Photopolarimetric investigations – Role of Pancharatnam retarder

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An optical polarimeter which uses Pancharatnam superachromatic half wave plate and quarter wave plate for modulation, was constructed at Physical Research Laboratory, Ahmedabad. This is a precision instrument capable of measuring polarization to an accuracy of 0.03%, in the flux limited case, in the whole of the optical region. The instrument works very efficiently on the telescope which is possible due to the use of superachromatic Pancharatnam retarders. Besides optical polarimeter, an infrared (IR) polarimeter, which also used superachromatic (1 to 2.5 micron) Pancharatnam retarders, has also been developed in PRL. The instrument has been tested in the laboratory and astronomical observations are planned in the near future. Several important results have already been obtained with optical photopolarimeter. Some of the results are briefly summarized in this article.

POLARIZATION observations are very important to understand the processes that are going on in astrophysical objects. Our knowledge of magnetic field within the galaxies, active galactic nuclei (AGN), star-forming regions, etc. is derived from polarization observations. In dark clouds (possible star-formation sites) polarimetric studies are important to understand the characteristics of dust grains and the magnetic field geometry which may play an important role during the collapse of the cloud, leading to the formation of stars. In AGN the measurement of polarization and its time variability put constraints on various models. In Seyfert galaxies it is not clear whether the polarization is due to dust scattering or synchrotron emission. Important polarimetric studies have been obtained in comet P/Halley and comet Austin (1989c1) and for some other objects of great importance.

An optical polarimeter was constructed in PRL[1] which works on the principal of rapid modulation produced by a rotating superachromatic Pancharatnam half wave plate[2]. The instrument is very efficient on a telescope due to the use of superachromatic half wave plate; otherwise one may have to change the retarder for each wave band, which may result in a complicated and inefficient instrument. The polarimeter is capable of measuring linear as well as circular polarization. For the measurement of circular polarization we introduce a superachromatic quarter wave plate. Recently an infrared polarimeter has been developed in PRL which also works on the rapid modulation principle. In this case also the modulating element is Pancharatnam superachromatic half wave plate (1 to 2.5 micron). The IR polarimeter was fully designed, developed and fabricated in PRL; laboratory tests have been conducted. Soon this will be taken to telescope for astrophysical observations.

Some astrophysical results

Star-formation studies in Bok globules

Star formation in its earliest phases is still not well understood; especially the role of magnetic field and the grains in the clouds where stars may form is very important but least understood. Bok globules are 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 protostar or proto protostar, but until recently there were no evidences of any protostar in a globule and therefore scientists did not pay much attention to these objects in the past. Recent IR observations by IRAS satellite and CO line measurements in mm wave have detected hot spots or IR sources in a few globules. B5 is one such important example.

Polarization measurements on globules B5, L134 and Heiles cloud 2 were made and the important results of the above work are as follows[3–5]:

(i) A polarization map representing the magnetic field geometry in all these globules has been produced; (ii) An interesting observation in B5 is that polarization vector is 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 100 μG. (iii) Polarization vectors in B5 in NW region are nearly perpendicular to the vectors in other regions. An alternative explanation to the whole scenario is that the cloud collapses parallel to the rotation axis or

magnetic field axis. A central object (IRS1?) 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 significantly larger in B5 than the normal interstellar value, indicating that the dust grains in B5 might be larger than the interstellar grains.

Polarization vectors in L134 and Heiles Cloud 2 show high degree of alignment. This probably indicates star formation has not yet set in or has not reached a stage where vigorous mass loss is expected. Degree of polarization in Heiles cloud 2 is quite high ($P \sim 6\%$). This is possible only if the magnetic field in the surrounding region is high and the disturbing factors are at minimum.

Active galactic nuclei (AGN)

AGN include 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 production mechanism of energy. Efforts are being made to understand these objects by studying them in various bands of electromagnetic spectrum, from radio to γ-rays; still there are many unanswered questions, viz. (i) what is the relationship between BL lacs and quasars? (ii) whether their central sources are anisotropic or multicomponent? (iii) whether the bulk relativistic motions are associated with them? (iv) what are the sizes of the sources? To answer the above questions we have started polarization measurements on a few objects and some important observations and results are given below:

Polarization and variability study of blazars

Rapid optical variations are expected in some of the BL lac objects. It is vital to investigate the high speed optical variability of these objects to understand the nature of their central energy sources. In particular, the presence of periodicity in the radiation would support the gravimagnetic rotator model while in case of the accreting black hole model we expect quasi periodic variation. Five blazars were studied with 61″ telescope at Mt. Catalina, University of Arizona, USA. Oscillations of duration 25 min were detected in polarimetric measurements on OJ287 (ref. 6). Such short period oscillations were detected for the first time by us. These oscillations are important findings as they give a clue to the physical processes going on in the central engine of OJ287. 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.

Polarimetric and photometric observations were continued on BL lac objects: OJ287, OI90.4 and Mrk 421 on 2.34 m Vainu Bappu Telescope of IIA at Kavalur. As a part of a program for seeking the evidence of rapid optical variability in BL lac objects we have carried out observations on OJ287 and Mrk 421. Although there is keen observational interest in short time scale variability, such data are lacking.

Micro variability in BL lac object OJ287

Micro variability has been detected in OJ287 and Mrk 421 during observations carried out in January–March 1991 and February 1992. The observations showed variability in flux and polarization in time scale as low as 6.3 min in OJ287 (ref. 7). Observations were continued during 10–20 March 1993 on 2.3 m Vainu Bappu Telescope. The observations confirm the 6.3 min time scale of variability detected earlier.

Variability in Mrk 421

In spite of the extensive study of Mrk 421 like multifrequency observations, spectroscopy, photometry and polarimetry, etc., only scattered information is available on the optical variability. Observations in white light, carried out on 23 January 1990, show rapid variability in flux in a time scale of about 45 min; the flux decreased by $m \sim 0.4$ mag (ref. 8). Polarimetric data show fluctuations in a time scale ~ 20 min. The signal to noise ratio S/N for the polarimetric data is always better than 20. The variations thus appear to be very significant. More observations are planned to know the detailed nature of the variability and to find correlation between variation in flux and degree of polarization. Present polarimetric observations indicate that short time periodic variations exist.

Photopolarimetric study of 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 multispectral band polarimetric observation through different size apertures. This was a new approach used for the first time and we have obtained very important results just by observing on 1 m size telescope. Some of the important results are discussed below: Four galaxies – NGC 2992,

NGC 3081, NGC 3227, IC 4329A – were observed during 1984–87. NGC 3081 shows significant time variation in the degree of polarization and position angle in all the bands; V band polarization changes between 1.34 ± 0.36 and $0.49 \pm 0.25\%$ within 1984–87 (ref. 9). These observations show that the nuclei of NGC 3081 are relatively strong non-thermal sources. Seyfert galaxies NGC 2992 and IC 4329A show significant decrease in polarization when observed through increasing aperture – 10 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. Spectropolarimetric observations show that the polarization in continuum and hydrogen emission line is the same, supporting dust scattering. The wavelength dependence of polarization and the observations through different apertures in NGC 3227 clearly demonstrate the dust scattering in the surrounding region of nucleus to be the main agent producing polarization.

Photopolarimetric observations on some Seyfert galaxies were continued on 2.3 m VBT through different size apertures. Galaxies NGC 2992, NGC 3081, NGC 3227 and NGC 4388 show sharp increase in degree of polarization[10] in small aperture (5 arcsec), indicating the presence of non-thermal source at the nuclei.

Comet study

In comet Halley and comet Austin, we have obtained several new and exciting results. Comet Halley is an old comet in the sense that it has already made several visits. The comet Austin is perhaps a new comet in the sense that this is its first visit. Detailed study of this new comet was done and compared with comet Halley or other comets.

Molecular band polarization is important to model the production mechanism and excitation states of different molecules. To understand the complete nature of molecular band polarization it is necessary to observe the comet over a wide range of phase angles. The other question, which we have addressed, is the composition of cometary dust. This is vital to understand the origin and subsequent evolution of comets. Through the model-based calculations in comet Halley, we have studied the composition of comet Halley's grains (in terms of its complex values of refractive indices) from our polarimetric data. We have obtained very interesting results on comet Halley. The calculations, based on wide coverage of the phase angle, give unique solutions. This kind of detailed calculations was performed for the first time in the sense that very wide phase coverage (20–66 degrees) of polarimetric observations has been taken into consideration and a least square solution has been sought. Similar work was done for comet Austin. The question we wanted to address is whether the same grain properties hold true for other comets also. This work is very important to settle the question whether the comets have same origin or different one.

We have a very good polarization data base on comet Halley and comet Austin which is based on our photo-polarimetric observations. Some supporting data available in the literature have also been used in the present study. Some of the important results are as follows:

Detection of submicron size particles in comets P/Halley and Austin and composition of cometary dusts

Comet Halley/P. Comet P/Halley was observed polarimetrically for seven nights in IHW and other continuum filters, during its pre- and post-perihelion passages. The observed polarization was found to increase with the wavelength and the nature of the wavelength dependence of polarization was different for the different parts of the comet, signifying the segregation of different size grains over different parts of the comet[11]. These polarimetric observations have been combined with the observations taken by other investigators and assuming spherical-shaped particles (with density $\rho = 1.0$). 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[12] that the existence of sub-micron size (~ 0.001 micron) particles is highly essential to reproduce the observed polarization properties of the comet. It has also 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. We have found that particles within the size range 0.001 μm to 20.0 μm are essential to produce the observed polarization. Further, this work indicated that the grains are dirty ice or silicate type or a combination of them[12]. These model calculations have yielded very important results on the composition of comet Halley. This was the first time that such detailed calculations were attempted taking into account the observations made for a large base in phase angle.

Polarimetric work on Comet Austin. Photopolarimetric observations on comet Austin were made on 90" Telescope, at Kavalur of Indian Institute of Astrophysics,

Bangalore during pre-perihelion phase of the comet. These were one of the first photopolarimetric observations made at the Cassegrain focus of 2.34 m Vainu Bappu Telescope of Indian Institute of Astrophysics at Kavalur. Observations were taken with IHW filters (UC:3650; CN:3871; C_3:4060; CO^+:4260; BC:4845; C_2:5140; RC:6840; H_2O^+:7000A) on 20 February 1990 (Note: UC, BC, RC: Ultraviolet, blue, red continuum respectively). Similar observations were continued on comet Austin on 1.2 m telescope of PRL at Mt. Abu during May 1990.

The flux distribution and wavelength dependence of polarization[13] when compared with the model calculation indicate that the dominant dust particles lie in a range of 0.1 and 0.5 μm in size.

Through the model-based calculations, we have studied the composition of comet Austin's grains (in terms of its complex values of refractive indices). We have obtained very interesting results on comet Austin. The calculations, being based on wide coverage of the phase angle, give unique solutions. Some of the results are discussed below:

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[14]. There were conjectures that dynamically older comet may be richer in coarser grains due to dynamical evolution. Thus it has been demonstrated experimentally that dynamically older comets are richer in coarser grains.
b) The composition of comet Austin does not seem to be very much different than that of comet Halley.

Molecular band polarization

The molecular band polarization of CN, C2, CO^+, C_3 and H_2O^+ in comet P/Halley[15] where the emission takes place by resonance fluorescence mechanism, shows that emissions from CN, C_2 and C_3 have polarization values between 5 and 7%, at a phase angle of 66.1 degree. For CN and C_2 the polarization values agree well with the theoretically predicted values, but for C_3 the polarization value falls much below the theoretically predicted value. The two ionic molecules CO^+ and H_2O^+ show large polarizations, 17.5% and 29.5% respectively. Presently neither theoretical nor experimental work is available on the molecular band polarization of these two molecules. These values can be used for appropriate modelling of the different excitation states and mechanisms for these molecules.

In comet Austin the observed polarization values for CN and C_2 molecules agree well with the theoretically predicted values, but for C_3 the polarization value falls much below the theoretically predicted value. Also, the observed polarization values for C_3 show significant variation from night to night. Neither theoretical nor experimental work is available on the molecular band polarization of these two molecules. These values can be used for appropriate modelling of the different excitation states for these molecules.

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