Pancharatnam achromatic retarders – some recent improvements and their applications to astronomy

S. Tapia

Phillips Laboratory/LIMA, Kirtland A F B, NM 87117, USA

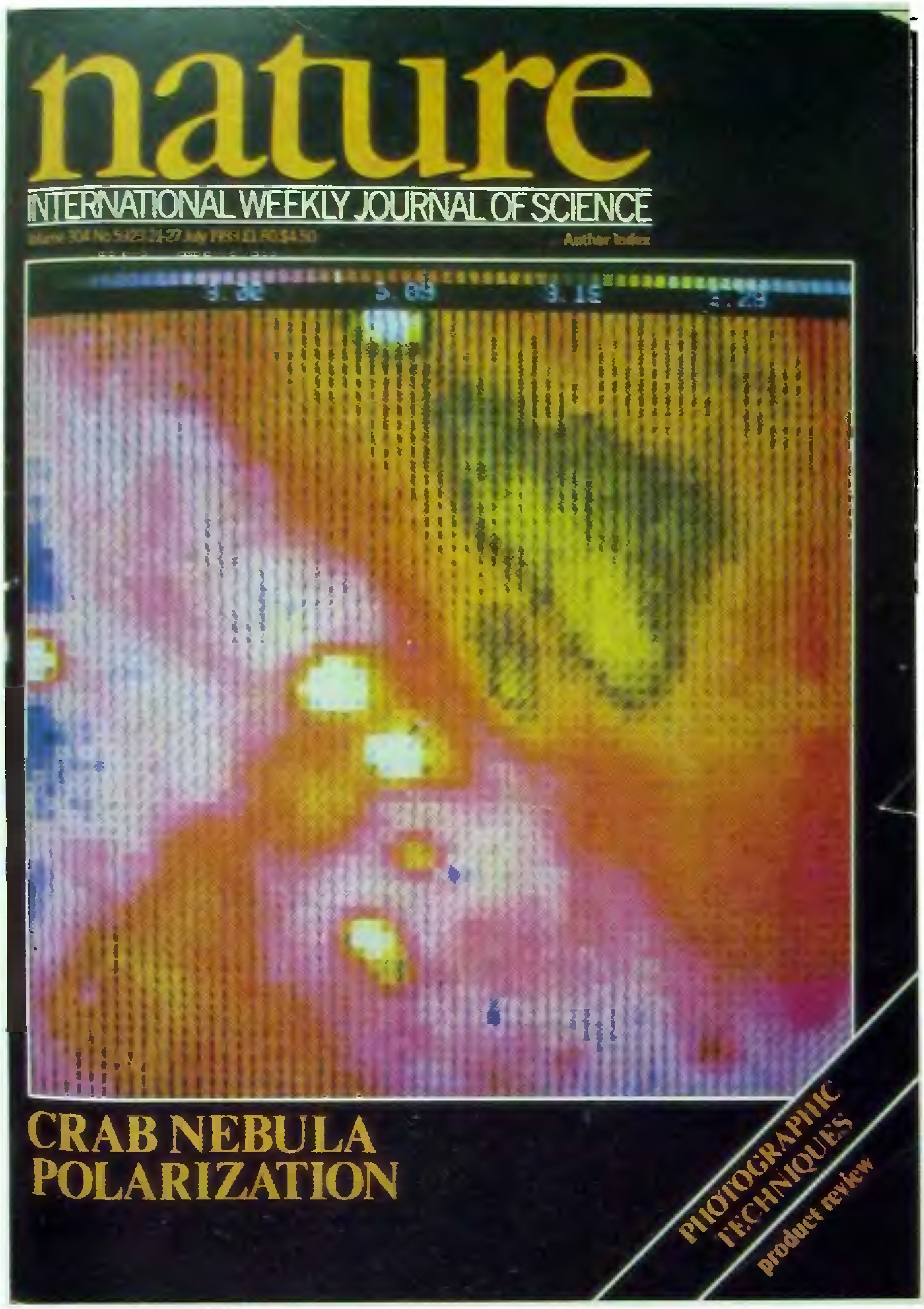
ALTHOUGH impressive figure covers are a frequent feature of the journal *Nature*, the issue of July 21, 1983, brought a specially interesting cover to most astronomers. Superimposed on a false-color image of the central region of the Crab Nebula was its optical linear polarization map with the highest spatial resolution observed, until then, in any astronomical object beyond the Solar System. That cover was the leader to the letter published by McLean *et al.*[1] describing the results obtained with an imaging polarimeter developed at the Royal Observatory of Edinburgh[2]. The impressive data reported there were due to two special technological advances adopted by astronomers in the last fifteen years: the CCD detectors and the superachromatic retarder designed by Pancharatnam[3].

To better understand the significance of those observations it is necessary to get acquainted with the nature of the Crab Nebula. Located 2.02 kiloparsecs from the Sun in the constellation of Taurus, the roughly elliptical cloud of gas is threaded by many filaments and covers a solid angle of about 3 by 4.2 arcmin. The nebula is the expanding remnant of the supernova observed in the year 1054. According to the records of Chinese and Japanese astronomers, the bright 'guest star' was visible for more than a year. The core of that supernova collapsed into the neutron star that today is spinning with a period of 0.033 s and is known as the Crab pulsar. The nebula and the pulsar radiate from radio to X-ray wavelengths, powered by the rotational energy of the pulsar. At the present rate of radiation the rotational energy of the pulsar will be exhausted in about 2500 years. Ginzburg[4] and Shklovski[5] suggested that the optical radiation of the Crab Nebula was synchrotron radiation and should be polarized. Observational confirmation was provided by Dombrovski[6] in the optical region and by Oort and Walraven[7] at radio wavelengths.

Soon astronomers realized that to refine the details of the synchrotron radiation and the energy conversion models it was necessary to optimize the spatial resolution of the polarization map. Employing the 5-m diameter Hale reflector at Palomar Observatory, the largest available then, Baade[8] and Woltjer[9] obtained photographic linear polarization maps at a resolution of 5.25 arcsec in a grid spacing of 5.59 arcsec. Convincing arguments for still higher spatial resolution were published by Felten[10]. Use of the CCD detectors allowed McLean *et al.*[1] to employ a 1.52-m diameter telescope. Use of a superachromatic Pancharatnam retarder allowed the same observers to optimize the spectral region and in that way attain the resolution provided by the natural size of the point spread function at the observing site: 1.5 arcsec. The higher resolution of the polarization map confirmed that, despite the complex structure of the filaments, there is magnetic field of remarkably simple geometry immersed in the nebula. Furthermore, the data corroborated the model of a pulsar that powers the nebula partly with a 30-Hz electromagnetic wave and partly with a relativistic wind of electrons in a toroidal structure.

This was not the first use of the Pancharatnam retarders in astronomy. Serkowski[11] designed a computer-controlled polarimeter, known as MINIPOL, based on two identical six-components half-wave Pancharatnam retarders. Six-component Pancharatnam retarders are accurate to better than 4% between the near ultraviolet and the near infrared (300–1100 nm). In the strict sense of the Pancharatnam design, this type of retarder is composed of three identical half-wave retarders each made of a pair of quartz (SiO_2) and magnesium fluoride (MgF_2) plates. These crystals were selected because both have a positive difference between the extrordinary and ordinary refractive indices; they are hard and easy to polish with high precision; and are transparent over a wide spectral range. Excerpts of Serkowski's specifications for the six-component half-wave Pancharatnam retarder follow:

> Each of the constituent half-wave retarders should produce 180 degrees of retardance at the wavelengths of 310 nm and 660 nm. The magnesium fluoride plate should have thickness of 0 2624 mm with uncertainty of 0 010 mm. The plate of crystallic quartz should have thickness of 0.3046 mm plus 1.24 times the thickness of the magnesium fluoride plate. The total uncertainty of the quartz plate thickness should be 0 005 mm. The individual plates should be plane parallel to 1 arcsec with both surfaces flat to *lambda-half* at the wavelength of 550 nm.
>
> The optical axis of the quartz plate should be placed at 90 degrees, plus or minus 1 degree, with the axis of the magnesium fluoride plate. Each crystal should be cut parallel to the optical axis, within half degree.



A false-colour CCD image of the central regions of the Crab Nebula supernova remnant. The pulsar is the lower of the two central stars Superimposed on this enhanced brightness image is a polarization vector map These maps provide the highest ever spatial resolution of the nebula [Reprinted with permission from Nature (vol 304, 21 July 1983), Copyright 1983, Macmillan Magazines Limited]

Figure 1. Wollaston polarimeter

Figure 2. CCD polarimeter.

Figure 3.

All plates should be cemented with Down Corning 63-488 optical cement or equivalent ultraviolet transmitting and resilient optical cement. The plates should be cemented in the order SiO_2, MgF_2, MgF_2, SiO_2, MgF_2, SiO_2. No protective cover plates are needed because they may introduce stress birefringence. The outer surfaces of the two end SiO_2 plates should have a single layer of antireflection coating which is *lambda-quarter* at 460 nm.

The basic concepts of MINIPOL were published by Frecker and Serkowski[12]. Figure 1 presents a schematic drawing of the optical system of this polarimeter. The superachromatic character of the Pancharatnam half-wave retarders is achieved with the combination of a rotating and stationary half-wave retarders. As described by Serkowski[13], this combination delivers significant improvements in the accuracy of the retardance and the level of achromatism.

Results from two initial research projects employing MINIPOL were published in *Astron. J.* in two series of papers that ended in 1979. In one case the objective was characterization of the interstellar polarization in the Galaxy. Guided by astronomers from the Lunar and Planetary Laboratory and the Steward Observatory of the University of Arizona, numerous investigators published 36 papers under the series titled 'Wavelength Dependence of Polarization'[14]. In the second case more than 28 papers were published under the series titled 'Minor Planets and Related Objects'[15].

Circular and linear polarization observations conducted with the superachromatic Pancharatnam half-wave retarders of MINIPOL and a quarter-wave plate made of acrylic resin, led to the discovery of the first four magnetic white-dwarf stars in X-ray emitting binary systems[16]. These discoveries gave significant impetus to the study of accretion power in astrophysics[17]. More recently MINIPOL has been used to investigate the linear polarization of active galactic nuclei[18]. With only cosmetic modifications, MINIPOL is still being used by numerous astronomical polarimetrists, most recently at the prime focus of the 6-m reflector of the Special Astrophysical Observatory in Russia.

Polarimeters similar to MINIPOL have been built by the Vatican Observatory[19] and by the Physical Research Laboratory, in Ahmedabad[20]. Both instruments are based on a pair of superachromatic Pancharatnam half-wave retarders.

Bailey[21] upgraded the Hatfield Polarimeter for the Anglo-Australian Observatory with superachromatic

Achromatic retarders

When polarized light of any form is incident on a birefringent plate, the phase retardation $\delta = (2\pi/\lambda)(\mu_1 - \mu_2)t$ varies inversely as the wavelength of the birefringence $(\mu_1 - \mu_2)$ does not disperse notably with wavelength. So much so that what acts as a quarter wave retardation plate for deep red will behave practically as a half wave plate in the deep violet. The problem of designing any achromatic retarder is that of transforming a particular state of polarization represented by P_1 (on the Poincaré sphere) to another particular state P_1'. But for it to be an achromatic retarder, one requires that it transform every P to corresponding P' obtained by rotating the sphere by an angle (ϕ) about an equatorial diameter. Pancharatnam[1,2] solved this problem by allowing light to pass through a succession of birefringent plates. He also used the theorem that any succession of rotations of a sphere can be compounded into one single rotation. The combination of birefringent plates therefore corresponds to a single rotation (ϕ) of the Poincaré sphere about some diameter EE', which will, in general, be inclined to the equatorial plane. The condition that the combination should act as a purely birefringent plate for a particular wavelength (λ) is that the axis EE' of the resultant rotation lies on the equatorial plane. The achromatic quarter wave retarder designed and fabricated by Pancharatnam consists of three birefringent plates of the same material (mica); the first and the third plates are identically equal and parallel and inclined at a specific angle to the middle plate whose retardation is half a wavelength at the centre frequency.

In his paper on 'Polarization of variable stars' K. Serkowski[3] writes that 'In the polarimeter achromatism is considerably improved by using the method proposed by Pancharatnam in 1955 and used in astronomical polarimetry by Appenzeller[4] in 1967'. Serkowski uses a six-component Pancharatnam retarder composed of three identical half wave retarders each made of a pair of quartz and MgF_2 plates. These crystals were selected because they have a positive difference between the extraordinary and ordinary refractive indices and they are hard and easy to polish with high precision. These three half wave plates are combined, the central one having its optical axis, oriented at an angle of 1.00 rad. to the other two. The retardation of this achromatic combination deviates from (π) rad. by not more than 0.06 rad. over 0.3 to 1.11 microns! The effect of this deviation is negligible because the results of the polarization measures at proportional to $1-\cos(\tau)$, where (τ) is the retardance.

The Pancharatnam device has however one disadvantage when used in astronomy. The position angle of its effective optical axis is wavelength-dependent and deviates from the mean value over the spectral range (0.3 to 1.1 microns) by as much as ± 0.04 rad. This would make the accurate measurements of position angle of polarization impossible unless one knows the spectral energy distribution in detail. The new idea introduced by Serkowski and his collaborators is the elimination of the wavelength dependence of the axis direction by using two identical achromatic half wave plates in front of the Wollaston prism, the plate closer to the Wollaston is stationary and has its optical axes approximately parallel to the principal planes of the Wollaston prism. The other half wave plate is continually rotated by a stepper motor for modulating the intensity.

1. Pancharatnam, S., *Proc. Indian Acad. Sci*, 1955, **A41**, 130
2. Pancharatnam, S., *Proc. Indian Acad Sci.*, 1955, **A42**, 86.
3. Serkowski, K., in *Proc. IAU Colloq.*, 15, Veroff. Remeis Sternw., Bamberg, 1971, vol. 9, p. 27.
4. Appenzeller, I., *Publ. ASP*, 1967, **79**, 136.
5. Frecker, J. E. and Serkowski, K., *Appl. Optics*, 1976, **15**, 605.

S.R.

Pancharatnam retarders. During the characterization period of that polarimeter, Bailey found that these retarders can still provide efficient polarimetry in the near infrared. Modulation efficiencies of 0.99 in the J band (1100–1400 nm); 0.93 in the H band (1500–1800 nm); and 0.87 in the K band (2000–2400 nm) were recorded. These levels of efficiency are common in simple achromatic retarders that skillful polarimetrists employ in many scientific disciplines producing still accurate results. Simultaneous modulation over the spectral range of 300 to 2500 nm for accurate polarimetry is another advantage furnished by the Pancharatnam retarders.

Two polarimeters, one designed for simultaneous measurements of the four Stokes parameters, the other one for wide band spectropolarimetry, have been implemented by Magalhaes and Velloso[22] at the Astronomic and Geophysic Institut of the University of Sao Paulo, Brazil. Both polarimeters are based on superachromatic Pancharatnam half-wave and quarter-wave retarders.

An innovative dual-beam optical spectropolarimeter, based on the superachromatic Pancharatnam half-wave retarder, has been described by Goodrich[23]. The design was implemented first in the Cassegrain spectrograph of the 2.7-m reflector at McDonald Observatory of the University of Texas and later in the Cassegrain spectrograph of the 5-m Hale reflector at Palomar Observatory. Goodrich *et al.*[24] are developing a spectropolarimeter, based on superachromatic Pancharatnam retarders and optimized for circular polarization, to be used at the 3-m reflector of Lick Observatory.

Other astronomical research centers that have implemented polarimeters with Pancharatnam superachromatic retarders are: the Crimean Astrophysical Observatory, in Ukraine; the Observatorio Astronomico di Torino, in Italy; the Copenhagen University Observatory, in Denmark; the Observatory and Astrophysics Laboratory of the University of Helsinki, in Finland; and the Tuorla Observatory of the University of Turku, in Finland[25].

Very likely the most recent application of superachromatic Pancharatnam retarders has been made in the area of surveillance of artificial satellites. Observations of artificial satellites illuminated by the Sun display significant amounts of linear polarization as expected from the Fresnel theory of specular reflection diluted by small fractions of diffuse reflection[26]. Monitoring the polarization variations with respect to the phase angle (Sun-satellite-observer angle) it is possible to deduce the complex refractive index of the reflecting material. Since most artificial satellites reflect light from an aggregate of different materials only an effective complex refractive index can be deduced. Individual changes in the real and/or the imaginary part of the complex refractive index can be traced to changes in the structure of the satellite or deterioration of a surface in the space environment. To investigate these changes the MIT Lincoln Laboratory developed a special imaging polarimeter based on the schematics presented in Figure 2.

Polarimetry of artificial satellites is much simpler than stellar polarimetry because the orientation of the plane of polarization is known as long as the local coordinates of the satellite are known. Normally the orbital elements of the satellite are used to derive the local coordinates *a priori* to track the satellite as it passes over the observing station. When the plane of linear polarization is known, just a properly oriented polarization analyser is required to measure the degree of polarization. Instead of orienting the analyser, the Pancharatnam half-wave retarder is used to rotate the plane of polarization into the ordinary ray of the analyser. The orientation of the optical axis of the half-wave retarder is controlled on line by a microprocessor that constantly reads the pointing coordinates of the tracking telescope. Figure 3 displays five complete frames with two images of the satellite catalogued under the number 4047, observed with the MIT Lincoln Laboratory imaging polarimeter, in April 1992. Launched in 1969, today it is the inactive payload of a communications satellite. In each frame the left image was produced by the extraordinary rays and the right image by the ordinary rays. The large difference in brightness between both images is produced by the amount of polarization in the light reflected off the satellite. During the interval of time covered by the five frames the linear polarization of this satellite was 37% with one sigma error of 3%.

As indicated by these examples the importance of Pancharatnam's contribution is widely recognized today within polarimetrists. Just consider that in 1971 there was only one polarimeter using this type of superachromatic retarder. The original perception that this was a very complicated optical component, with tolerances too strict even for custom fabrication, has been proven incorrect. Most of the superachromatic Pancharatnam-type retarders have been fabricated by the Bernhard Halle Nachfl. optical factory in Berlin. In the last decade some excellent superachromatic Pancharatnam retarders have been fabricated by Vitaliy Kucherov at the Main Astronomical Observatory of the Ukrainian Academy of Sciences, in Kiev, Ukraine. He produces custom half-wave and quarter-wave retarders in wide spectral regions, ranging from 330 nm to 1400 nm. These retarders have efficient transmissions, range in thicknesses from 2 to 12 mm, and can be as large as 30 mm on a side. More recently, superachromatic Pancharatnam retarders have been manufactured by the Karl Lambrecht Corporation of Chicago, USA.

1. McLean, I. S., Aspin, C. and Reitsema, H., *Nature*, 1983, **304**, 243

2. Aspin, C., in *Polarized Radiation of Circumstellar Origin* (eds Coyne, G. V., Magalhaes, A. M., Moffat, A. F. J., Schulte-Ladbeck, R. E., Tapia, S. and Wickramasinghe, D. T.), Univ. of Arizona Press, Tucson, 1988, p. 693
3. Pancharatnam, S., *Proc. Indian Acad Sci*, 1955, **A41**, 137.
4. Ginzburg, V. L., *Usp. Fiz. Nauk*, 1953, **51**, 343.
5. Shklovskii, I. S., *Doklady Akad Nauk S.S.S.R.*, 1953, **90**, 983
6. Dombrovskii, V. A., *Doklady Akad. Nauk S.S.S.R.*, 1954, **94**, 1021.
7. Oort, J. H. and Walraven, T., *Bull. Astron. Inst. Neth.*, 1956, **12**, 285.
8. Baade, W., *Bull. Astron. Inst. Neth.*, 1956, **12**, 312.
9. Woltjer, L., *Bull. Astron. Inst. Neth.*, 1957, **13**, 301.
10. Felten, J. E., in *Planets Star and Nebulae Studied with Photopolarimetry* (ed Gehrels, T.), Univ. Arizona Press, 1974, p 1014.
11. Serkowski, K., in *Proc. IAU Colloq 15, Veroff. Remeis Sternw. Bamberg*, 1971, vol. **9**, p 11.
12. Frecker, J. E. and Serkowski, K., *Appl. Opt.*, 1976, **15**, 605.
13. Serkowski, K., in *Methods of Experimental Physics*, **12**, *Astrophysics, Part A Optical and Infrared* (ed. Carleton, N.), Academic Press, 1974, p. 361.
14. Coyne, G. V. and Magalhaes, A. M., *Astron. J*, 1979, **84**, 1200.
15. Gehrels, T. and Tedesco, E. F., *Astron. J.*, 1979, **84**, 1079.
16. Cropper, M., *Space Sci. Rev*, 1990, **54**, 195.
17. Frank, J., King, A. R. and Raine, D. J., *Accretion Power in Astrophysics*, Cambridge Univ. Press, 1985.
18. Impey, C. D., Malkan, M. A. and Tapia, S., *Astrophys J.*, 1989, **347**, 96.
19. Magalhaes, A. M., Benedetti, E. and Roland, E. H., *Pub Astron. Soc. Pacific*, 1984, **96**, 383.
20. Joshi, U. C., Sen, A. K., Deshpande, M. R. and Kulshrestha, A. K., 1986, *IAU Circ.* No. 4212.
21. Bailey, J., in *Polarized Radiation of Circumstellar Origin* (eds Coyne, G. V., Magalhaes, A. M., Moffat, A. F. J., Schulte-Ladbeck, R. E., Tapia, S. and Wickramasinghe, D. T.), Univ of Arizona Press, Tucson, 1988, p. 747.
22. Magalhaes, A. M. and Velloso, W. F. in *Polarized Radiation of Circumstellar Origin* (eds. Coyne, G. V., Magalhaes, A. M., Moffat, A. F. J., Schulte-Ladbeck, R. E., Tapia, S. and Wickramasinghe, D. T.), Univ. of Arizona Press, Tucson, 1988, p. 727.
23. Goodrich, R. W., *Pub Astron. Soc. Pacific*, 1991, **103**, 1314.
24. Goodrich, R. W., Cohen, M. H. and Putney, A., 1994, in preparation.
25. Piirola, V., Hakala, P. and Coyne, G. V., *Astrophys. J. Lett.*, 1993, **410**, L107.
26. Tapia, S., Beavers, W. I. and Cho, J. Y-K., in *SPIE Vol. 1317 Polarimetry: Radar, Infrared, Visible, Ultraviolet and X-ray*, 1990, p. 252.