Abstract

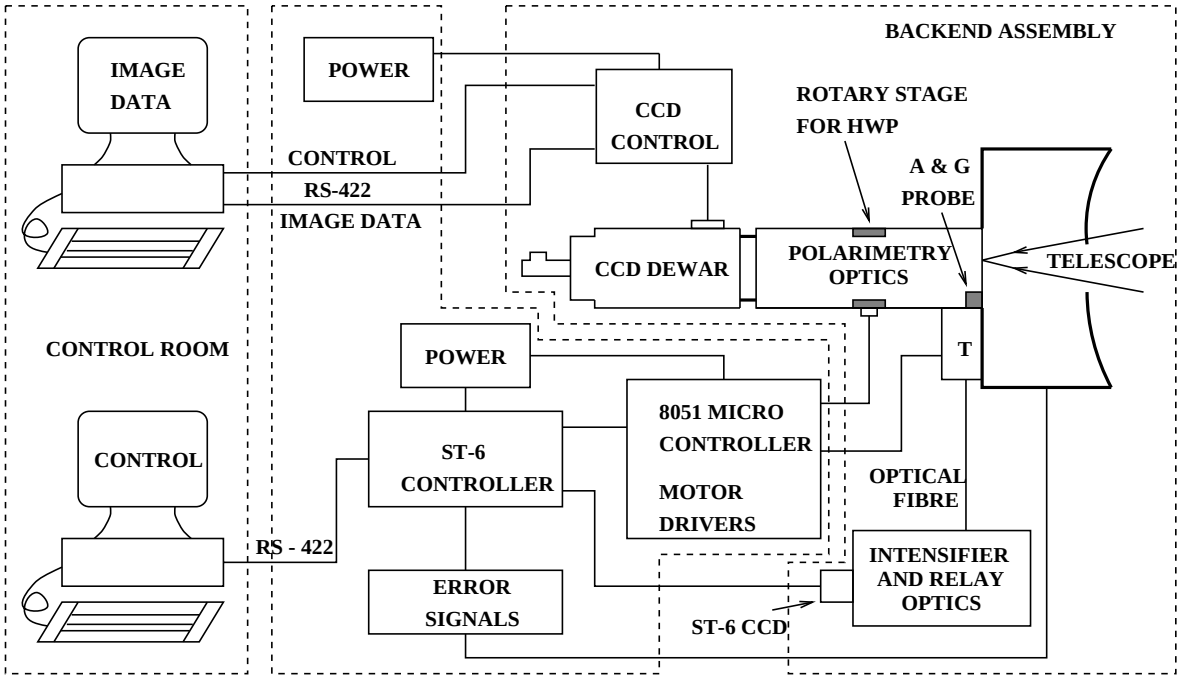
Our primary interest is to study, employing polarimetric techniques, the role of magnetic fields in the dynamics and evolution of molecular clouds in the interstellar medium of our Galaxy and star-formation occurring in them. In spite of the classical nature of the problem, it has been least addressed with, mainly because of the difficulty of doing polarimetry with conventional aperture photometric techniques. The situation has completely changed with the advent of accurate array detectors and the instrument described in this thesis, makes good use of these developments.

Bok globules, as a class of objects, are ideally suited for studying the formation and evolution of a simple, self-gravitating system, not contaminated by environmental effects. It is now confirmed that a majority of Bok globules are in the process of forming stars. There are also evidences which show that there is an evolutionary connection between the elephant trunk globules, cometary globules and Bok globules. Magnetic fields are known to be of considerable importance in all of these phenomena. Another interesting class of objects in the Galaxy are the elongated clouds, which might be truly filamentary in nature or are sheets seen edge-on. Magnetic fields influence the formation of these clouds and the field patterns are associated with their structure. Magnetic fields also produce alignment in the aspherical, dichroic, dust grains in the molecular clouds. When unpolarized starlight scatters through these dust grains, it becomes partially polarized and the polarization vector traces the magnetic field. Thus imaging polarimetry of stars background to these clouds offer a powerful technique of determining the magentic field patterns as projected in the plane of the sky. Quantitative studies of the magnetic field patterns, have become now feasible because of the high angular resolution and high accuracy with which polarimetry can be carried out with the imaging instrument.

In order to carry out such observations, it was conceived to design, develop and commission a CCD Imaging Polarimeter (IMPOL) suitable for observations at some of the telescope facilities in India. Though the design uses standard optical and electronic components, by paying careful attention to the various sources of errors like atmospheric scintillation, moving optical components, reflection from surfaces, tracking etc., an instrument could be constructed which gives photon-noise limited performance for linear polarization measurement accuracies better than 0.05% in the optical wavelength bands.

A Wollaston prism is used as the analyzer in the instrument and the two orthogonal

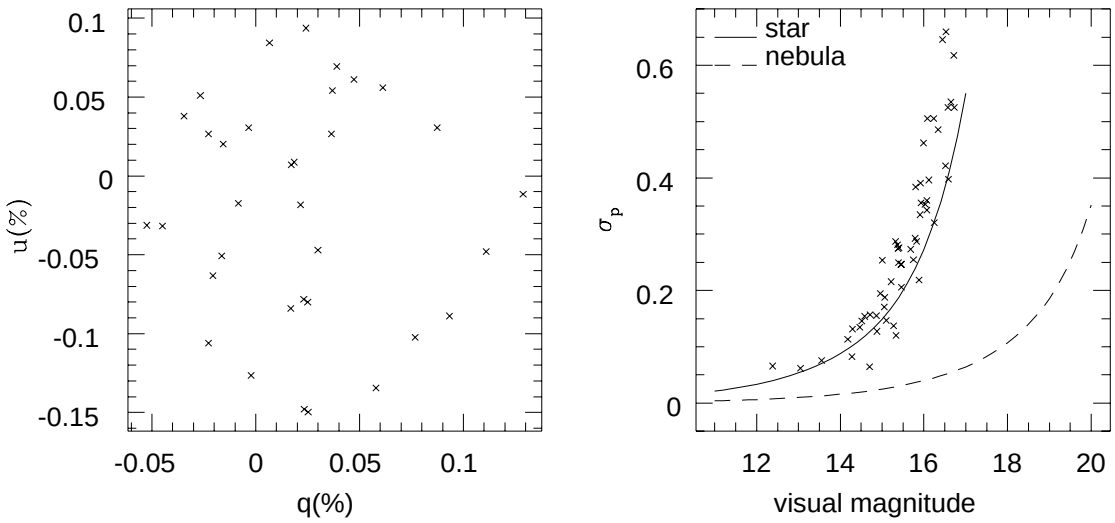
components of polarization are recorded simultaneously on a cooled CCD detector. In order to determine the three parameters namely, the total intensity, the fraction of light in linear polarized condition and the position angle of polarization, at least one more independent measurement is required. This is accomplished by rotating the plane of polarization of the incoming beam through a known angle using a half-wave plate kept in front of the Wollaston prism and then making another measurement. The Wollaston prism and the half-wave plate are placed in the path of a reimaging system, in which a field lens reimages the primary mirror on to the half-wave plate and a camera lens reimages the telescope focal plane on to the CCD. Because of the Wollaston prism two images (ordinary and extraordinary) are produced on the CCD plane per source point and in order to avoid the overlap of the images of adjacent points, a grid of parallel obscuring strips is placed at the telescope focal plane.



A block schematic representation of IMPOL is shown in the above figure. The polarimetry optics and CCD are mounted at the Cassegrain port of the telescope, so is the acquisition and guidance system. Most of the electronic subassemblies associated with instrument control and image acquisition are also mounted on the telescope. The two computers in the telescope control room allow the observer to monitor instrument control and image acquisition operations.

The instrument development took two years, from February 1994 to February 1996, during which time, the mechanical fabrication and assembling of the instrument as well as the development of the electronics back-bone and the software tools for user-interface, instrument control and image acquisition were carried out. This phase ended with the laboratory commissioning of IMPOL, which involved operating, testing and

optimizing the instrument in the laboratory when various sources of error were investigated in detail and some improvements made. In the second phase, the instrument was taken to the 1.2 m telescope(GIRT) facility at Gurusikhar, Mt. Abu in March 1996 and during the three day observation run it was interfaced to the telescope and several polarized and unpolarized standard stars were observed in various filters for instrument calibration. Observations required for implementing the off-axis acquisition and guidance (A&G) unit of the instrument also were made at this time. The A&G unit was successfully incorporated during a second observation run in May 1996. During this second observation, optical polarimetry of the stars behind the periphery of some dark molecular clouds were made. The results of these observations are summarized in the following two figures.

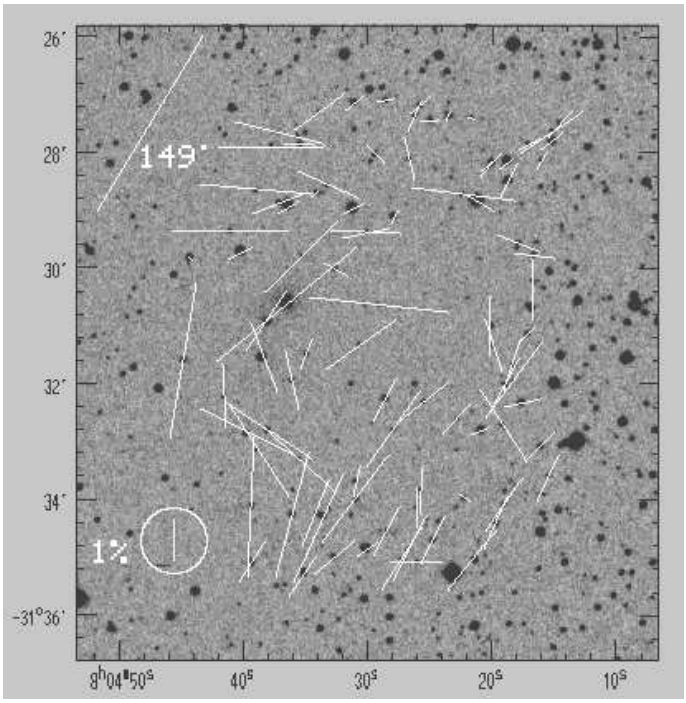


The figure on the left, shows the normalized Stoke's parameters q against u, plotted for all the unpolarized star measurements made. The extremely low correlation coefficient (0.06) of the points indicates the absence of systematic effects in the measurement of polarization, which if present, should make these points tend to cluster. The mean values $\bar{q}$ and $\bar{u}$ are equal to 0.022 and -0.022 respectively, which gives an instrumental polarization floor of about 0.03%. The points in the righthand side figure are the 1σ errors, for about an hour of observation time, in the measurement of polarization of stars behind B133 as a function of their visual magnitudes. The solid curve in that figure is the theoretical estimate of the errors based on photon statistics alone, which is the dominant noise source. This curve rises fast around 15^{th} mag. because of the high sky brightness during the observations due to the presence of the moon.

The data analysis is carried out from within the IRAF environment using a polarimetry package that has been developed for the purpose. The data is in the form of a set of image frames for each filter, with about 12-20 frames per set, the exact number depending on the nature of the source and the accuracy of measurement demanded visà-vis the photon noise. Aperture photometric techniques are used to determine the intensities. Provision has been made to slightly dither the telescope pointing while

tracking so that optimum sampling of about 3 pixels is obtained in stellar images. The polarization information is extracted in terms of the ratios of the intensities in the ordinary and extraordinary images in these frames and hence is devoid of the effects of atmospheric scintillation, variation in effective exposure times etc. These ratios correspond to the normalized Stoke's parameters q and u and a non-linear chi-square fitting technique is used to estimate the polarization parameters and the errors. Since the polarization values follow the Ricean distribution, they are corrected for bias using the maximum likelihood estimate method.

Several observations of Galactic molecular clouds have been made with the instrument so far. We find very interesting features in the magnetic field patterns which are closely associated with the dynamical conditions of the clouds. In two Bok globules, CB 16 and CB 17, which are known not to show any signs of star-formation, the magnetic fields are quite uniform and are aligned closely with the ambient Galactic magnetic field. However, another Bok globule, CB 60, which harbors an young stellar object, displays a very disturbed magnetic field pattern (see Fig. 6.3 below). We have also observed two cometary globules, which show that the magnetic fields tend to align along their bright rims. This probably indicates that the fields are anchored to the ionized rims of these globules and are being stretched by the movement of the material along their tails. Our observations of an elongated molecular cloud near the open cluster IC 5146, are consistent with the hypothesis that the cloud is supported against gravitational collapse along its long axis, by the magnetic field.



A brief outline of the presentation

Considerable effort has been made to make the thesis concise – repetitions have been avoided wherever possible. Instead, the appropriate sections have been referred to, whenever a relevant discussion has been made in a different context. Once in a while, this has led to the inconvenience of having to refer forward, but the material has been arranged so as to minimize such instances.

All topics which are not directly part of the basic theme of the thesis – the development of the instrument, using it for observations and analyzing the results – but are complementary, have been collected together in five appendices. Appendix A discusses briefly the Stokes vector formalism of representing light, which has been employed extensively in the description of the instrument's working; appendix B presents how polarized light results from some of the physical phenomena of relevance in astronomy; appendix C contains brief descriptions of two polarization sensitive optical elements that have been employed in the instrument. The last two appendices are intended to serve as a User's guide while making observations with the instrument.

Chapter 1, begins by briefly tracing the history of our understanding of the phenomenon of polarization, but soon focuses onto astronomical polarimetry and the merits and demerits of the different techniques practised. Based on this understanding, in chapter 2, we first arrive at a set of guidelines for the construction of an imaging polarimeter with a view of achieving specific scientific goals. This is followed by descriptions of the various phases in the development of the instrument, beginning from the optical principle and components, their testing, mechanical structure, assembling, electronics and software for instrument control and image acquisition. In chapter 3, we consider the various sources of uncertainties involved in the measurement of polarization with such an instrument and make theoretical estimates of the performance limits which it can reach when used for realistic observations. We conclude this chapter by discussing a few issues of relevance during the extraction of polarimetric information from raw observational data. The need for an accurate acquisition and guidance system for the instrument, was realized at the very beginning of the project. In chapter 4, we discuss the design and construction of such a system and how it has been integrated as part of the main instrument. Estimates are also made to verify that this system is sufficient to serve the requirements of polarimetry. The commissioning of the instrument, in two stages – first in the laboratory and then on the telescope – is the subject of chapter 5 and with this we come to the end of part I. Part II is concerned with using the instrument for real observations, which is the ultimate test of performance an instrument. Chapter 6 and 7 presents the results of our observations of magnetic field patterns in some classes of molecular clouds in the Galaxy, employing polarimetry of field stars behind the clouds as tracers of the field pattern.

The following articles have been published based on this work :

- A. N. Ramaprakash, R. Gupta, A. K. Sen and S. N. Tandon, *Imaging Polarimeter(IMPOL)*, 1995, in: *Ground-based Astronomy in Asia*, Proceedings of the Third East-Asian Meeting on Astronomy, ed. Kaifu N., National Astronomy

Observatory, Japan

- Ramaprakash A. N., Gupta R., Sen A. K., Tandon S. N., *An Imaging Polarimeter (IMPOL) for multi-wavelength observations*, Astronomy and Astrophysics Supplement, 1998, **128**, pp.369-375

- Ramaprakash A. N., Gupta R., Tandon S. N., *Flexible off-axis acquisition and guidance system*, To appear in *Telescope Control Systems III*, SPIE proceedings, **3351**, 1998

- A. N. Ramaprakash, R. Gupta and S. N. Tandon, *Magnetic Fields in Molecular Clouds*, To appear in Proceedings of the 104-cm Sampurnanand Telescope Silver Jubilee Workshop, 1997

- A. N. Ramaprakash, R. Gupta and S. N. Tandon, 1997, *Imaging Polarimetry of nearby molecular clouds*, To appear in *The Local Bubble and Beyond*, Proceedings of the IAU Colloquim No. 166