Chapter 1

Optical Polarimetry in Astronomy

1.1 A brief historical introduction

In the early part of nineteenth century, A. J. Fresnel (1788-1827) and D. F. Arago (1786-1853) conducted a series of experiments to understand the influence of polarization on the interference experiments of T. Young (1773-1829). In order to understand the results of these experiments, Young proposed that one should accept R. Hooke's (1635-1703) suggestion about light being composed of only two orthogonal, transverse components and there being no longitudinal component. Though Fresnel and Arago were able to coin the four general interference laws based on this, they completely failed in encoding these laws in mathematical statements. The, otherwise successful, wave theory of light, of which Fresnel himself was the greatest proponent, was unable to describe mathematically, the phenomenon of unpolarized light, also known as natural light. Obviously, a crisis was at hand.

This was how matters stood until 1852; when Sir G. G. Stokes (1819-1903) succeeded in framing a mathematical formalism which can represent any polarized state of light. His success hinged on his readiness to abandon the amplitude-formalism of light in favour of a description based only on observable quantities, namely intensities. It is noteworthy that such an approach, unique at his time, went on to become one of the conceptual pillars on which, about a century later, the magnificent edifice of quantum theory was constructed. The Stokes parameter formalism of light and some of its relevant properties are briefly described in Appendix A.

Polarization is the manifestation of some anisotropy associated with either the emission/detection mechanism of light or the medium through which it propagates or both. It may be due to simple reflection from a surface or it may be the subtle Zeeman effect; let it be radio waves or let it be gamma-rays – myriad are the physical phenomena, which nature expresses in terms of polarization properties of light. Astronomy is no different in this respect; sunlight reflected from the comets in our solar-system backyard is polarized, so is the case of light scattering out of the dusty torii that are thought to surround the active galactic nuclei at the very edges of the visible universe.

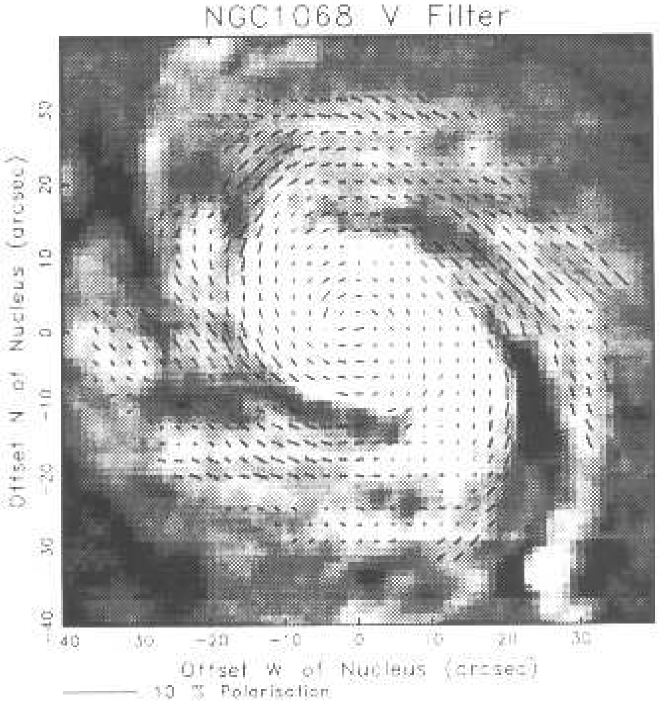

Figure 1.1: Linear polarization in light emitted at visible wavelengths, along the spiral arms of the galaxy NGC 1068 (adapted from Scarrott, 1991). The length of the vectors marked give the degree of linear polarization while their orientation, the polarization position angle.

See the beautiful symmetry of the polarization vectors, in Fig. 1.1, that trace out the spectacular spiral arms of the galaxy NGC 1068. Appendix B briefly illustrates, employing the Stoke's parameter formalism, how some of the phenomena of relevance in astronomy, affect the polarization properties of light.

The recorded history of astronomical polarimetry dates back to 1811, when Arago discovered that light reflected from the moon's surface is polarized. In spite of the early start and the universal nature of polarization of light, polarimetry did not make much headway as an effective astronomical tool, for a long time. However, this period saw many discoveries concerning polarization properties of materials as well as the development of techniques which employ these materials for polarimetric studies. The next major landmark in the history of astronomical polarimetry occurred in the late 1940s, when trying to verify a prediction by S. Chandrasekhar (1910-1997), that electron scattered starlight will be linearly polarized, Hiltner (1949) and Hall (1949) stumbled upon the phenomenon of interstellar polarization (see Sec B.3.2). Astronomical polarimetry came of age with this discovery and from then on there was no looking back. Now polarimetry occupies a permanent position in the regular astronomer's toolkit – quite advanced polarimetric techniques have been developed in the optical and radio wavelengths; ultraviolet, infrared and sub-millimeter wavelengths are close on the heels; X-ray techniques are in vogue and γ-ray observations are expected soon.

1.2 Polarimetric techniques

An important reason for polarimetry taking so long to be developed into a viable astronomical tool, is that the degree of polarization seen in astronomical situations is often small – typically, a few percent. An accurate measurement of such small signals, essentially involves determining small differences between large intensities. Secondly, due to the vector nature of polarization, it becomes necessary to make multiple observations under as identical conditions as is possible, to obtain full information about the polarization. Though this relative nature of the measurement process eliminates many of the problems which astronomical photometry is fraught with, polarimetry does have its own share to deal with. Several of these difficulties are discussed in the next two sections, with a view to crystallize the major concerns that would define the design of an astronomical polarimeter.

1.2.1 Single aperture polarimetry

The earlier polarimetric methods involved aperture photometry with suitable polarization sensitive elements inserted in the beam path. An excellent review of optical polarimeters based on aperture photometry is given by Serkowski (1975). Considering the vector nature of the signal and low levels of astronomical polarization, several techniques have been devised to minimize or eliminate the various errors associated with the measurement of polarization.

Since there are at least three unknown parameters to be determined, namely, the degree of linear polarization, the plane of polarization and the total flux, polarimetry normally involves taking multiple exposures. Therefore, atmospheric effects like scintillation, varying transparency etc. severely limit the accuracy with which relative intensities can be determined. A preferred way of solving this problem is by placing a half-wave plate in the beam path and rotating it rapidly. Then the direction of polarization is modulated at twice the frequency (f) of rotation of the half-wave plate and the measured intensity is modulated at a frequency of $4f$. The polarization information can then be gleaned from the resulting signal by extracting the component which is modulated at $4f$. Since image motion due to the rotation, affects the signal at f or $2f$, it can be easily eliminated. For such an arrangement, it is advisable to have the surfaces of the rotating element to be plane parallel.

A better, though more difficult to implement, solution to the above problem is to measure the two orthogonal polarization components simultaneously. This technique takes advantage of the fact that the atmosphere is not birefringent, and hence it affects both the polarization components equally. Besides, the normalized Stokes parameters q or u (see App. A) may be obtained from the ratio of intensities in the two orthogonal polarization components (see Eq. 2.4). Therefore, the effect of any multiplying factor in the measurement of intensities may be eliminated by measuring both the orthogonal polarization components simultaneously.

The sensitivity of most detectors is non-uniform across its light sensitive area. Thus if the image of the astronomical source is formed directly on the detector, any image motion caused by atmospheric seeing, bad telescope tracking, flexures etc. would render the intensity measurements erroneous. Thus it is advisable to reimage the entrance pupil (primary mirror of the telescope) on the detector with a Fabry lens arrangement so that the image on the detector remains stable irrespective of the above effects.

Since the sensitivity of the detector may also be polarization dependent, it is beneficial to have an arrangement where the analyzer is fixed with respect to the detector. Reflections from surfaces and edges of aperture stops, stray scattered light, thermal stress birefringence in optical components etc. cause instrumental polarization. Any spectral dispersion will change the state of polarization and hence all the optical components should be sufficiently achromatic over the wavelength range of interest.

All the above sources of errors become relevant typically when one is trying to obtain accuracies better than about 0.1%. Above this, the measurement accuracy is usually determined by the fundamental limit set by photon noise (see Chap. 3). The minimum error that has been achieved through aperture photometry is about 0.001%, and was obtained using photomultiplier tubes as detectors.

One of the serious difficulties with aperture polarimetric techniques is its limited sensitivity when high accuracy is demanded. It is almost impossible to eliminate varying sky polarization since the sky is not observed simultaneously with the object. It is often the aim of observations to map the polarization vectors over a region with high spatial resolution. This is extremely difficult and too time-consuming to achieve with aperture polarimetric techniques.

1.2.2 Imaging polarimetry

The advent of sensitive, two dimensional array detectors for the optical and infrared wavelength regions, has revolutionized astronomical observations, over the last decade or so. These detectors provide many fold increase in sensitivity, simultaneous sky measurement, high spatial multiplexing capability and the possibility of operating with seeing limited angular resolution. Astronomers have recognized the potential of the imaging mode and have developed several new polarimetric techniques in the optical (eg. Scarrott 1991; Jannuzi et. al. 1993; Jarrett et. al. 1994; Wolstencroft et. al. 1995; Simmons et. al. 1995) and near infrared (eg. Kastner & Weintraub 1994; Moore & Yamashita 1995; Weintraub et. al. 1995) wavelengths to study phenomena in a variety of Galactic and extragalactic astrophysical objects.

The primary application of an imaging polarimeter is in the study of extended astrophysical objects like reflection nebulae, structures near star-forming regions, dusty active galaxies etc. These objects are typically a few arcminutes in size and often fainter than 20th mag. per sq. arcsec. The complexity of structure present in these objects often demands observations with an angular resolution of a few arcseconds.

Dichroic extinction of background starlight by magnetically aligned dust particles at the periphery of dark molecular clouds in the Galaxy, introduces polarization in the starlight and hence can be employed to obtain magnetic field maps of these regions (see Sec. B.3.2). In order to make statistically significant estimates, it is necessary to have polarimetry of several tens of stars within the few arcminutes field of view. Since light from these stars are moderately reddened ($A_V \lesssim 4$) as it passes through the dust, this demands a device which is sensitive enough to measure polarizations less than 5% in stars as faint as 18-19th magnitude.

With these and other similar observations in mind, an imaging polarimeter has been constructed at the Inter-University Centre for Astronomy and Astrophysics, Pune. One of the primary design criteria, is high accuracy of polarimetric measurements – better than 0.1%, which is the best that have been achieved with current CCD polarimeters (Tinbergen 1997). Two orthogonal polarization components are measured simultaneously to eliminate atmospheric scintillation effects, image motion on the detector is minimized by employing a design with only one moving optical component and an accurate guiding mechanism is provided to allow long exposures necessary to obtain sufficient signal to noise ratio. Such considerations form the subject of the next four chapters, where we discuss the design and construction of the instrument in some detail, and make estimates of its performance.