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Wide Field Cometary Polarimetry using a Novel Device

Abstract

The polarization of cometary comae and tails had already been detected by Arago in the comets 1819-III and 1835-III-Halley, but it was Öhman in 1941 who found for the first time that two mechanisms produced the polarization of comets: the scattering of sunlight by the cometary dust particles and the fluorescence of the molecular cometary plasma.

Due to the strong and variable polarimetric contribution of the moon-lit or dusk/dawn night sky, the study of polarimetry of comets is one of the most difficult tasks in observational astronomy. It demands that the Stokes parameter for linear polarization are obtained simultaneously, otherwise too many systematic errors make a quantitative interpretation of the observations unsafe.

Recently I have developed a new type of polarimetric device for simultaneous astronomical point sources and extended object linear polarimetry, and which is presently being tested at our observatory.

The device consists of a double Wollaston calcite prism, the two halves of which are arranged in a special way. The device is inserted into the exit pupil of a telescope – focal reducer and splits a point source into four images, each having by 45° different polarization angles. For extended astronomical objects like comets, surface polarimetry is possible by a masking technique (multi-object observing mode) in the focal plane of the telescope.

1. Introduction

Together with laboratory experiments, the polarization measurements of comets and generally for all solar system bodies is an important observational approach for the understanding of their constituents of their outer layers.

As cometary comae and tails can be considered as strongly variable atmospheres of scattering molecular plasma and dust constituents, the scattered solar light is more or less polarized for the observer.

Although the discovery of the polarised light from the moon and the comets 1819-III and 1835-III-Halley by Arago roots back in the first half of the last century, it was only until 1941 when Öhman found, that the cometary polarization is produced by two different mechanisms:

a) the scattering of the sunlight by the cometary dust particles;
b) the fluorescence of the molecular cometary plasma.

The main contribution to the total polarization of comets is that of mechanism a). Therefore the circular polarised light contributes only marginally.

Recent reviews and compilations about the polarization observations in comets have been given by Dobrovolsky et al. (1986), Lamy (1985) and McDonnel et al. (1991), which show that the basic observational photopolarimetric material for different comets is sparse and in most cases concentrated into the inner coma and nucleus. Only the last comet Halley apparition yielded a satisfactory set of polarimetric measurements by several groups over a phase angle range of about 80°, but also mainly for its inner parts.

There are several reasons for this observational lack of intrinsic polarimetric measurements on comets, especially their outer coma and tails:

a) the bulk of existing astro-polarimeters is based on photomultiplier detectors, which have only a very limited field of view and low spatial resolution, given by the focal plane diaphragm. Therefore the polarimetry of many different parts of extended celestial objects cannot be done simultaneously, and demands long observing runs;

b) due to the fast proper motion of comets the recentering onto certain positions is unsafe and difficult with ground based telescopes;

c) as comets are mainly observable with phase angles < 90° (dusk or dawn observations) the sky fore- /background is polarimetrically strongly variable. To this also contributes the stellar background on account of the comets' proper motion. Both influences are difficult to account for.

The state of art of these types of astro-polarimeters has been given nearly 20 years ago by Serkowski (1974), though many improvements for astro-polarimeters have been made in the meantime.

1.1 Polarimetric definitions

Conventionally the (linear) polarisation in astronomy is given by the polarisation degree P and the azimuth angle ϕ of the direction of the vibration of the electric field vector. Normally the Stokes parameters I, Q, U, V are used:

$$I = \langle E^2_{x0} \rangle + \langle E^2_{y0} \rangle; \quad Q = \langle E^2_{x0} \rangle - \langle E^2_{y0} \rangle;$$

$$U = \langle 2E_{x0}\, E_{y0} \cos(\delta y - \delta x) \rangle; \quad V = \langle 2E_{x0}\, E_{y0} \sin(\delta y - \delta y) \rangle.$$

Here E_x and E_y are the field vectors amplitudes, δx, δy the phases. For linear polarisation $(\delta y - \delta x) = 0$. P and ϕ are given by:

$$P = (Q^2 + U^2 + V^2)^{½}/I; \quad \phi = ½ \tan^{-1}(U/Q).$$

In normalized form the Stokes parameters for linear polarized light are easily obtained by measuring the flux in 4 different orientations of the polarizer:

$$Q/I = \{I(0^\circ) - I(90^\circ)\} \,/\, \{I(0^\circ) + I(90^\circ)\};$$

$$U/I = \{I(45^\circ) - I(135^\circ)\} \,/\, \{I(45^\circ) + I(135^\circ)\}.$$

2. Optical Layout of the New Focal Reducer Surface Astro-Polarimeter

Nearly 10 years ago, when I and my collaborators had developed the focal reducer techniques for the 1 m Cassegrain telescope of the Hoher List Observatory, I had the idea for incorporating a device for obtaining *simultaneously* I(0°), I(45°), I(90°) and I(135°) and thus the Stokes parameters for linear polarisation of stars and extended cosmic objects over a large part of the telescope field.

Yet at that time CCD detector systems were not available to us, and it did not make sense to use photoplates on account of their limited photometric accuracy. It was only recently that I could realise this idea after having a good CCD detector system acquired by the support of the Deutsche Forschungsgemeinschaft.

The basic principles and purposes of a focal reducer system (FRS) are:

a) to reduce the large f-number of a long focus telescope to a small one, thus reducing the image scale;

b) to decrease the diameter of the telescope entrance pupil to a small exit pupil (EP);

c) to increase the field effectiveness of a telescope for small detectors like CCDs.

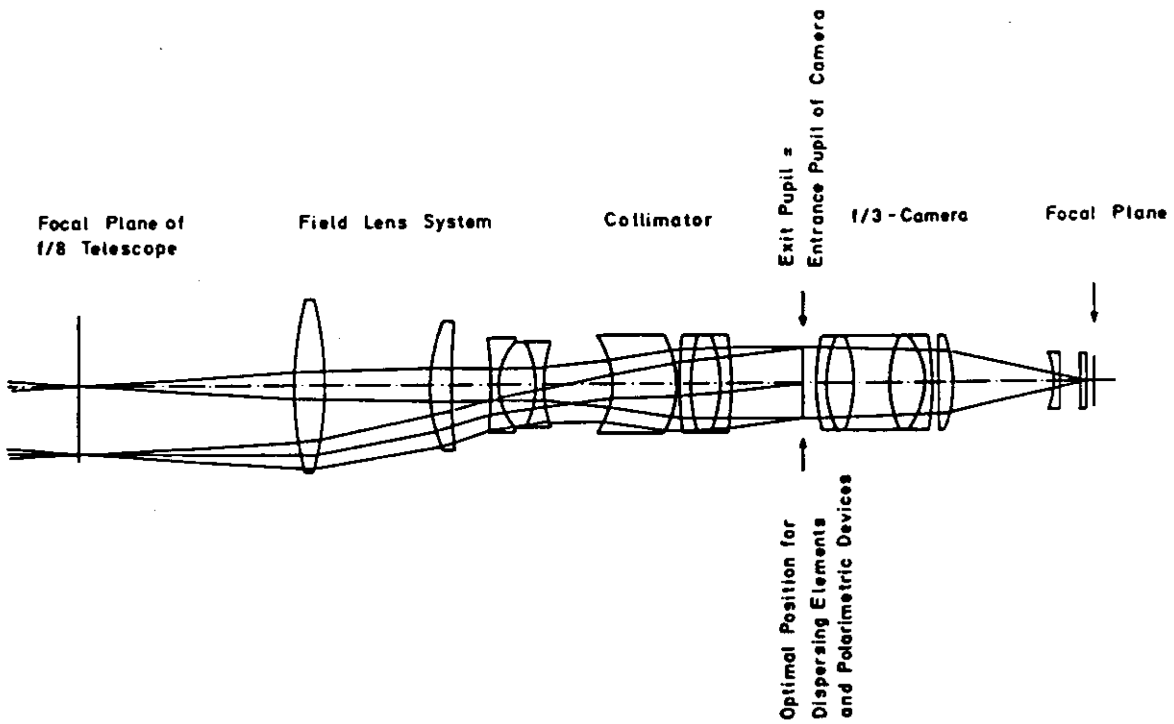

Figure 1. The C. Zeiss-Jenoptik focal reducer system for f/8 RC telescopes. The effective f-number of the system is 3.

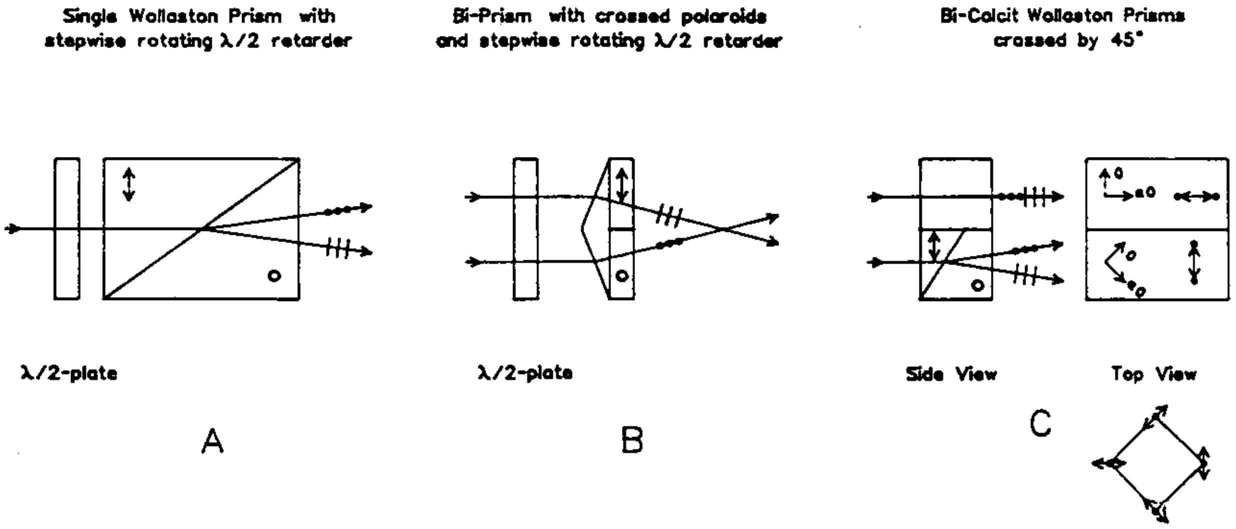

Figure 2. A, B, C. Schematic sketch of polarizer arrangements for focal reducer systems. Only the novel device (C) allows the simultaneous analysis of light in 4 directions of polarization, and which are shown in the lower part of C.

There are two kinds of focal reducers:

1) in the case of a so-called 'focal' FR, the telescope focal plane is refocussed by it directly onto the detector. The exit pupil is then in front of the detector, with the disadvantage that each bright star within the telescope field produces unsharp images of the telescope entrance pupil;

2) in the second case, the 'afocal' focal reducer, the optics works like a collimator with a field lens forming a *real exit pupil* with *parallel* light bundles (similar to a Kellner eyepieces of a binocular glass) into which optical filters, dispersing and polarising elements can be optimally placed. With a camera optics, the entrance pupil of which has to coincide with the exit pupil of the collimator, the telescope focal plane is finally focused onto the detector. As this type of FRS decouples completely the telescope optics from that of the camera, it has the best performance.

As both systems use a *field lens*, which should be behind the telescope focal surface, a large field of the telescope may be more or less usable, depending on the size of the detector. In addition the telescope focal surface is thus fully accessible with the advantage that positive or negative *masking technique* can be applied. As we shall see this is essential for surface polarimetry. Figure 1 shows schematically a recently designed, by C. Zeiss-Jenoptik, 'afocal' focal reducer for f/8 Ritchey-Chrétien telescopes of perfect quality over a wide spectral range. As the Hoher List Observatory 1 m telescope has an f/14.5 focal ratio such a complex optic is not necessary for the field lens collimator.

There are several possibilities for polarizers of different designs to be placed into the exit pupil of an FRS:

1) Figure 2 A shows the classical Wollaston prism which yields symmetrically arranged double images which are perpendicularly polarized. *Simultaneity* for polarization measurement is not achieved as a second exposure has to be taken by turning the FRS by 45° against the telescope focal plane or by a stepwise rotating a half-wavelength retarder plate. As both devices must have the size of the FR exit pupil (≥ 50 mm) they are extremely expensive;

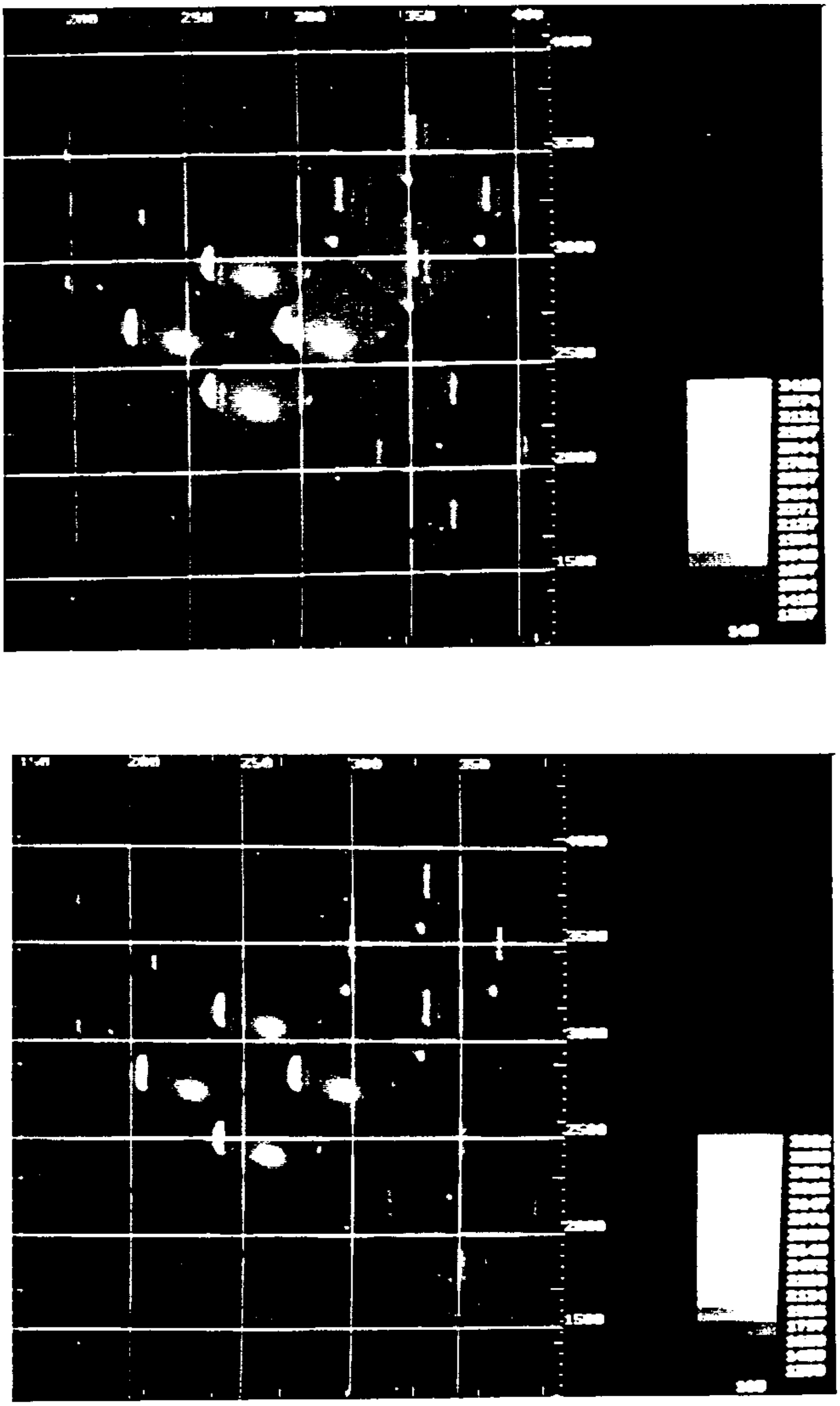

Figure 3 A, B. Double Wollaston / R-filter CCD-frame of Comet (1992d) Tanaka-Machholz on May 3, 1992. Exposure time was 900 secs. Overlaid on these CRT computer photographs are horizontal scans of height 8 pixels through the comet (upper picture) and the upper right comparison sky field.

2) a much cheaper version is shown in Fig. 2 B. Here the FR exit pupil is divided into halves by a double wedge. Each wedge half is covered on their back by crossed polaroids thus yielding double images similar to the Wollaston arrangement of Fig. 2 A. Simultaneity is also not possible and the FR has to be rotated or a half-wavelength retarder has to be used. In addition this type of polarizer is inefficient as the polaroid itself transmits only less than 50% of the oncoming flux.

The principle of the novel polarimetric device — the *Double Wollaston* — is shown in in Fig. 2 C. Here again the exit pupil of the FRS is divided into two halves each covered by a single Wollaston prism: the lower Wollaston is specially cut and turned towards the upper half, so that the 4 resulting light bundles have E-vector directions differing by 45° each. The flux of a non-polarized *point source* thus produces in the focal plane of the FR camera *simultaneously four images*, which are linearly polarized and arranged in a *rhomb*, containing ¼ of the flux energy (neglecting light losses). This is schematically shown in the lower part of Fig. 2 C.

For polarization observations of extended cosmic objects we apply the so-called *masking technique* as previously mentioned: in the focal plane of the telescope we place a multi-hole mask of circular or square form onto which the extended celestial objects are imaged by the telescope; thus certain parts of the telescope field are masked. Each hole with an angular diameter corresponding to the divergence angle of the Wollaston halves and relevant distances to avoid image overlapping is imaged by the FRS via the double Wollaston onto the detector in the above mentioned rhomb form. The hole arrangement of the mask and its orientation can be optimized in such a way that the CCD detector is optimally used.

Figure 3 shows the CCD double Wollaston observation of comet (1992d) Tanaka-Machholz on May 3, 1992, made by Dr. K. Jockers and Dr. N.N. Kiselev of MPI-Aeronomie with the above mentioned instrumentation of the Hoher List Observatory.

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