr>
<tr>
<td>amorphous ices</td>
<td>mantles on</td>
<td>IR absorption bands,</td>
</tr>
<tr>
<td>(H$_2$O, CO, CO$_2$,</td>
<td>silicate grains</td>
<td>polarized 3 μm H$_2$O ice band</td>
</tr>
<tr>
<td>CH$_2$OH, H$_2$CO, etc.)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 1.2: Table showing the dust properties from ?).

The reajustment of the temperatures of grains occurs through processes of re-radiation. A prefect radiator would reflect the energy content of space and be equal to the black-body temperature $T_{BB} \approx 3$ K. However, this is not possible as the peak of the Planck function would be in the millimetre range and grains of approximately $10^{-7}$ m radii cannot readily radiate at these wavelengths, and also as grains interior to the cloud absorb infrared photons emitted by hotter grains at the edges of a cloud, the temperature of the grain, $T_g$, must be higher than $T_{BB}$.

Grain temperature can be an important parameter in determining mechanisms by which grains may act as catalysts. Calculating the radius and the temperature of the grains depend on the efficiency for absorption of radiation by a grain, $Q_{abs}$, in the IR, which in turn depends on the refractive index in that region. Grain temperatures are generally above the critical value at which H$_2$ formation is suppressed for weakly bound H atoms. However, sites of slightly larger binding energy will allow H$_2$ formation to proceed with these temperatures permitting the formation of other molecules than H$_2$ if high enough.

The electric charge on the grain is also important in connection with catalysis. Ions in the gas, such as C$^+$ or H$^+$, will have either enhanced or inhibited collision rates with grains depending on whether the grain is charged negatively or positively. They are two main factors involved in determining the charge of the grain - collisions of positive ions and electrons with grains will affect the charge, therefore altering the rate of such collisions on grains, and photoelectric emission from grains. At visible wavelengths, the efficiency of photoelectric emission, $y$, is rather small, near $10^{-4}$, i.e. about $10^4$ photons may be needed for the emission of one electron, whereas for photons in the UV, efficiencies are thought to be higher, especially in the case of very small particles ($a \approx 10\text{nm}$) where electrons escape easily, and can be compared with a collision rate for electrons. We see that if $y$ can be as large as 0.1 then typical low-density clouds in which $n_e \approx 10^5 \text{ m}^{-3}$ have grains whose charge is dominated by the photoelectric effect and are therefore positively charged. In this case, collisions of C$^+$ and H$^+$ will be spatially suppressed having consequences for catalysis involving these ions. But since the grain material cannot be positively identified, we can only make assumptions about its photoelectric properties.

**Destruction of Grains**

Few processes that cause the destruction of dust grains are photon-grain interactions (Photodesorption, sublimation and coulomb explosion), Atom/ion-grain interaction (sputtering - a process in which an incident high velocity atom knocks one of the lattice atoms completely out of the lattice) for grains made of durable materials and grain-grain interactions (coagulation, shattering disaggresion, vaporization if the grain accretes icy mantles).
The Interstellar Dust Model is needed to fit all the observational constraints raised due to interaction of grain with ambient gas and the interstellar radiation field, but also contain many unresolved issues, a few being the efficiency of dust formation in various sources, the composition and survival of newly formed dust, efficiency of dust destruction, the reconstitution of dust particles by accretion and the resulting dust composition and the global effect of dust evolution, which provide avenues for future research.
Chapter 2

Magnetic Fields In Molecular Clouds

Magnetic fields are very crucial to many astrophysical processes, such as star formation, accretion of mater, transport processes (e.g. transport of heat), modifying turbulence and cosmic rays.

Conducting matter is caught up in magnetic field lines with magnetic pressure and tension defining its dynamics. Alignment of dust grains, be it paramagnetic, mechanical, or by radiative torque mechanisms, cause polarization of light from background stars which allow the magnetic field to be traced and provide information about the field structure and topology.

2.1 Polarization

Light is classified as an electromagnetic (EM) wave, which is transverse and has vector characteristics. The instantaneous electric field of the wave can be resolved into two components at right angles to each other (and to the direction of propagation) - one component depicting the magnetic field, \( B \), and the other the electric field.

In "natural" light, the directions of polarization (specified by the plane of oscillation of the electric vector) of various photons are randomly orientated, and the overall light beam has no net polarization or preferred phase of oscillation. A light beam is said to be polarized when there is a preferred plane of oscillation, with more photons oscillating in this plane than in other planes. A polarized beam can be completely (100%) polarized if all photons oscillate in the same plane, or the beam can be only slightly polarized, with a small excess oscillating in some preferred plane. The polarization, \( P \), may also be described as a fraction (or percentage) by specifying the intensity of the excess polarization relative to the total intensity of the beam, \( I_{\text{tot}} = I_{\text{min}} + I_{\text{max}} \), as given below:

\[
P = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{tot}}} \tag{2.1}
\]

The most general form of polarization is elliptical, with linear and circular polarizations being special cases of this form, for which the tip of the electric vector executes an ellipse at the signal frequency. The distinguishing parameters of the ellipse are orientation, axial ratio and handedness. Monochromatic elliptically polarized waves can be described as either two unequal linearly polarized components with a phase difference of \( \pm 90^\circ \), or as the sum of two linearly polarized components (which may or may not be equal) with a phase difference of something other than \( 0^\circ \) or \( \pm 90^\circ \). Quasi-monochromatic 100% elliptically polarized light is obtained when (correlated) slow and often random variations of amplitudes and phases were introduced to the linearly polarized waves constructing the elliptically polarized wave. The elliptical pattern, however, is a constant of the wave. Polychromatic 100% elliptically polarized radiation is a sum of quasi-monochromatic components, which remain constantly elliptical in spite of the amplitude and phase variations.

Linear polarization (when photons oscillate in one preferred direction), is characterized as being:

- monochromatic: wave at constant orientation, amplitude and frequency with it’s strength at one point in space varying strictly sinusoidally with time,
- quasi-monochromatic 100% linearly polarized: the amplitude and phase vary slowly and often randomly with time and when modified still remains 100% linearly polarized, and lastly,
Figure 2.1: Three polarization mechanisms involving interstellar grains (Dust polarisations from extinction measurements P.Bastien)

- polychromatic 100% linearly polarized occurs when the radiation is a superposition of quasi-monochromatic waves at various frequencies with no stable phase relation between the electromagnetic field between them.

Two independent monochromatic linearly polarized waves, of the same frequency but with vibration directions at right angles to each other, can propagate through empty space and other homogeneous isotropic media, along the same path at the same time. They are both solutions of Maxwell’s equations and only two independent solutions are possible: a linearly polarized wave of any other orientation can be seen as an in-phase combination of these two basic waves, the ratio between their amplitudes determining the position angle of the direction of vibration of the result.

It is also possible for light to be circularly polarized, with the electric vector describing a right or left helix in space at some instant, which will be seen to rotate as the light beam passes an observer.

2.2 Polarization of Interstellar Grains

Three common mechanisms for producing polarization in the ISM are dichroic extinction, scattering of stellar light (refer to Fig. 2.2) by circumstellar grains or by grains in reflection nebulositis and birefringence.

2.2.1 Dichroic Extinction

Extinction is the attenuation of an EM wave by scattering and absorption as it traverses a particulate medium. Dichroism is the differential extinction of orthogonally polarized radiation components.

Interstellar dust particles being non-spherical (may have crystalline structure) have different scattering cross-sections for light linearly polarized parallel to the geometric or crystalline axis than for light polarized at right angles to it, and may introduce a slight preferential orientation with respect to the field, due to its influence on magnetic and electrical properties. These deviations from perfect isotropy produce a certain amount of polarization by differential extinction of the linear polarizations along and across the transverse magnetic field component. The degree of polarization of light from distant stars peaks at a wavelength which is related to the median size of the interstellar grains with the difference of extinctions related to the properties of aligned grains by taking into account that the extinction is proportional to the product of the grain density and their cross-sections.

If the extinction in the direction of alignment is $\tau_\parallel$ and the perpendicular direction is $\tau_\perp$, the polarization, $P_{\text{abs}}$, by selective grains can be described as (Tracing Magnetic Fields with Aligned Grains, A.LAzarian)

$$P_{\text{abs}} = \frac{e^{-\tau_\parallel} - e^{-\tau_\perp}}{e^{-\tau_\parallel} + e^{-\tau_\perp}} \approx -\frac{\tau_\parallel - \tau_\perp}{2}$$

(2.2)

where the latter approximation is valid for $\tau_\parallel - \tau_\perp \ll 1$. Although absorption and scattering processes occur simultaneously, there are instances where one or the other dominates.

Absorption dominates over scattering for sufficiently small absorbing particles (with the volumetric extinction being independent of their size), and is mainly important in the NIR regime. It is usually manifested by absorption bands or absorption edges and can strongly affect extinction in several ways: extinction may either increase or decrease with increasing absorption, symmetric absorption bands in bulk matter may be transformed into highly assymetric or even inverted extinction bands in small particles. (Absorption and scattering of light by small particles, Craig F. Bohren, Donald R. Huffman). Polarized true absorption will - according to Kirchhoff’s law - be accompanied by polarized emission; see Aitken et al (1986) and Hildebrand (1988).

Scattering dominates when the particle is about the same size as or larger than the wavelength, usually in the optical range of the EM spectrum.
Polarized Emission

Emission by aligned grains produces polarization in the thermal IR and into the submm (check out Vaillancourt).

Fig 2. Polarization involving interstellar grains (Tracing Magnetic Fields with Aligned Grains, Lazarian (2007))

The difference in $\tau_\parallel$ and $\tau_\perp$ (both assumed to be small) for aligned dust grains results in the emission polarization, $P_{em}$:

$$P_{em} = \frac{(1 - e^{-\tau_\parallel}) - (1 - e^{-\tau_\perp})}{(1 - e^{-\tau_\parallel}) + (1 - e^{-\tau_\perp})} \approx \frac{\tau_\parallel - \tau_\perp}{\tau_\parallel + \tau_\perp}$$

In the UV, visible and NIR, polarization is dominated by dichroic extinction and scattering.

2.2.2 Scattering

There are a number of situations in astronomy in which scattered radiation reaches the observer. Microscopic scattering of radiation, by free electrons, aroms, molecules, or very small dust grains, through an angle of roughly $\pi/2$, results in radiation that is predominantly linearly polarized in the plane normal to the scattering plane, the plane containing the incident and the scattered rays. The scattered photon may be at the same frequency as the incident photon (Rayleigh and Thomson scattering) or the frequency may be different (Compton or Raman scattering). // If scattering plane is horizontal and photon incident is vertically polarized, it will induce vertical oscillations in the scattering particle, the radiation from the scattering particle may be emitted in any direction in the horizontal plane, and the scattered radiation will be vertically polarized. If the incident radiation is horizontally polarized, the scattering particle will oscillate horizontally, normal to the direction of the incident photon, and the radiation will be strongest for forward or backwards scattering. In the horizontal plane, a scattering angle of near $\pi/2$ is parallel to the oscillation direction of the scatterer, so the amplitude of scattered radiation is minimum in that direction, and the probability of emitting horizontally polarized radiation is small, allowing most of the radiation emitted at a scattering angle of about $\pi/2$ to be polarized vertically.// Measurement of the linear polarization can help identify the scattering mechanism by pinpointing an obscured source, or by yielding information on the properties of the source (e.g. orientation as projected on the sky, spottedness) and/or the scattering medium (e.g. size, shape, degree of alignment and refractive index of the particles), with spectro-polarimetry seperating different components according to thir frequency. Scattering is very important in circumstellar environments. If the density of the material is low, single scattering occurs and produces a centro-symmetric pattern where the vectors are perpendicular to the scattering plane defined by the star, the scatterer and the observer. In the presence of a dense disk, a pattern of aligned vectors can be produced due to multiple scattering.

2.2.3 Birefringence

The other way in which the intervening medium can influence the state of polarization is by birefringence of the medium. For birefringence to have any effect, the radiation generally must have been polarized elsewhere in the first place. Linear birefringence is expected to occur at optical wavelengths in the ISM, due to the optical properties of the aligned dust particles that also cause the linear polarization. This linear birefringence can convert previously generated linear polarization into circular polarization, if the magnetic field is twisted in some systematic way. The interstellar circular polarization is very small, and good measurements are only available for a few stars; the main use of this phenomenon has been for estimating the (real part of the) refractive index of the interstellar grains. Deguchi and Watson (1985) have estimated linear birefringence effects in absorption lines at radio wavelengths; in this case, the birefringence is due to unequal populations in the magnetic substates of atoms and molecules.

Circular birefringence due to a longitudinal magnetic field component is called Faraday Rotation and is an important observable at radio wavelengths. Faraday rotation is proportional to the square of the wavelength, which means that there is only a relatively small wavelength range over which it is observable in any one application; if the wavelength is too short, the rotation is too small to detect; if it is too long, the inhomogenities in the intervening medium cause many different values of the rotation to be present within the telescope beam and no net polarization remains (Stokes Q and U average out to 0). On the other hand, the wavelength-squared
dependence of polarization angle (in simple cases) is the one sure proof that we are measuring a linealy polarized component rather than some instrumental effect. It is also the only observable connected with the longitudinal field component when linear polarization is all we can detect (see Spoelstra (1984) and Sofue et al. (1986)): the quantity measured is the product of longitudinal magnetic field component and density of thermal electrons, integrated over the line of sight. Faraday rotation has been exploited to investigate fields within distant radio sources, the intergalactic medium and the galaxy.

For an arbitrary los, a magnetized plasma will have elliptically polarized eigenmodes and will be elliptically birefringent. In general, elliptical birefringence will cause conversion from one form of elliptical polarization to another (conversions between the stokes parameters). On astronomy, there is usually too little information to make it worthwhile to refer to the general case, and quasi-longitudinal or quasi-transverse conditions are invoked.

2.3 Grain Alignment Theory: Major Mechanisms

All grains are always aligned and the alignment happens with the longer grain axes perpendicular to magnetic field. However, observational data indicated a few exceptions - Grains smaller than a critical size (which can be $10^{-4}\text{ cm}$ or larger) are either not aligned or marginally aligned (Mathis 1986, Kim & Martin 1995), Carbonaceous grains are not aligned, whereas silicate grains are aligned (Mathis 1986), Small grains deep within molecular clouds are not aligned (Goodman et Al. 1995, Lazarian, Goodman & Myers 1997, Cho & Lazarian 2005 and references therein) and grains might be aligned with longer axes parallel to magnetic fields (Rao et al 1998).

2.3.1 Paramagnetic Alignment

The Davis-Greenstein (1951) mechanism (D-G mechanism) is based on the paramagnetic dissipation that is experienced by rapidly rotating grains (angular velocities of $10^5 - 10^6 \text{ rad/sec}$). Paramagnetic materials contain unpaired electrons that get orientated by the interstellar magnetic field $B$, causing grain magnetization that varies as the vector of magnetization rotates in the grain body coordinates. Paramagnetic loses occur at the expense of the grain rotational energy. If the grain rotational velocity $\Omega$ is parallel to $B$, the grain magnetization does not change with time and no dissipation takes place, allowing the paramagnetic dissipation to decrease the component of $\Omega$ perpendicular to $B$ and one may expect that eventually grains will tend to rotate with $\Omega \parallel B$ provided that the time of relaxation $t_{D-G}$ is much shorter than the time of randomization through chaotic gaseous bombardment, $t_{gas}$, which is difficult to satisfy in practical terms.

2.3.2 Mechanical Alignment And Radiative Torque Alignment

The Gold (1951) mechanism is a process of mechanical alignment of grains, involving an ellipsoidal grain interacting with a stream of atoms of mass $m_a$ and velocity $v_a$. Assuming inelastic collisions taking place, every bombarding atom transfers to the grain an angular momentum,

$$\delta J = m_a r \times v_a$$

perpendicular to both the grain axis, $r$ and the velocity of the atoms $v_a$. This type of alignment is efficient when limited to supersonic flows.

Radiative torques caused by anisotopic starlight radiation induce spinning and the alignment of prolate grains (??) with the longer axis perpendicular to the magnetic field.

These effects result in broad-band linear polarization of light from distant stars, of magnitude typically 1% polarization per kpc of distance. The direction of polarization reveals the predominant direction of the interstellar magnetic lines of force along the line of sight (los).
Chapter 3

Turbulence

Turbulence, very simply defined, is the gas flow resulting from random motions at many scales.

Often turbulence is treated as incompressible, with reference to terrestrial applications - Subsonic root-mean-square (rms) velocities and constant densities with energy dissipation primarily occurring in the smallest vortices, such as filamentary vortex tubes (where the dynamical scale $l$ is shorter than the length on which the viscosity acts $l_{visc}$).

However, in the ISM, gas flows vary significantly in three important ways. Firstly, the gas here is highly compressible. The Mach number, the ratio of the speed of an object moving through any fluid to the speed of sound in the substance, range from unity in the warm diffuse ISM ($\approx 10^4$K) to about 50 in cold dense molecular clouds (10 K). Also, the equation of state of the gas is very soft due to radiative cooling, so that pressure, $P \propto \rho^\gamma$ with the polytropic index falling in the range $0.4 < \gamma < 1.2$ as a function of density and temperature. Lastly, the driving of turbulence is not uniform, but comes from blast waves and other inhomogeneous processes.

In its simplest form, the Kolmogorov-turbulence describes an incompressible, non magnetic fluid in which the statistical properties of the flow are independent of the scale within the inertial range giving a fractal, spatial structure. Other turbulence fluid models describe a supersonic, isothermal turbulent flow or turbulence by individual motion of cloudlets.

Turbulence, is a very important factor controlling evolution and, perhaps, formation of molecular clouds and the subsequent production of stars. It is created and sustained via sources of energy injection in several forms, and cascades down to the smallest scales, creating eddies and stirring up the cloud. Field supernovae, often dominant in regions where they occur, spatio-temporally intermittent development of outflows, stellar winds and HII regions within the cloud which, although initially start off as small scale motions, can expand their spheres of influence over time and may ultimately contribute to large-scale turbulent motions but fail to explain the origin of the molecular cloud as a whole, shocks in spiral arms potentials and magneto-rotational instability in galactic disks or in background levels in molecular clouds are some of the main driving sources. These mechanisms may be distinguished by the effective spatial scale at which they preferentially operate, and clues to the nature of the energy injection mechanisms may be extracted from spectral line imaging observations of molecular clouds.

Molecular clouds are dominated by turbulence driven on large scales compared to their cloud sizes, which may be simply a result of the driving scale itself determining the size of molecular clouds. Most of these processes likely require that the molecular turbulence is inherited from still larger scale motions in the atomic ISM. The presence of large-scale turbulence in molecular clouds would be a natural, inevitable consequence of their formation, with their subsequent evolution significantly affected by dynamical events occurring in the larger scale ISM and evolving on longer timescales than that present in the central core region. Internal driving of turbulence can be important in sub-parsec regions of larger clouds, where a large number of outflows can develop, although it is not currently clear how (or if) the effective fractional driving scale would increase.

Molecular clouds are continually driven on large scales with most sufficiently young that the initial seeding of turbulence by the large scale flows that created the cloud has not yet dissipated, with replenishing in the more dense regions occurring by both local sources and external "driving" by larger-scale flows originating in the surrounding cloud, as part of the overall hierarchy of turbulent motions. Central star-forming regions in such clouds cannot be considered as closed systems, evolving independently of their larger scale surroundings. It is not
yet clear whether clouds are continually driven, or whether the turbulence is in a decaying state. If clouds are driven at large scales, the turbulent dissipation time is comparable to their dynamical time.

A number of methods for studying resolved velocity fields in molecular clouds have been developed and applied. These include projected velocity (line centroid) analysis (D.C. Lis, T.G. Phillips & al, 1998), the spectral correlation function (Erik W. Rosolskys, Alyssa A. Goodman & al, 1999), velocity channel analysis, and principal component analysis. To date, these methods have been used to estimate the power law indices of the velocity structure function/power spectrum in molecular clouds from observed data cubes of molecular line emission. Application of PCA to Outer Galaxy molecular clouds revealed that, in comparison to simple models, the observational record favoured large-scale driving of turbulence in the molecular clouds. In their study of the Polaris Molecular Cloud, Ossenkopf and Mac Low (2002) also found that large-scale driving of turbulence provided a better explanation of the cloud’s velocity structure.

### 3.0.3 Supersonic Turbulence

Supersonic turbulence can naturally lead to the complex structure and the large density contrast found in molecular clouds, a process often referred to as turbulent fragmentation. Magnetic fields can affect the outcome of the turbulent fragmentation by reducing the density contrast of shocks, by providing support under gravitational collapse, and by enhancing angular momentum transfer.

### 3.0.4 Subsonic Turbulence

Tracing Turbulent Ambipolar Diffusion in Molecular Clouds - Hua-Bai Li, Martin Houde, Shih-ping Lai, T.K.Sridharan

Ambipolar Diffusion (AD), most clearly visible towards small scales, refers specifically to the decoupling of neutral flows from magnetic fields and plasma in the initial stage of star formation. At small scales, this might enhance the efficiency of large-scale AD and the friction between the ions and the neutrals may accelerate the dissipation of turbulent energy. Since both turbulence dissipation and mean-field AD can be crucial effects for mass condensation, the turbulent AD scale is an important parameter for the star formation process. Turbulent AD can cause differences between the velocity dispersions (VDs) of coexistent ions and neutrals.

The neutral particles in this case are mostly hydrogen molecules in a cloud that would undergo gravitational collapse if it were not collisionally coupled to the plasma. The plasma is composed of ions (mostly protons) and electrons, which are tied to the interstellar magnetic field and therefore resist collapse. In a molecular cloud where the fractional ionization is very low (one part per million or less), neutral particles only rarely encounter charged particles, and so are not hindered in their collapse into a star.
Chapter 4

Star Formation

High density regions of Interstellar clouds are sites of star formation, usually Giant molecular clouds. Cloud collapse is the most vital step in the process of star formation. As long as the kinetic energy of the gas pressure is equal to the internal gravitational forces potential energy, the gas cloud will remain in hydrostatic equilibrium. However, the cloud will undergo gravitational collapse if the gas pressure is not sufficient enough for its mass - Jeans Mass, which depends on the temperature and the density of the cloud. Another process, Triggered Star Formation, where several events, such as collision of molecular clouds, nearby supernova explosion, relativistic jets from black holes, galactic collisions, etc can cause collapse.

As a cloud collapses, it breaks into smaller fragments until it reaches stellar mass. Energy, from the release of gravitational potential energy, is radiated away causing the density and the temperature to increase, until it condenses into rotating spheres of gas, Stellar Embryos. IR spectroscopy can be used in conjunction with the images from the HST to give us a clear picture on the properties of star forming regions - temperatures and densities to give the physical properties, abundance and distribution of elements analysing the chemical composition, as well as the rates of collapse and their velocity structures.

We know for sure that they are caused by gravitational collapse, but there are other features which must be taken into account - turbulence effects, macroscopic flows, rare rotation, magnetic fields and the cloud geometry itself. Turbulence caused fragmentation of the cloud and collapse on smaller scales, whereas, both the rotation and magnetic fields can hinder collapse.

There are many unanswered fundamental questions on the process of star formation, the most important, perhaps being, What drives the Star Formation process? The current accepted theoretical models are:

1. Magnetic support of self-gravitating clouds with ambipolar diffusion removing support in cores and triggering collapse
   However, this model has been questioned under observations of ratios of starless cores to cores with protostars and young stars that suggest that the timescales of molecular clouds are much shorter than the ambipolar diffusion timescale, hence star formation must take place on a cloud crossing time. This allows us to come to the conclusion that molecular clouds are intermittent phenomena in an interstellar medium dominated by turbulence with magnetic fields seemingly unimportant.

2. Compressible turbulence forming self-gravitating clumps that collapse as soon as the turbulent cascade produces insufficient turbulent support.

Two crucial parameters citing differences between the two models are the ratio of thermal to magnetic pressure, $\beta_p$, also sometimes listed in terms of the energies, $\beta$ where $\beta_p = 2\beta$, and the mass to magnetic flux ratio, $M/\Phi$, which defines the extent to which a static magnetic field can support a cloud against gravitational collapse. It is convenient to state the ratio in terms of the critical value, $(M/\Phi)_{crit} = \frac{1}{2\pi\sqrt{G}}$ (for disks with only thermal support along field lines), and hence defining $\lambda \equiv (M/\Phi)_{actual}/(M/\Phi)_{crit}$, which can be obtained from observation, given that the column density, $N$, in $cm^{-2}$ and the magnetic Field strength, $B$, in $\mu G$, are measured:

$$\lambda = \frac{(M/\Phi)_{obs}}{(M/\Phi)_{crit}} = \frac{mNA/|B|A}{1/2\pi\sqrt{G}} = 7.6 \times 10^{-21} \frac{N(H_2)}{|B|}$$

(4.1)

Where $m = 2.8m_H$ allowing for He and $A$ is the cloud area of the observations.
Magnetically strong clouds (e.g. $\beta = 0.01$, $\lambda < 1$), structurally thin disks or oblate spheroids, consist of field lines, supported by thermal pressure, which are smooth in nature, mildly changed from the original morphology, and found to be parallel to the minor axes of the cloud. An original morphology with parallel magnetic field lines will be transformed into an hourglass morphology, as the field lines are drawn towards the core with the tension of the bent field lines providing support. These initial magnetically subcritical clouds will be very stable against collapse but will become unstable in its core due to ambipolar diffusion (fastest in shielded, high density cores), causing a drift of neutrals into the core with no significant rise in magnetic flux, becoming supercritical ($\lambda \approx 1$), allowing dynamical collapse and star formation process to occur. The envelope will still continue to be supported by the magnetic field. The prediction for this particular model is that $\lambda < 1$ in cloud envelopes, with the core $\lambda$ being approximately 1. However, as the collapse phase has a very short timescale, very few supercritical cores, $\lambda > 1$, would be observed. Hence, this model tightly constrains $\lambda$.

![Collapsing of a cloud core](image.png)

Figure 4.1: Collapsing of a cloud core ?).

Compressible turbulence allows no specific prediction to be made for $M/\Phi$, but in general the diffuse ISM should be magnetically supercritical (e.g. $\beta = 1$) if turbulence is to form clouds, hence $M/\Phi$ must be supercritical ($\lambda > 1$) in molecular clouds if magnetic support does not dominate. Due to the weak magnetic field, the field lines cannot resist twisting due to turbulence, hence forming a chaotic mess, with small-scale irregular structure. Averaging along the line of sight might cause some smoothing to take place, however, significant irregularity can still be observed in polarization maps with no correlation to the cloud morphology. Being initially supercritical, these clouds collapse to form stars once turbulence dissipates, within a relatively short timescale ($\approx 5 - 10$ Myr), unless turbulence supports the cloud and is maintained by continuous forcing. If no sufficient magnetic field was present to prevent collapse of self-gravitating clumps formed by compressible turbulence, its compression during collapse cannot achieve equilibrium and halt collapse. This model places no constraints on the value of $\lambda$ and may take any value $> 1$, although with very weak magnetic fields, clouds will be highly supercritical, $\lambda >> 1$. 

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At the present moment, the observations of molecular cloud cores suggest that they are approximately critical with no clear evidence that sub- or supercritical clouds dominate, causing observations to remain inconclusive in deciding between the two extreme-case models of what drives star formation.

Further advancement in understanding the role of magnetic fields in the star formation process is required and additional high sensitivity surveys of magnetic field strengths must be conducted in order to further refine the assessment of the importance of magnetic fields in molecular cores and envelopes.
Chapter 5

Observation Of Interstellar Magnetic Fields

5.1 Observational Methods

Observations of the magnetic field and the turbulence field can help us determine the cause of star formation in molecular clouds. The 3 most important techniques, used till date, are:

5.2 Zeeman Splitting

The Zeeman effect causes the splitting of a spectral line, in the presence of a static magnetic field, $\mathbf{B}$, into 3 separate frequencies: $\nu_{\pi} = \nu_0 - \nu_Z$; $\nu_{\sigma} = \nu_0$; and $\nu_{\sigma+} = \nu_0 + \nu_Z$; given that $\nu_0$ is the line frequency, $\nu_Z = |\mathbf{B}| \times Z$, where $Z$ is the Zeeman Sensitivity measured in Hz/$\mu$G, and $\nu_Z \approx \Delta \nu$, where $\Delta \nu$ is the line width, if $\mathbf{B}$ is sufficiently large. In this case, the 3 components may appear separated, allowing $\mathbf{B}$ to be derived directly from the measured $\nu_Z$. Generally, this is not possible as $\nu_Z \ll \Delta \nu$. However, Observation of the Stokes V Spectra, $V = (dI/d\nu)\nu_Z \cos(\theta)$, discloses the direction and the magnitude of the line-of-sight component, $B_{los} = \nu_Z \cos(\theta)/Z$, can be calculated by fitting the frequency derivative of the Stokes Parameter I, $dI/d\nu$, spectrum to the observed V spectrum. Correcting statistically for the fact that only one component of $\mathbf{B}$ is measured, $B_{los} = B \cos(\theta)$. For a large number of clouds with randomly orientated magnetic fields with respect to the observed line of sight:

$$B_{los} = \int_{0}^{\pi} |\mathbf{B}| \cos(\theta) \sin(\theta) d\theta = \frac{1}{2} |\mathbf{B}|$$ (5.1)

Molecular lines sensitive to the Zeeman Effect usually have a value, $Z \approx M_B$ and usually are those species with an unpaired outer electron will have a magnetic moment about the value of the Bohr Magneton, $M_B = \frac{eh}{4\pi mc}$ which is approximately 1.4 Hz/$\mu$G. However most molecules atour disposal do not have large Zeeman Splitting factors, and hence, our possibilities to obtain a measure of the Interstellar Magnetic Field successfully, are limited to the 21-cm line of H I, 18-cm and 2-cm lines of OH, 1.3-cm maser line of H$_2$O, and the 3-mm lines of CN, among others. The Zeeman Effect is the only available technique for measuring the magnetic field strengths directly of interstellar clouds.

5.3 Spectral-Line Linear Polarization

Linear Polarisation may also arise in radio-frequency spectral lines formed in the interstellar medium, even when the Zeeman effect seems to be negligible. The Goldreich-Kylafis (GK) effect causes certain molecular line emission, limited to strong lines, to be weakly linearly polarized, e.g., in the presence of a magnetic field, which has the potential to yield information on magnetic field morphologies along the line of sight through its dependence on
5.4 Polarization of Dust Emission

Elongated interstellar dust grains, normally with their short axes, have the property to be aligned with magnetic fields giving rise to linear polarization of thermal emission, in the optical, millimetre and infrared wavelengths. Frictional Processes internal to the grain will dissipate rotational energy as heat, by Barnett Dissipation processes, causing the grain to spin about its minor axis - the axis with the greatest moment of inertia, in an effort to conserve the angular momentum, $\mathbf{J}$. (Barnett Relaxation in Thermally Rotating Grains, A.Lazarian and W.G. Roberge, 1997). Therefore, the Davis-Greenstein mechanism, in which, the spin axes of the grains are aligned via paramagnetic relaxation by dampening the angular momentum components perpendicular to $\mathbf{B}$, is normally assumed. Maximum extinction cross section is produced perpendicular to the field, $B_{\text{pos}}$, hence, extinction will be maximal in this direction other than parallel, and by default its position angle as well, allowing the morphology of the plane of the sky to be determined from maps of polarized dust emission. However, there are also other alignment mechanisms, such as Gold Alignment which dominates paramagnetic relaxation in protostellar jets or wind regions.

This technique allows the dispersion of polarization position angles, $\delta \theta$, to be determined, which can be used in conjunction with the above technique in the Chandrasekhar Fermi Method to estimate $B_{\text{pos}}$ and combined with $B_{\text{los}}$ from the Zeeman Effect, an estimate for the total magnetic field strength, $\mathbf{B}$, can be obtained.

5.5 Chandrasekhar-Fermi Method

An estimation for the magnetic field strength, $H$, was obtained theoretically using 2 different methods and observations of the spiral arm of our galaxy (Chandrasekhar & Fermi (1953)).

The first method involved interpreting the dispersion in the observed planes of polarization of light from distant stars in a direction perpendicular to the spiral arm, which yielded the conclusion of there being irregular fluctuations in the direction of polarization of the distant star, indicating that the magnetic field lines were 'wavy' (weak magnetic field).

The velocity, $V$, of the transverse magneto-hydrodynamic wave is given by:

$$ V = \frac{B}{(4\pi \rho)^{\frac{1}{2}}} $$  (5.2)

where $\rho$ is the density of the diffused matter, not including the average density due to the stars. The transverse oscillations of lines of force, according to $V$ is described by:

$$ y = \theta \cos k(x - Vt) $$  (5.3)

where $\theta$ is the angular deviation from the plane of polarization, $x$ is the longitudinal coordinates and $y$ is the lateral displacement. A relationship between $\theta$ and the strength of the magnetic field, $B$, was obtained by equating the lateral velocity of the lines of force with the lateral velocity of the turbulent gas, derivatives of the equation above with respect to $x$ and $t$, and combining the equations with an equation for $v$, the root mean-square velocity of the turbulent motion, to give a simple relationship:

$$ B = \left(\frac{4}{3} \pi \rho\right)^{\frac{1}{2}} \frac{v}{\theta} $$  (5.4)
The same relationship can be obtained using a second method involving equating the gravitational pressure to the sum of the material pressure and the pressure due to the magnetic field, as per conditions of equilibrium.

However, a few modifications are applied to the basic CF analysis in order to be utilised to the scenario of molecular clouds (??). The basis is the same, but, in the case of galactic arms, the dispersion is due to magnetohydrodynamic (MHD) waves - the displacements are perpendicular to the direction of propagation, and in the case of turbulent dispersion in molecular clouds, no preferable direction exists. Also, structures due to the effects of differential rotation, gravitational collapse or expanding HII regions, need to be taken into account, which yield a larger dispersion than in galactic arms. In reality, contributions from the turbulence, denoted by $b$ and the dispersion function of the angles are combined quadratically along with the measurement uncertainties on the polarization angles, $\sigma_M(l)$ to produce an expression for the total dispersion, $\Delta \theta$, calculated from the polarization map:

$$< \Delta \theta^2(l) >_{\text{tot}} \simeq b^2 + m^2 l^2 + \sigma_M^2(l)$$

(5.5)

The dispersion, $\sigma_\theta$ in the polarization angles, $\theta(x)$ is further assumed to be

$$\sigma_\theta \simeq \frac{\delta B}{B_0}$$

(5.6)

This combined with the expression for the velocity, in this case is the Alfven speed, gives us the more precise version of the CF analysis in terms of molecular clouds:

$$B \simeq \sqrt{8 \pi \rho \frac{\sigma(v)}{b}}$$

(5.7)

where $\sigma(v)$ is the one-dimensional velocity dispersion of the gas (of mass density $\rho$) coupled to the magnetic field.
5.6 Observations of the polarized light

5.6.1 The Stokes’ Parameters

The Stokes parameters describing the polarization of light beams, often written in the form of vectors - I, Q, U, V, are determined by using perfect polarization analysers ("polaroids") which transmit either linearly polarized light in some specific plane while rejecting completely light orthogonal to this plane, or which transmit one sense of circular polarization while rejecting the other.

- The \( I \) parameter is simply a measure of the total intensity of the beam.
- The \( Q \) parameter is determined by measuring the intensity, \( I_0 \) of the beam, at \( 0^\circ \) to the vertical, and the intensity \( I_{90} \), at \( 90^\circ \) to the vertical:
  \[ Q = I_0 - I_{90} = P^2 \cos(2\theta) \]  
  (5.8)
- Similarly, the \( U \) component is the difference between the intensity of light measured at \( 45^\circ \) and \( 135^\circ \) to the vertical:
  \[ U = I_{45} - I_{135} = P^2 \sin(2\theta) \]  
  (5.9)
- The circular polarization parameter \( V \) is measured using the circular analyser, and is the difference between the intensity of the beam in right and left circularly polarized light:
  \[ V = I_L - I_R \]

The polarization components \( Q, U, \) and \( V \) are often expressed in normalised form by dividing by \( I \).

5.6.2 The Observations

The observations were carried out on the 1.6 m telescope at the “Observatoire du Mont Mégantic” (OMM), Quebec, Canada, in March 2010, using an 8" aperture hole and a broadband red filter (RG645: 76608 central wavelength, 2410 Â FWHM). Polarization data were taken with “Beauty and the Beast”, a two-channel photoelectric polarimeter, which uses a Wollaston prism, a Pockels cell, and an additional quarter wave plate. The high sensitivity of the B&B allows to observe lines of sight towards stars with R-band magnitudes up to 15, with correct signal-to-noise ratio (SNR) in typically 1 minute, depending on the weather conditions. The polarimeter is cooled down with carbon ice (replaced every \( \approx 2 \) hours), down to a temperature of \( \approx -70^\circ \) C. A typical observation session consists in 1/ optimization of the instrument (power supply of the Pockels cell and of the photomultipliers (PMT)), measurement of the dark currents 2/ set the correct filter, the aperture hole 3/ measurement towards a standard (polarized and unpolarized). One observation then consists of a sequence of 8 steps, each corresponding to two measurements (sky and star) at 4 given angles of the instrument. The typical sequence is: star(0), sky(0), sky(45), star(45), star(90), sky(90), sky(90), and star(135). For more details on the instrument and the observational method, see the Appendix and Manset & Bastien (1995). The time of integration on the star depends on its magnitude, and was typically 1 to 2 minutes. The empty-sky integration time depends on the weather conditions and was optimized to reach the desired SNR. The raw outputs from the PMTs consist in counts which are then translated into a polarization degree \( P \) and angle \( \theta \).

5.6.3 Correction for Errors - Biases and Systematics

Calibration measurements is obtained to remove the polarization due to the telescope’s mirrors, with the aid of unpolarized standard stars, to correct for the efficiency of the polarimeter, found to be \((80 \pm 2)\%\) (refer to Appendix B) due to the Pockels cell, determined with the use of a polarizer, and to determine the origin of the position angles which is determined by observing polarized standards with known values of \( \theta \), found to be \(45.4^\circ \pm 2\) for every bandpass and constant throughout the whole run (measurements taken at regular intervals). The Wardle & Kronberg (1974) bias correction, \( \sigma(P) \) is applied to get the true polarization value, due to experimental noise, particularly at low levels of polarization or measurements with low signal-to-noise ratios. The final uncertainty on individual measurements of the polarization \( P \) is usually less than 0.05\%.
5.6.4 Data Analysis - Raw Data Reduction

The raw data was processed using the software Microsoft Excel for the data reduction, GREG/Gildas for any histograms produced and for mapping.

The computers from the Beauty and The Beast produced raw data already in terms of $P$, error in $P$ and $\theta$, which was then imported into Excel to allow for easy manipulation. However, each measurement was recorded in such a way that it was not possible to easily recover individual counts. As a consequence, averaging several measurements towards a given star was simply not feasible starting from the raw counts. Instead, the average of several measurements were computed from the values of $P$, $\sigma_P$ and $\theta$ as described below. The raw data reduction took a substantial amount of time due to certain problems with the format of the original file.

1. The Stokes parameters $U$ and $Q$ (slightly varied to include for the bias correction) were calculated for each individual reading using the following formulae:

\[
Q = (P^2 + \sigma^2(P)) \cos(2\theta) \\
U = P^2 + \sigma^2(P) \sin(2\theta)
\]

2. The Instrumental polarisation, obtained from measuring the polarisation and its angle of the light from an unpolarized standard and it’s stokes’ parameters, $\langle U_{IP} \rangle$ and $\langle Q_{IP} \rangle$ calculated using the same relations above, was then subtracted from each $U$ and $Q$ to give only the polarization occurring due to the cloud, $U_*$ and $Q_*$.  

\[
U_* = U - \langle U_{IP} \rangle \\
Q_* = Q - \langle Q_{IP} \rangle
\]

3. The average Stokes parameters for multiple readings was then obtained by taking the weighted mean, and their relative uncertainties acquired. The average polarisation and its uncertainty, and the polarisation angle were then deduced from the following formulae:

\[
\langle P \rangle = \sqrt{\langle Q \rangle^2 + \langle U \rangle^2 - \langle \sigma_P \rangle^2} \\
\sigma(\langle P \rangle) = \sqrt{\frac{\langle Q \rangle^2 \sigma^2_Q + \langle U \rangle^2 \sigma^2_U}{\langle Q \rangle^2 + \langle U \rangle^2}} \\
\langle \theta \rangle = \frac{1}{2} \arctan \frac{\langle U \rangle}{\langle Q \rangle} \\
\sigma(\langle \theta \rangle) = \frac{1}{2} \frac{\sigma(\langle P \rangle)}{\langle P \rangle}
\]

In the case of when the square of the polarisation uncertainty was greater than the sum of the squares of the stokes parameters, the polarisation measurements were neglected.

4. The polarisation and the uncertainty were then corrected for the efficiency of the telescope, which was found to be approximately $(80 \pm 2)\%$, by multiplying each value by a factor of 1.25. This could be taken at the end due to the the process undergoing a linear transformation.

5. The uncertainty on the polarisation angle was then determined, due to its dependence on $P$.

6. The angles were then manipulated according to their respective quadrants on the U-Q plane, depending upon their values of $U$ and $Q$, as shown in the figure below:

Figure of the angles in their respective quadrants on the U-Q plane.
7. The offset angle, $\theta_{\text{off}}$ obtained from calibrator stars, caused by any adjustments made to the telescope, was then added to the mean.

$$\theta = \theta_{\text{telescope}} + \theta_{\text{off}}$$  \hspace{1cm} (5.18)

8. Before the histograms were built, the reliability of the results was taken into account and any unreliable readings discarded. The readings were filtered by comparing each individual reading to a threshold number of its standard deviations. The threshold number was varied from 1 - 6, and using the thetas filtered out, histograms were drawn up for each set of data.

The resulting polarization degree and angles are summarized in Table A.1. The analysis of these results is the subject of the next Section.
Chapter 6

Results

6.1 Morphology of the field lines

6.1.1 Comparison with the dust

Using the GREG software, the initial raw data measurements of the polarisation angles (PA) were mapped onto the 100µm dust emission of the cloud, obtained from the SkyView database, which served as a comparison between the morphology and the polarization measurements obtained. The resulting map is shown in Fig. 6.1.

The most glaringly obvious structure, labelled the **Main Structure** highlighted in red, spans the majority of the Flare. Other structures, such as rings that seemingly curve around the main structure like **Outer Rings** are visible in blue, along with other structures labelled in green.

6.1.2 Comparison with the gas

The CO maps of the Polaris Flare used in this Section consist of:

- Large Scale (30 pc) and low spatial resolution (0.5°) CO(1-0) map from Heithausen & Thaddeus (1990).
- Small Scale (1 pc) and high spatial resolution (11") IRAM-30m data CO(2-1) from Hily-Blant & Falgarone (2009).

From the left panel of Fig. 6.2, we see that the contour lines, depicting CO emission are very well correlated with the main structure in the background. However, we observe that some of the most prominent dust features, clearly shown as filaments do not appear to have strong CO emission, due to the lack of contour lines as an overlay. Looking at the magnetic lines field lines on a map depicting the integrated intensity (right panel of Fig. 6.2), we further confirm the fit with the main structure, however, the other structures, mainly the outer rings are not well detected.

Information on the velocity field of the gas is inferred from the CO(1 − 0) map of Heithausen & Thaddeus (1990). Figure 6.3 shows the CO emission (in K) in each of the spectral channels, where the projected velocity ranges from -7.8 km s$^{-1}$ to 3.25 km s$^{-1}$. Observing each of these, we can trace the movement (projected on the los) of the gas: the CO emission travels from bottom-left to the upper-right, seemingly along the main structure. The average spectrum of the CO line gives information on the total excursion of the projection of the velocity. The average spectrum (Fig. 6.4) is not Gaussian, and shows a shoulder at positive velocities. From the channel map, we can identify this shoulder to be associated with the gas at the upper end of the main structure. The equivalent width of the spectrum is $\Delta v_{eq} = \int T dv / T_{peak} = 4.6$ km s$^{-1}$. A Gaussian fit allowed for the obtainment of a value for the FWHM of the velocities, $\Delta v \approx 4.1$ km s$^{-1}$. 

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6.2 Statistics and Histograms

Histograms, with varying bin sizes were drawn up for the measurements to try and model a gaussian fit atop the data.

Due to a good fit not being obtained, statistical manipulation was carried out to calculate directly the weighted average and root-mean-square dispersion of the angles from the measurements, as shown in the table below. To further the investigation, the intensity of the starlight was plotted against the polarization, but no obvious correlation was observed.

6.3 Discussion

6.3.1 Magnetic field topology

The Main structure is very well correlated with the polarization angles obtained from the measurements, with the magnetic field lines following the dust emission with all the vectors positioned parallel to the filament-like structures clearly visible, which suggest that the field lines are strongly coupled with matter and imprint their configuration on the distribution of the matter. The vectors depicting the outer rings are perpendicular to the field lines of the main structure and to the dust structures, and are situated at close proximity to the main structure. The distances of the individual data points were also questioned and the idea of sheets present within...
molecular cloud was put forth. Vectors maps showing vectors whose length denoted the polarization at angle $\theta$ and histograms of distances for the individual structures was then drawn up as shown in Fig. 6.6.

Manipulation and analysis of Fig. 6.6 to show different scenarios, conclusions were drawn. As no visible differentiation in distances were seen, a definative sheet structure could not be stated, but on the other hand, could not be ruled out either. Further information would be required such as the width of the sheets, densities at different points, etc. to draw definite conclusions.

Emission from CO, further support the scenario of matter coupled to the field lines, however, there are certain instances where strongly visible filament like structures do not have any CO emission, allowing the possibility of depletion. Depletion occurs when CO settles in matter in the cold and dense medium, often called 'frosting', which sufficiently reduces the abundance of CO remaining in the gas (Carbon Monoxide frosts in the interstellar medium, D.C.B. Whittet, W.W. Duley (1991)).

### 6.4 Estimation of Magnetic Field Strength

The magnetic field strength, $\mathbf{B}$ can be estimated using the Chandrasekhar-Fermi method (See Section Observations):

$$B_{pos} = 6.6\sqrt{\langle n_H \rangle \Delta v / \delta \theta}$$

(6.1)

where $\langle n_H \rangle$ is the average density of the diffuse matter, in this case hydrogen (see Appendix), $\Delta v$ is the dispersion of velocities, obtained via CO emission, and $\delta \theta$ is the dispersion of polarization angles. We calculate the average density, $\langle n_H \rangle$, under the assumptions that the mass is uniformly distributed across the cloud, which is taken to be a sphere. The value obtained is approximately $6 \pm 1$ cm$^{-3}$.

For the Polaris molecular cloud, as per the observations, we obtain $\Delta v \approx 4.71$ km/s, but three different values for $\delta \theta$, giving rise to 3 different cases:

1. From the histogram, we obtain a value $\delta \theta \approx 22.6^\circ$ S, giving us a $B_{pos} \sim 3.4\mu$G. However, the dispersion obtained is quite unreliable, due to questionable gaussian fit on the histogram. As the bin size increases or decreases, the dispersion changes substantially due to the small number of measurements taken into account. Statistical analysis was applied directly to the results in an attempt to increase the reliability.

2. As per statistical analysis, taking the average of all the readings yields the dispersion to be approximately $15.11^\circ$, hence a $B_{pos}$ of about $5.04\mu$G.
Figure 6.3: Channel map showing the CO(1 – 0) emission in adjacent velocity channels. (Note that the RA offsets, in this plot, increase to the right, in the opposite direction to that of e.g. Fig. 6.2).

Table 6.1: Table showing the averages and the dispersion of the polarisation angles (PA) as per statistical manipulation of the measurements. $\theta$ are the unweighted PA, whilst $\theta_w$ are weighted PAs.

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3. Taking into account the reliability of the measurements, the weighted average was found to be 11.5°, hence resulting in a $B_{\text{pos}}$ of about 6.62 $\mu$G.

6.5 Comparison to the Taurus Molecular Cloud

The Taurus Molecular Cloud, in the constellation of the Taurus at approximately 900 parsecs away, is one of the biggest clouds with a mass of $44000 M_\odot$ covering an area of diameter 30pc.

Comparing the morphology between both the clouds, we observe that the magnetic field tends to be coupled with matter. However, in Polaris, we see sharp changes in the polarization angles in a given area while in Taurus, the field seems to vary smoothly with a plausible reason being the organization of the field by gravity. These different orientations overlap each other in projection, which was also found in another high latitude cloud by Gomez et al. In the case of Polaris, where three thin layers, each with a magnetic field oriented in a different direction superposed in the field can be imagined, in the Taurus, we cannot distinguish layers, but can describe the structure as being smooth and continuous throughout the field. As in Polaris, polarization angles seem to be spread over the map, we cannot trace filaments definitively.

Applying the Chandrasekhar Fermi Method to obtain the magnetic field strength, with values of $\delta \theta \approx 24.3^\circ$ and $\Delta v \approx 3.8$ km/s from the relevant histograms, and calculating the average density, $\langle n_H \rangle = M/V \sim (50 \pm 5)$ cm$^{-3}$ (about 10 times bigger than Polaris), we obtain a value of $B_{\text{pos}} = 7.31$ $\mu$G.
Further calculations to find the ratio of the magnetic energy density, $\epsilon_{\text{mag}} \approx \frac{B^2}{8\pi}$ to the turbulent energy density, $\epsilon_{\text{kin}} \approx \frac{1}{2} \rho \sigma_v^2$ (where the most probable velocity, $\sigma_v^2$ is given by $\sqrt{2 \Delta v^2}$):

$$\frac{\epsilon_{\text{mag}}}{\epsilon_{\text{kin}}} \approx \left( \frac{38}{\delta \theta} \right)^2$$

(6.2)

is very important in determining the behaviour of the cloud, be it sub-Alfvenic ($\epsilon_{\text{mag}}/\epsilon_{\text{kin}} > 1$), super-Alfvenic ($\epsilon_{\text{mag}}/\epsilon_{\text{kin}} < 1$) or trans-Alfvenic ($\epsilon_{\text{mag}}/\epsilon_{\text{kin}} \sim 1$).

Applying the data for the Taurus cloud, the ratio obtained is approximately 2.5 (see Appendix), whereas for the Polaris molecular cloud, the ratio is about 2.8 (as per the dispersion from the histogram), both describing sub-Alfvenic behaviour. Although the gaussian fit is questionable for the Polaris cloud, the important factor is that the ratio is larger than 1. The applicability of this method is limited to certain regimes: it fails when the angular dispersion $\delta \theta > 25^\circ$, when the field can be described as very tangled, and also for very small $\delta \theta$, where the infinite limit of the ratio has no meaning.

Given that the ratio is similar between Polaris and Taurus, some interesting questions can be raised.
Figure 6.5: Histogram of the polarization angles (see Table A.1).

Figure 6.6: PA as a function of the distance of the stars. Left panel: \( d \leq 200 \) pc. Right panel: \( d > 200 \) pc.
Figure 6.7: The Magnetic Field Lines detailed on the IRAS 100 \( \mu \)m dust emission towards the Taurus Molecular Cloud (Hily-Blant et al. 2008).
Chapter 7

Conclusions

Observations of polarization of starlight from background stars, from Belle et la Bete Polarimeter at the Universite de Montreal, aided the analysis of the morphology and the magnetic field strength of the Polaris molecular cloud. Clear visible structures, such as a main structure that spans the length of the Polaris Flare and outer rings around them, were seen and in comparing them with measurements of CO emission, we can draw conclusions that the matter was very strongly coupled to the field lines in the main structure, however not so much in the outer rings, due to a lack of emission from the gas. Obtaining values for the magnetic field strength of and the ratio of the magnetic energy density, $\epsilon_{\text{mag}}$ to the turbulent energy density, $\epsilon_{\text{kin}} \approx 2.8$ and comparing it with the Taurus Molecular Cloud which has a field strength of and a ratio of 2.5......

Some of the limitations and problems encountered were the comparatively small number of readings in Polaris than in Taurus and the most important being the questionable fit of the Gaussian to the data.

However, this opens up a lot more avenues for future research work, such as investigations into the lack of correlation between the intensity from the IRAS 100 $\mu$m and the polarization (one would assume there to be some correlation), how the results change when more measurements of polarization and the angles are taken, comparisons with numerical simulations of turbulence and $\mathbf{B}$ in molecular clouds and the change in the ratio, $\epsilon_{\text{mag}}/\epsilon_{\text{kin}}$, across stages in star formation, to name a few.
Bibliography

Hildebrand, R. H. 1988, Q. Jl R. astr. Soc., 29, 327
Appendix A

Data reduction

A.1 Polarisation measurements

Table A.1 give the amount of polarisation towards all the lines of sight observed at Mont-Mégantic Observatory in March 2010. The table also lists the polarization angles, as measured positively from North to East, between 0 and 180°. The uncertainties are at the 1σ level.

A.2 Formulae Analysis

A.2.1 Stokes parameters

The Stokes’ Parameters, U and Q that we are interested in, can be obtained from the polarisation, error in polarisation and the polarisation angle from the following formulae:

\[ P = \sqrt{Q^2 + U^2 - \sigma^2(P)} \]

\[ \theta = \frac{1}{2} \arctan \frac{U}{Q} \]

Hence, using substitution and elimination:

\[ P^2 + \sigma^2(P) = (Q^2 + U^2) = (P')^2 \quad (A.1) \]

\[ U = Q \tan(2\theta) \quad (A.2) \]

\[ P^2 + \sigma^2(P) = Q^2 + Q^2 \tan^2(2\theta) \quad (A.3) \]

\[ Q = \left( \frac{P^2 + \sigma^2(P)}{1 + \tan^2(2\theta)} \right) \]

\[ = \sqrt{P^2 + \sigma^2(P)} \cos(2\theta) \quad (A.4) \]

This formula can further be simplified using the trigonometric identity:

\[ 1 + \tan^2 \theta = \sec^2 \theta = \frac{1}{\cos^2 \theta} \]

to give:

\[ U = Q \tan(2\theta) = (P)^2 \cos(2\theta) \tan(2\theta) = (P)^2 \sin(2\theta) \quad (A.6) \]
A.2.2 Uncertainties

The uncertainties on the values of P and θ are evaluated as:

\[
\sigma^2(P) = \left( \frac{\partial P}{\partial Q} \right)^2 dQ + \left( \frac{\partial P}{\partial U} \right)^2 dU \]  

(A.7)

\[
= \left( \sqrt{\frac{1}{2} \frac{2Q}{\sqrt{Q^2 + U^2}} \sigma_Q^2 + \left( \frac{1}{2} \frac{2U}{\sqrt{Q^2 + U^2}} \right)^2 \sigma_U^2} \right) \]  

(A.8)

\[
= \sqrt{\frac{Q^2 \sigma_Q^2}{Q^2 + U^2}} \]  

(A.9)

\[
\sigma(\theta) = \left( \sqrt{\left( \frac{\partial \theta}{\partial Q} \right)^2 (dQ)^2 + \left( \frac{\partial \theta}{\partial U} \right)^2 (dU)^2} \right) \]  

(A.10)
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Appendix B

Correcting for Instrumental Effects

The Stokes Parameters, Q and U for the Instrumental Polarisation was found by measuring the polarization and its angle constituted by the telescope for light from an unpolarized standard:

\[ P = 0.01, \sigma(P) = 0.02, \theta = 53^\circ \]

Efficiency was found to be \( \approx 80\% \) from the following data obtained from the individual nights:

4th March, 07.30pm: Eff = 83 \% (PMT 1), 83.8 \% (PMT 2)
5th March, 08.00pm: Eff = 82 \% (PMT 1), 79 \% (PMT 2)
6th March, 00.30am: Eff = 81.7 \% (PMT 1), 80.5 \% (PMT 2) ; 07.30pm: Eff = (80.85 \pm 0.08) \% (PMT 2)
7th March, 01.00am: Eff = (80.6 \pm 0.09) \% (Prisme)
8th March: Eff = 84 \% (PMT 1,2)

Errors of the efficiency were negligible, and hence not taken into account. (minimal when squared)

The Offset Angle was found measuring the polarisation and its angle for polarised standards, whos value is very well recorded, and is obtained from: Polarised Standard HD43384:

Measured data: \( P = 2.538 \pm 0.001; \theta = 171.8^\circ \)
Recorded data: \( P = 2.038 \pm 0.020; \theta = (126.4 \pm 0.30)^\circ \)

Hence, the difference between the angles, 45.4\(^\circ\), constitutes to the instrumental effects.

Article: Standardization of polarisation measurements....Landstreet

B.1 La Belle et la Bête

The Beauty and the Beast is a two-channel, computer-controlled, Pockels-cell polarimeter, which can work in linear or circular polarization, allows for the selection of neutral density filters, polarizers, quarter-wave plate, and filters remotely, and does data acquisition, display, storage, and reduction. The original instrument was designed in the late 1970s at the University of Toronto, and at the University of Western Ontario by P.Martin and J.D.Landstreet. The instrument is composed of 2 main parts: “The Beast” - The optical system, the mechanical design, the computer, electronic components (interfaces, motor control, security systems, counters, temperature control, and monitoring), and “The Beauty” - the software.
B.1.1 The Beast - Optics

The Beast consists of all the optical components encompasses within 3 cylindrical sections, with horizontal divisions preventing wayward lights from contaminating the signal and a little gap between them providing easy access to each of the components, as detailed in Fig. (Optical Layout).

The upper section includes the aperture hole plate, the neutral density filters wheel, and the collimating lens - The Cassegrain Focus. The middle section holds the Pockels cell, which can be used as a reversible quarter-wave plate effective for circular polarizations, and an additional quarter-wave plate for linear polarization observations, in a double cylinder; the outer one is fixed with respect to the telescope, and the inner one rotates with the lower parts of the polarimeter. The third section has the Wollaston prism, the filter slide for 6 filters (the optimum diameter being 25mm), two tiltable interference filters, two Fabry lenses and the shutter, with the fourth section containing 2 RCA C31034A Photomultipliers (PMTs) sensitive from 220 to 890 nm, kept cooled by dry ice.

The heart of the system is comprised of a Wollaston Prism, 2 wedges of an uniaxial crystal whose optical axes are perpendicular to each other and the beam which acts as the analyser which divides the incoming light into 2 beams of linearly and perpendicularly polarized light, a quarter-wave plate for linear polarization observations and a Pockels Cell, a KD*P crystal that transforms the incoming circularly polarized light into linearly polarized light (acting as a reversible quarter-wave plate) which can then be analysed by the prism. The Pockels Cell, connected to 2 electrodes, acts also as a variable retarder - its retardation depending on the high voltage supplied to it, which changes by 50V per °C, and the ambient temperature. The voltage increases with temperature. The temperature drift depends on the actual shape of the passband and its effective wavelength, which often varies from star to star.

The polarity of the high voltage is inverted 125 times per second (by the use of a 125 Hz square wave), allowing instantaneous 90° "virtual" rotations of the cell. The photomultiplier tubes (PMT's) will then alternatively receive horizontally and perpendicularly polarized light, eliminating certain unwanted effects, such as variable seeing, transparency, slow drifts in detector characteristics and guiding. When linear polarization is desired, an additional quarter-wave plate, achromatic with four elements is added giving a retardation close to a quarter wave over the useful band of the polarimeter with an exact quarter wave at 4000 and 7500 Angstroms.

Six aperture holes are available, drilled in an aluminized plexiglass plate with any excess aluminium carefully removed to avoid spurious polarization introduced by the star, giving the following diameters at the f/8 focal plane of the Mont Megantic telescope: 5″52, 8″18, 10″64, 15″54, 22″49 and 31″08. An inclined mirror, which allows one to use the light from a small lamp, and a calibrating prism, which polarizes light linearly, is also present. The collimating lens provides the rest of the optical system with a parallel beam. The Fabry lenses refocus the image of the star onto the cathodes of the PMT's along with an image of the primary mirror of the telescope, to prevent the image from moving on to the photocathodes.

Calibration of linear polarization over a very broad of wavelength range is carried out using polarizing sheets (due to the large focal ratio) - one for the visible and one for the near infrared, which polarize the light to ≈ 98%. Calibration of circular polarization also uses the same principle, the only difference being the chromatic quarter-wave plates used in conjunction with the sheets.

B.1.2 Beauty - Computer and Electronics

The computer linked to the polarimeter is a Macintosh Centris 650 computer, using a MC68040 processor, a 25 MHz clock and 8 Megabytes RAM, an IEEE interface with a digital input/output unit (for the control and status of the shutter, and the control of the five original motors along with their absolute encoders), and an Intelligent Instrumentation Interface to use with 4 32-bots 8 MHz counters. 2 motors with their driving system (for the aperture hole plate and the neutral-density filters wheel) and power supplies were added to complete the circuit along with some modifications made to the original instrumentation to allow for various other functions to be carried out, such as the protection of the PMTs against bright sources of light and the maintenance of a constant temperature of the Pockel cell.

Protection of the PMTs are carried out by a software protection, which ensures that the PMTs receive less than 2 × 10^5 counts per second, as well as an independent hardware protection circuit which does the same, in the form of a shutter which automatically closes (hardware and software protections) and the high voltage to the PMTs terminated (hardware protection only).
Due to the temperature dependence of the voltage applied to the Pockels Cell, a heating system is utilized to keep it at a constant temperature of $10.0 \pm 0.1^\circ C$. Constant heating at $10.0 \pm 0.1^\circ C$ is also supplied to the two Fabry lenses to prevent fogging. The temperatures of the different pieces of equipment can be read with the use of an effective analog input unit.

The signals coming from the PMTs are amplified, filtered by two discriminators with an electronic circuit dividing the pulses of each PMT into two groups - one when the polarity of the Pockels cell is positive, one when negative, with the four resulting signals then being fed into four counters.

Software

The software, written in C, allows the use of all the possibilities of the instrument. The program works with the use of menus with up to six overlapping windows displayed at any one instant - to get information from the user, provide the user with the menus, information on the motors (position and what they correspond to), the counts, and error messages. During an observation, a single window gives the date and the hour of the observation, the filters installed, integration time, time remaining, which steps of the cycle have been performed and which one is being performed, the counts per second for the four counters and the two PMTs, the accumulated counts, partial calculations of the polarization with the available numbers at the moment, rate of counting on the star, and star/sky counts ratio. All actions performed and counts are kept in log files with the results saved in another final file at the end of each run.
In addition to single integrations (used primarily to test the counting rates and for quick calibration checks), four observing sequences are available - two for linear and two for circular polarization, which allow the observation of the object and then the sky, or an alternation between the star and the sky, chosen as per the user. The instrument is then moved through the positions needed with the positions of the motor and the status of the shutter (open/closed) checked. The sky integration time, \( t_{\text{sky}} = t_{\text{star}} \sqrt{R_{\text{sky}}/R_{\text{star}}} \), is automatically calculated to optimize the use of the telescope time, where \( R_{\text{sky}} \) and \( R_{\text{star}} \) are the count rates on the sky and the star, respectively, with an useful option that tests the counting rate on the star and gives an estimation of the integration time needed to reach a given error. An integration may be aborted or paused at any time, along with the possibility of closing the shutter in case of a problem.

However, the high voltage supplied for the Pockels cell and the PMTs must be adjusted manually, but can be controlled by the computer via an analog output unit. The high voltage for the PMTs is always 1700 V; for the Pockels cell, it varies with wavelength and also with the outside temperature when it goes above 10°C.

B.1.3 Principles of Operation

To obtain a circular polarization measurement, with all instrumental effects removed, such as degeneracy of angles, integration on the star and the sky as well as another set star/sky, with the instrument rotated by 90°, is recorded. Conversion of linear polarization to circular polarization, another set star/sky is made with the instrument rotated by 90°. The difference over the sum of the two channels concerning one PMT - one channel giving the pulses that were detected when the polarity on the Pockels cell was positive, and the other when negative, provides the percentage of circular polarization. A mean is calculated with the two PMTs, and the final result is the mean of the two observations with the instrument at 0° and 90°.

For linear polarization, 4 star/sky sets of measurements are made with the instrument at 0° and 45° gives the Stokes Parameter \( Q \), and another set at 45° and 135° gives the other parameter \( U \); the square of the polarization \( P \) is then the quadratic sum of \( Q \) and \( U \), with the final result being a mean of the two.