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Recent development in optical and IR polarimetry

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Abstract. Polarimetry in recent years has matured and high precision measurements, from radio to UV wavelength, are possible in various modes : photo polarimetry, spectropolarimetry or imaging polarimetry. Within the country polarization studies are being carried out in different institutions. In PRL a high precision optical polarimeter is operational for the last ten years and important new results have been obtained using this instrument. An IR polarimeter is expected to be operational soon. Some of the results based on optical polarimetry are discussed.

Key words : polarimetry—optical and infrared—comets—BL Lac

1. Introduction

Polarization observations are very important to understand the physics of several astrophysical objects and their environment. Our knowledge of magnetic field structures within galaxies, AGNs, star forming regions etc. is derived from observations of the polarization characteristics of their emission. In AGNs the measurements of polarization and its time variability put constraints on various models of the central engine. In Seyferts it is not clear at present whether the polarization is due to dust scattering or due to the synchrotron emission. In dark clouds polarimetric studies are important to understand the characteristics of the dust grains and magnetic field geometry which play a very important role during the collapse of the cloud and subsequent fragmentation eventually leading to the formation of stars. Important results have been obtained in comet P/Halley and comet Austin (1989C_1) with polarimetric observations (photo polarimetry and imaging polarimetry) and for some other objects of great interest. There are number of articles which have discussed the particular aspects of polarization observations. For extra galactic radio sources an excellent review is by Saikia & Slater (1988). No single contribution in the optical and infrared polarization observation of extra galactic objects has appeared after seminal work of Angle & Stockman (1980). Polarization observations and mechanisms that produce polarization in various other objects within our galaxy (i.e. cataclysmic variables, symbiotic stars, late type variable stars, evolving stars near the main sequence) are covered in detail in the book "Polarized Radiation of Circumstellar Origin" edited by Coyne *et al.* (1988). A few topics (e.g. AGNs, dark clouds, comet) which are of current interest to us and not covered in detail elsewhere are discussed in this article. These objects are suitable for polarimetric observation on VBT or on 1m size telescope available in the country.

1.1. *Polarimetric definitions*

Radiation from astrophysical objects is in general partially polarized. The most convenient way to specify polarization information is in terms of the Stokes parameters (I, Q, U, V). These have the great advantage of being easily derived from the measurements and provide the full polarization characteristics of sources and can be easily manipulated as they follow the law of superposition. In defining the Stokes parameters we can consider either (a) the transverse electric fields in two orthogonal directions, E_x and E_y and the equivalent right- and left-circularly polarized fields E_R and E_L, or (b) I_ϑ, the intensity of the wave at an orientation ϑ with intensities of the equivalent right- and left-hand circularly polarized wave being I_R and I_L. Thus the most rigorous definitions of the Stokes parameters are :

$$I = < E_x E_x^* + E_y E_y^* > = < E_R E_R^* + E_L E_L^* > = I_0 + I_{90} = I_{45} + I_{135} = I_R + I_L$$

$$Q = < E_y E_y^* - E_x E_x^* > = < E_L^* E_R + E_L E_R^* > = I_0 - I_{90}$$

$$U = < E_y^* E_x + E_y E_x^* > = < E_L^* E_R - E_L E_R^* > = I_{45} - I_{135}$$

$$V = < E_y^* E_x + E_y E_x^* > = < E_R^* E_R + E_L^* E_L > = I_R - I_L.$$

In the above definition ϑ is measured in the equatorial co-ordinate system from the north increasing toward east. For circular polarization, the right-handed component (V positive) has the position angle of the electric vector of an incoming wave increasing with time as measured at a fixed point.

The degree of linear polarization is defined as :

$$p_L = \frac{I_P}{I} = \frac{(Q^2 + U^2)^{1/2}}{I} = \frac{(I_{max} - I_{min})}{(I_{max} + I_{min})}$$

where I_{max} and I_{min} are maximum and minimum intensities when a polarizer is placed in front of an incoming beam and rotated through a half turn. The polarization position angle is the orientation of the major axis of the polarization ellipse and can be obtained from

$$\tan (2\vartheta) = \frac{U}{Q}.$$

Similarly the degree of circular polarization is given by

$$p_c = \frac{V}{I} = \frac{(I_R - I_L)}{(I_R + I_L)}$$

and the total degree of polarization is given by

$$p = \frac{(Q^2 + U^2 + V^2)^{1/2}}{I}.$$

1.2. *Sources of error in polarization observations*

In astrophysical objects the observed polarization is generally very small, typically < 3% but in some cases, (e.g. comets, BL Lac objects) it is quite high—10 to 20%. High polarimetric precision is essential. The principal sources of error in polarimetry are : photon noise, atmospheric scintillation, instrumental polarization or depolarization and linear to circular conversion, bad seeing, variable sky background etc. Modern polarimetric techniques can achieve high degree of precision in polarimetric measurements (order of magnitude higher than photometric precision) using : (a) rapid modulation techniques which eliminate atmospheric scintillation, bad seeing, variable sky background, (b) simultaneous recording of two orthogonal components of light along with the background sky. A polarimeter based on the rapid modulation technique, developed in PRL (Deshpande *et al.* 1985), is operational for last couple of years and several important results, obtained with this instrument, are already published. The precision in polarization measurement is only limited by photon noise.

Photon noise : The principal limitation of precision in astronomical polarimetry results from photon statistics. Other sources of error become important only when better accuracy is needed. Ideally the mean error of each of the simultaneously measured normalized stokes parameters Q/I and U/I is : $\varepsilon(Q/I) = \varepsilon(U/I) = \sqrt{(2/N)}$ where N is the total number of photons counted. The only way to reduce the error resulting from photon statistics is to count more photons. The number of photo electrons produced per second by the photo cathode of quantum efficiency q illuminated by the light of a star of magnitude m collected by a telescope of diameter D equals :

$$N = 3.95 \times 10^{18} \lambda \cdot \Delta\lambda \cdot F_{\lambda} \cdot T \cdot q \cdot D^2 \cdot 10^{-0.4m}$$

where λ and $\Delta\lambda$ are respectively wavelength and the width of the spectral interval in micrometer, T is the joint transmittance of unpolarized light by the Earth's atmosphere, the telescope optics, and the analyzer, F_{λ} is the absolute flux density of the 0th magnitude A0V type star, h is Planck constant and c is the velocity of light. The number of photo electrons expected for the blue spectral region of the UBV system $\lambda = 0.44\mu$m, $\Delta\lambda = 0.09\mu$m for 100 cm telescope are ~45000 e^-/sec for a star of $m_B = 10$. In calculations we have assumed $T = 0.2$ and $q = 0.20$. The mean error in measurement of degree of polarization for an integration time of 10 minutes with a single channel polarimeter is $\varepsilon = 0.03\%$. This error would be smaller by a factor of $\sqrt{2}$ for a double channel polarimeter in which two photomultipliers are placed in the two perpendicularly polarized beams emerging from a Wollaston prism. Error due to photon noise for a 16 mag star when observed on VBT is estimated to be ~0.2 % (integration time is assumed to be 10 minutes). This gives a rough idea to choose an observational program using telescopes available in the country. Certain polarimetric programs demand high spatial resolution for which VBT is a unique choice. This point is clarified latter.

There are different methods to measure polarization which in a broad sense can be put in three classes : photo polarimetry, imaging polarimetry and spectro polarimetry; the choice may be governed by the research program. PRL photo polarimeter for optical region (0.35-0.85 micron) based on the rapid modulation principal is in operation since 1984 and has produced several important results. An Infrared Polarimeter is being built in PRL and expected to be operational soon. There are other institutions like IIA, Bangalore who are interested in polarimetry and have developed aperture and imaging polarimeters. IUCCA has plans to develop an imaging polarimeter based on CCD. It is difficult to cover polarimetric work being done elsewhere in the world in the limited space and time available for this review. Therefore, I have confined to the work being done in India; international work will be highlighted at appropriate places. A good description of various optical and IR polarimeters operational at different observatories across the world is given in the book edited by Coyne *et al.* (1988).

2. Astrophysical programs

There are several exciting programs where polarization measurements are extremely important and provide very useful information on physical processes that are taking place in the source. Some of the processes that produce polarization are as follows : Non thermal emission in a magnetic field; thermal processes in a magnetic field; electron and Compton scattering; atomic and molecular scattering; scattering by dust particles; interstellar polarization.

Some of the astrophysical sources, where polarization observations in optical and IR bands are important, are given below :

(a) Solar system objects : planets, comets etc;
(b) Stellar objects : T Tauri stars, late type stars, symbiotic stars, binary stars, B_e stars, A_P stars, magnetic white dwarfs, cataclysmic variables, RS CVn stars etc.
(c) Supernova;
(d) Molecular clouds and dark clouds;
(e) Reflection nebulae and cometary nebulae;
(d) Interstellar polarization;
(f) Active galactic nuclei : BL Lac objects, OVVs, HPQs, Seyfert galaxies etc.

In the following polarization characteristics of some of the objects (e.g. AGNs, dark clouds, comets) are discussed. As it is beyond the scope of present article to cover polarization characteristics of all the above mentioned objects of astrophysical interest, only topics of interests to us are discussed.

2.1. *Active Galactic Nuclei (AGNs)*

AGNs include the study of Seyfert galaxies, Quasars and Blazars. It is important to study these objects as they are different in many respects from the nuclei of normal galaxies, especially in the energy production mechanism. There are serious efforts all around the world to understand the physics of these objects through different window of radiation-gamma rays to radio region; still there are many unanswered questions viz. (a) what is the relationship between BL Lacs and Quasars? (b) whether their central sources are anisotropic or multi component? (c) whether the bulk relativistic motions are associated with them? (d) what is the size of the source? Polarization (wavelength dependence and its variability) measurements will put constraints on various models.

2.1.1. SHORT TIME SCALE VARIABILITY IN BL LAC OBJECTS

AGNs in general show variability both in flux and polarization; BL Lacs and HPQs especially show violent variations. Polarimetry can be made with much higher precision compared to the photometry as has been discussed earlier; small variations in polarization can be detected far more easily. Time scale of variability is an important parameter to put constraints on the size of the nuclei. Short time scales (couple of minutes to few hours) have been reported for some BL Lacs and HPQs.

OJ 287 : Oscillations of duration 25 minutes were detected in polarimetric measurements on OJ 287 (Kulshrestha *et al.* 1985). These oscillations are important findings as they give a clue to the physical processes going on in the central engine of OJ 287. The observed high degree of polarization (up to 17%) and its short period oscillations indicate that either the bulk relativistic streaming was responsible for these oscillations or the central engine source is very compact—probably a black hole with an accretion disc system.

Different models have been proposed to explain the short time scale variability in BL Lac object : Shock-in-jet model (Marsher & Gear 1985); Gravitational microlensing (Gopalkrishna & Subramanian 1991); accretion disc with hot spots (Wiita 1991). Shock-in-jet model explains most of the observed properties of BL Lac objects except the redshift distribution. BL Lac objects are found to be the nuclei of elliptical galaxies and in some cases multiple nuclei, which may be due to gravitational lensing, have been detected. This and the redshift distribution of BL Lac object have led to propose gravitational microlensing as the cause for short time scale variability. However it is difficult to explain, on the basis of gravitational microlensing, the polarization behaviour of the source. The polarization vector is observed to be aligned with the jet observed in VLBI mapping e.g. VLBI measurements of OJ 287 of Gabuzda *et al.* (1989) and our polarimetric measurements show the VLBI jet is aligned with the polarization vector. More observations are needed to settle these questions.

2.1.2. POLARIZATION STUDY OF BLAZARS

Five blazars were observed with 61″ telescope at Mt. Catalina, University of Arizona, USA. Polarization observations were carried out to look for the existence of multi component in the nuclei of these objects. Two objects-PKS0735 + 178 and ON-325 exhibit wavelength independent polarization and position angle. Existence of synchrotron radiation mechanism in these sources is suggested. In another object which is a highly polarized Quasar (4C29.45) a very interesting feature on the rotation of polarization angle has been observed with two distinct slopes (Kulshrestha *et al.* 1987). This has demonstrated for the first time, in optical windows, the presence of two components in the nucleus of the quasar which are synchrotron radiation dominated. This also gives evidence for the existence of two black holes in the nucleus of this quasar.

2.1.3. EVIDENCE OF DUST SCATTERING IN SEYFERT GALAXIES

Quasars and nuclei of Seyfert galaxies show many similarities. The energy released by quasar is of non thermal origin (synchrotron). However, the problem of energy release mechanism in Seyfert galaxies is not resolved. To understand the nature of nuclear energy in Seyfert nuclei, we have made mutli spectral band polarimetric observation through different size (more than 10 arcsec) aperture. This approach has not been exploited previously and we have obtained very important results by observations made on 1m size telescope. Some of the important results are discussed here.

Four galaxies NGC 2992, NGC 3081, NGC 3227, IC 4329A were observed during the year 1984-87 and important results have been obtained (Joshi *et al.* 1988). NGC 3081 shows significant time variation of the degree of polarization and position angle in all the bands; V band polarization changes between 1.34 ± 0.36 to 0.49 ± 0.25% during 1984-87. These observations show that the nuclei of NGC 3081 is a relatively strong non thermal source. Further observations are planned on NGC 3081 to investigate this source in detail. Seyfert galaxies NGC 2992 and IC 4329A show significant decrease in polarization when observed through increasing aperture 6 to 30 arcsec. However the polarization increases towards the shorter wavelength, which is indicative of the dust scattering. Wavelength dependence of polarization in NGC 2992 shows a hump in R band observations, which also support the dust scattering model. The wavelength dependence of polarization and the observations through different apertures in NGC 3227 clearly demonstrate that the dust scattering in the surrounding region of nucleus is to be the main agent producing polarization.

2.2. *Dark clouds and star formation*

Star formation in earliest phases is still not well understood; especially the role of magnetic field and the grains. The magnetic field in dark clouds is expected to impede the collapse and retard the formation of protostars. It is not known how the interstellar material breaks free of the field. Polarimetric studies where stars have recently formed or are forming are useful to map the magnetic field and to study its relation to the cloud and young stellar objects.

Bok globules are one of the likely birth places of stars. Bok globules, generally roundish in shape, appear as dark patches in the sky. Bok believed these dark patches to be proto star or proto proto star, but until recently there was no evidence of any proto star in a globule and therefore scientists did not pay much attention to these objects. Recent IR observations (especially IRAS measurements) and CO line measurements have detected hot spots or IR sources in a few globules. B5 is an important example of such a case.

Another question to address is the role of dust grains in the clouds? Grains play an important role during the collapse of the clouds leading to the formation of stars but the details are not known.

A program to measure polarization of the background stars in the region of nearby Bok globules was started by us. When light from a background star passes through a dark globule it gets attenuated and polarized. Degree of polarization and its wave length dependence depends on the degree of grain alignment in the globule and grains's characteristics. The polarization vectors tell us about the magnetic field geometry and the wave length dependence of polarization is helpful to understand the characteristics of the grains. We carried out polarimetric measurements in dark globules : B5, L134, Heiles cloud 2 (Joshi *et al.* 1985, Joshi *et al.* 1986, Kulkarni *et al.* 1987). Observations on B5 were done on the 154 cm telescope of the University of Arizona whereas the observations on L134 and Heiles cloud 2 were performed on the 100 cm size telescope of IIA, Kavalur.

Dark clouds contain dust grains which are generally non spherical and can be aligned by the ambient magnetic field by Davis-Greenstein mechanism. When light passes through such medium it gets attenuated and polarized as well. The direction of polarization vectors represent the projection of magnetic field in the sky. The wavelength dependence of polarization reflects the characteristics of the grains.

The observations could be made only in the outer region of the globules. The important results of the above work are as follows : (i) Polarization maps representing the magnetic field geometry in all the globules have been produced. (ii) An interesting observation in B5 is that polarization vector are parallel to the major axis of B5 which is also the rotation axis in projection. Our interpretation was that bulk of the B5 cloud parallel to the rotation axis is supported against gravity by stellar wind from the embedded IR sources. Magnetic field being parallel to the elongation axis cannot support the collapse of the cloud against gravity in this situation. The strength of the magnetic field in the cloud is estimated to be about 100μG. (iii) Polarization vectors in B5 in NW region are nearly perpendicular to the vectors in other regions. Hot spots in B5 have been detected by IRAS (Beichmann *et al*. 1984). An alternative explanation of the whole scenario is that the cloud collapses parallel to the rotation axis/or magnetic field axis. A central object (IRSI?) forms with a torus around it. The orientation of this torus is perpendicular to the rotation axis. The torus collimates the mass loss (bipolar?) from the central object, which may restrict further collapse. The magnetic field is constricted by the collapse and follows the torus. The polarization vectors in the NW region may be explained this way. The form of brighter contour of CO map also supports this view. (iv) The wavelength of maximum polarization is significntly larger in B5 than the normal interstellar value, indicating that the dust grains in B5 might be larger than the interstellar grains. (v) Polarization vectors in L134 and Heiles Cloud 2 show high degree of alignment. This probably indicates star formation has not reached a stage were vigorous mass loss is expected. Degree of polarization in Heiles cloud 2 is quite high (P ~6%). This is possible only if the magnetic field in the surrounding region is high or the disturbing factors are at minimum. Further work is required to probe into the denser portions of the cloud, which are of great interest.

Theoretical models on the distribution of grains in globules have also been proposed (Kenyon & Starfield 1979; Williams & Bhatt 1982). In the model by Kenyon & Starfield the gas and dust density both increases towards the centre. The dust density increases more rapidly than the gas density in the model given by Williams & Bhatt; in such a model the larger grains settle faster than small ones, so a size variation with large grains towards the centre and smaller in the periphery is expected (Bhatt and Desai, 1982). A detailed study of the wavelength dependence of polarization is needed to understand the characteristics of the grain and their distribution in globules.

2.3. *Polarimetric studies on comets*

Polarimetric observations of comet p/Halley and comet Austin were made during pre- and post-perihelion phases to find out the physical properties of the cometary grains, their distribution, composition (in terms of its complex refractive index) etc. Observations have been taken through the IHW filters covering phase angle from 44 to 66 degrees in case of Halley and 106-108 degrees in case of Austin. Some of the new exciting results are presented here.

2.3.1. DUST DISTRIBUTION IN COMETS

Comet Austin has been studied along with comet Halley and a comparison of their dust properties has been made through polarization measurements. It is vital to understand the origin and dynamical evolution of comets. Through model based calculations we have studied the composition of comets Halley and Austin's grains (in terms of its complex values of refractive indices). The results are very interesting. The calculations, being based on wide coverage of the phase angle, give unique solutions. This kind of detailed calculations were performed for the first time in the sense that very wide phase coverage of polarimetric observations have been taken into consideration and a least square solution has been sought. Some of the results are discussed in the following :

(a) *The dust size distribution of comet Halley* (dynamically older) is different than that of comet Austin (a new comet) in the sense that Halley is relatively richer in coarser grains than Austin. There were conjectures that dynamically older comets may be richer in coarser grains due to dynamical evolution. Thus for the first time it has been demonstrated experimentally that dynamically older comets are richer in coarser grains (Sen *et al.* 1991; Joshi *et al.* 1992).

In comet Halley it is found that dust grains are segregated, the coarser ones being in the central region of the coma. Also the coma is found to be richer in dust content as compared to tail region. There is segregation of grains in comet Austin also. The composition of comet Austin does not seem to be very much different than that of comet Halley.

(b) *Detection of sub micron size particles in comet p/Halley* : We have conducted model dependent calculations, assuming Mie scattering, which can fit the observed polarization data. These model calculations were fitted to the seven night's data in pre- and post-perihelion observations. Our calculations show that the existence of sub micron size (~0.001 micron) particles is highly essential to reproduce the observed polarization properties of the comet (Sen *et al.* 1991). Also it has been found from the values of refractive index and absorption coefficient that the grains are dirty silicate or dirty ice type or organic type (containing C, H, O, N, etc. having values of refractive index = 1.39 ± 0.03 and absorption coefficient = 0.033 ± 0.004). At the same time these values have been found to be varying with wavelength. The refractive index decreases and the absorption coefficient increases within the above range as the wavelength changes from 0.365 to 0.684 micron.

2.3.2. DETECTION OF RESONANCE FLUORESCENCE POLARIZATION

We have detected polarization in the neutral (CN, C_2, and C_3) and the ionic (CO^+, and H_2O^+) bands (Sen *et al.* 1989; Joshi *et al.* 1992). The neutral bands show polarization of the order of 6%. In case of C_2, the maximum theoretically expected polarization at phase angle 90° is 8%. Our observations on comet Halley at phase angle 66° show a polarization of 6% which is in good agreement with the theory. In case of C_3 the observed polarization is much lower than the model predicted value. The production mechanism of C_3 in comet is not yet known. Our observations have shown interesting phenomenon in the nucleus of the comet which may help in understanding the production mechanism of C_3. Around March 18, 1986 several ejections from the cometary nucleus have been observed by other investigators. Our observations of March 18 have shown drastic reduction in C_3 emission with an associated enhancement in H_2O^+. It is believed that C_3 is produced due to the photo dissociation of C_3H_4. During normal conditions C_3H_4 and H_2O are present in the nucleus. However, during an eruption the H_2O molecules are pushed out side the nucleus owing to their large mobility compared to that of C_3H_4. This leads to the formation of a halo of H_2O around the comet nucleus, leaving behind the C_3H_4 molecules in the nucleus. Owing to this halo the UV radiation reaching the nucleus decreases, which causes a decrease in the production of C_3. Hence the observed enhancement in H_2O^+ and the depletion in C_3 is explained due to eruption in the comet.

2.3.3. IMAGING POLARIMETRY OF COMET P/HALLEY AND COMET AUSTIN

Imaging polarimetry is very important to understand the nuclear activity and the dust distribution in the comets. Comet P/Halley was observed on 5th January 1986 on Celestron 14 at Gurusikhar.

The white light images of the comet were obtained with the image intensifier placed at the focal plane, with a polaroid sheet placed in front of the telescope. Three photographs were taken in three different orientation of the polaroid sheet with respect to the celestial NS. These images were later digitized on PDS machine in IIA, Bangalore. Further analysis of these images were done on image processing system developed in our group by us. The software has been developed for image matching (spatially). Each image was filtered to remove any pixel defects or noise. Polarization vectors were determined and mapped on the entire image of the comet (Sen *et al.* 1990).

In case of comet Halley in the inner coma a small region has been found which has very low (< 2%) polarization but in the tailward direction beyond the outer coma (> 10^5 km) two separate regions of enhanced polarization (> 8%) are found. Perhaps the low polarization in the inner coma region is connected with fresh dust jet ejecta where the low polarization results from multiple scattering in a region of high dust concentration. For all these cases the polarization vectors have been found to be perpendicular to the scattering plane.

Pockets/blobs of high and low polarization were detected in Halley. In order to study the motion of such blobs (which are connected with nuclear jets) and dust dynamics (Syncrone and syncdyne) repeated imaging polarimetric observations have been made on comet Austin on several nights during the last week of April and first week of May 1990. The polarization map for April 30 does not show activity as strong as is seen in comet Halley. There are regions of high and low polarization nearly symmetric about the nucleus. The outer coma shows a region of high polarization (~16%) nearly in the form of a shell. Near the nucleas the polarization is low. Details are discussed in a paper in the same issue of the journal (Joshi *et al.* 1993).

3. Concluding remarks

Polarization measurements with high accuracy are possible (1 part in 100000); the only limitation is the flux collection. Polarization studies are extremely important to understand several astrophysical problems. In active galactic nuclei, especially in BL Lac objecs, HPQs and OVVs, polarization studies are important to understand the nature of the central engine, cause of variability etc. To understand the role of magnetic field and dust grains in star formation in dark clouds and molecular clouds, detailed polarization observations are needed. Similarly to understand the mass loss processes in the early phases of star formation i.e. in proto stars polarization observations are quite useful. Such observations tell about the geometrical shape of the dust shell and also the composition of the dust. One of the important areas is to understand the formation of the solar system. Comets are considered to have formed with the solar system and their material is still in the pristine form. The distribution of dust and its composition may give us clues about the physical conditions existing at the time of the solar system formation. One of the important research areas in present time is the study of cataclysmic variables. There are groups in the country who are interested in these objects. This topic could not be covered here due to limited time and space. However, the polarization behaviour of these objects is extensively covered in the book edited by Coyne *et al.* (1988) and mentioned above.

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