Polarimetric Investigations in Ukraine: Past, Present and Future

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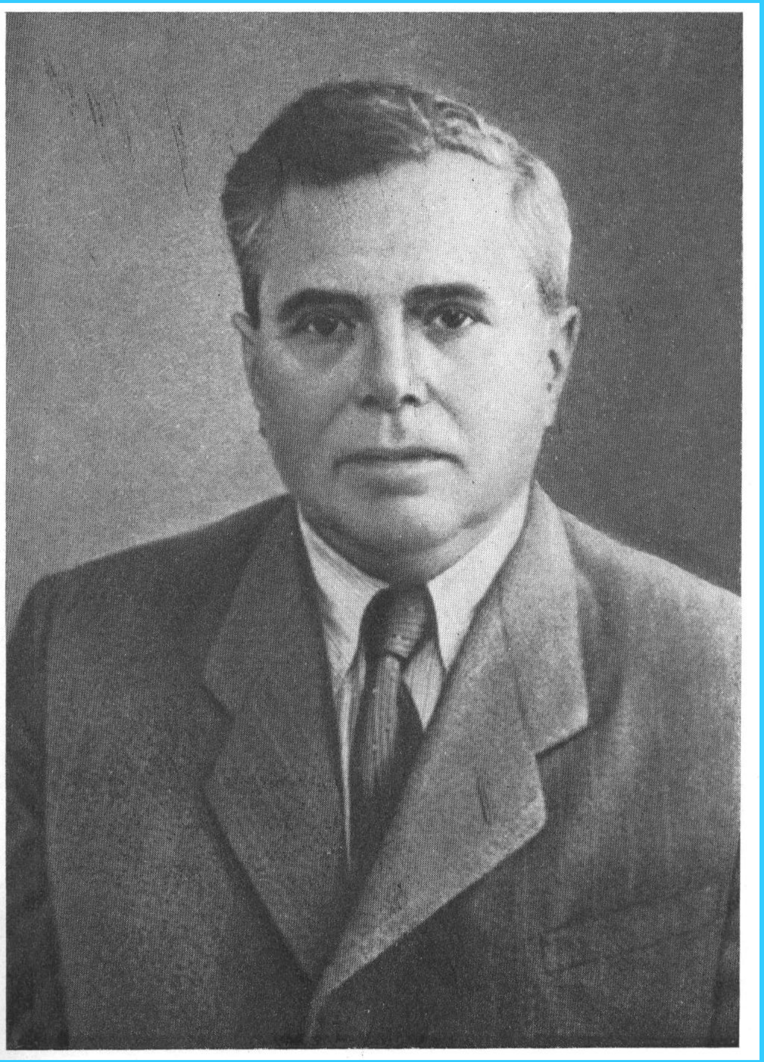
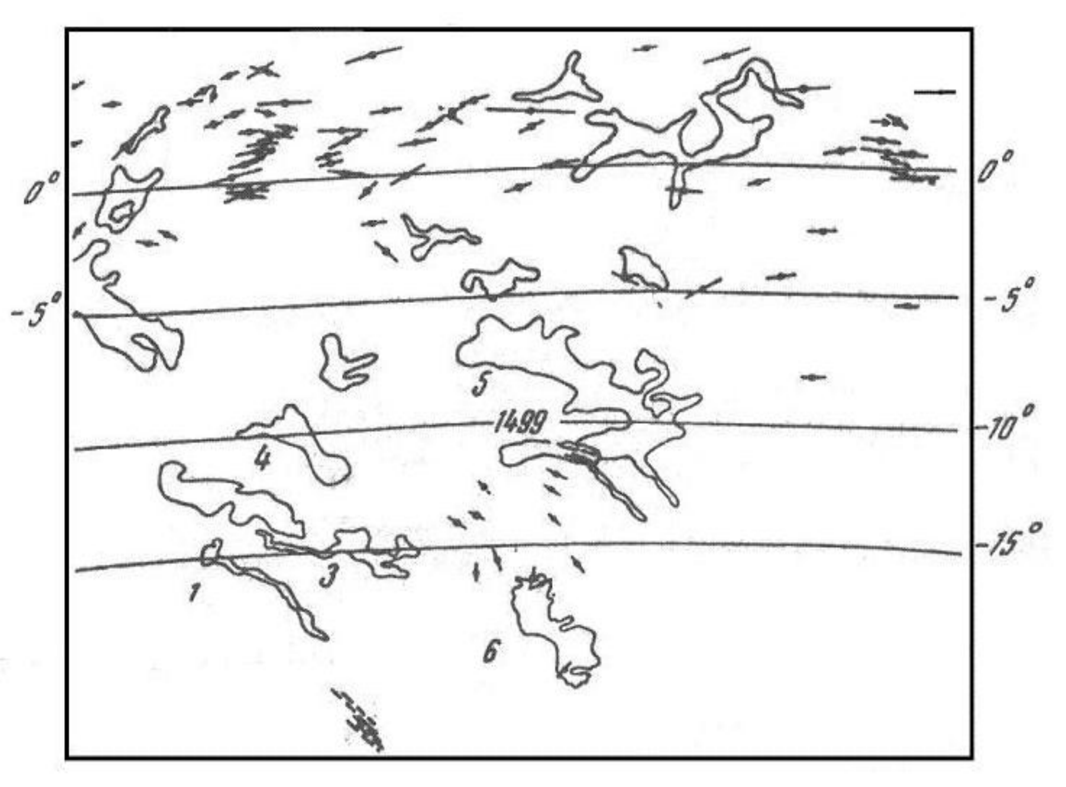
The beginning of active applications of polarimetry in astrophysics

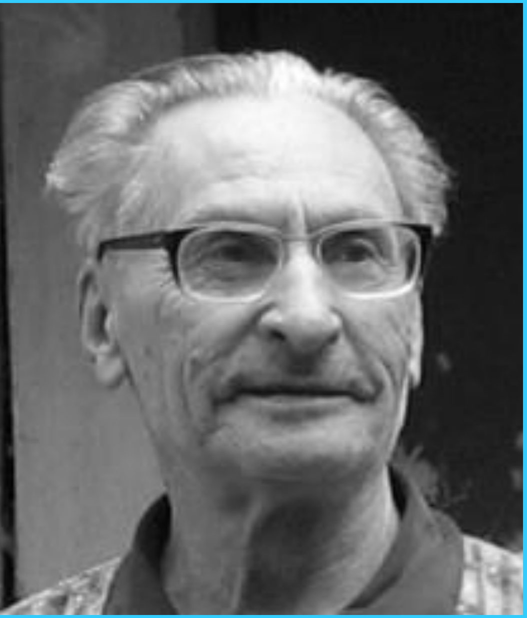


G. A. Shain

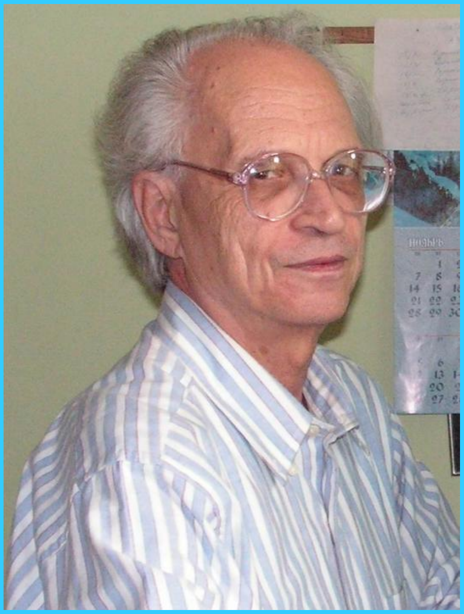


G. A. Shain (1955) identified a correlation between orientations of filaments in diffuse nebulae and the plane of polarization of neighboring stars and suggested that it could be caused by a global magnetic field of our Galaxy.

Polarimetry at CrAO



N. M. Shakhovskoy



Yu. S. Efimov

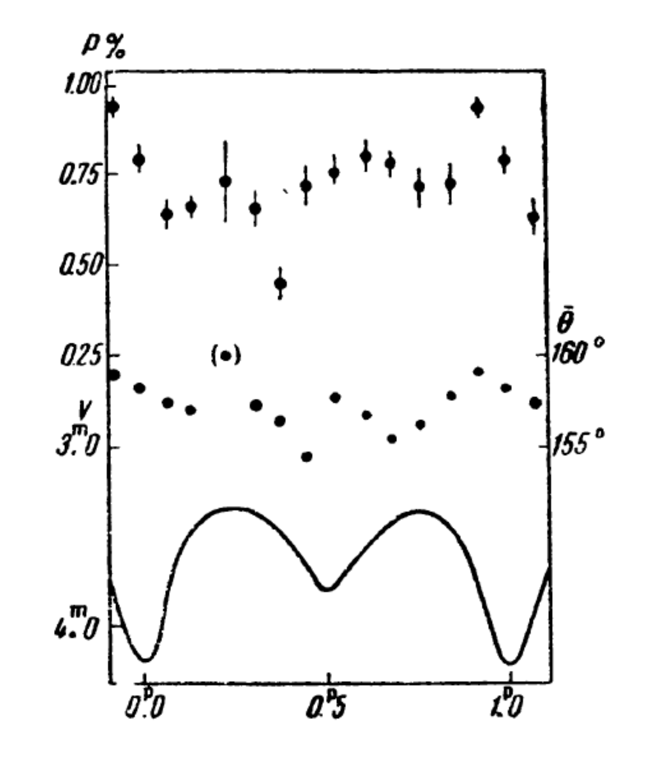
In 1962-2001 N. Shakhovskoy and Yu. Efimov with colleagues built several series of advanced polarimeters for telescopes of the Crimean Astrophysical Observatory.

The latest version of the modified single-channel photoelectric polarimeter of the 2.6-m telescope includes a rotating achromatic quarter-wave phase plate followed by a fixed Glan prism.

The installation of the 1.25-m telescope and the availability of the UBVRI photopolarimeter of the Helsinki University Observatory (Piirola 1988) have dramatically expanded the range of polarimetric observations in CrAO.

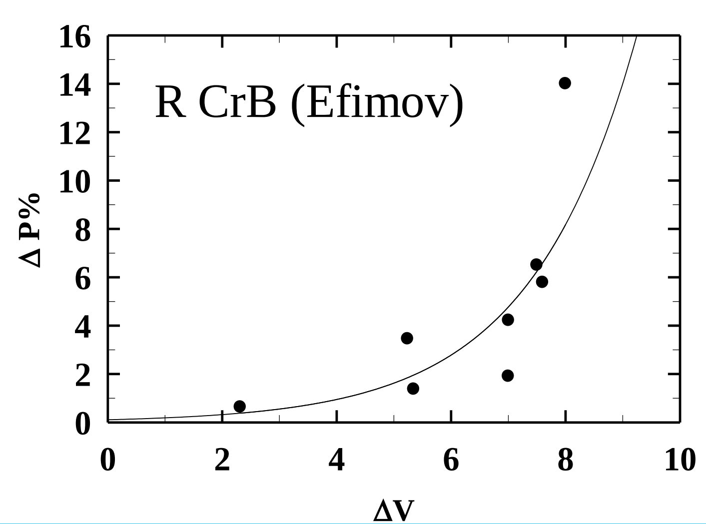
Polarimetry at CrAO

N. Shakhovskoy and Yu. Efimov carried out extensive multidecadal observations of polarization for different types of variable stars, including double systems, Mira stars, flare stars, polars (stars of the AM Her type with magnetic fields reaching millions of Gauss), symbiotic stars, novae and supernovae, nebulae, and galaxies with active nuclei.

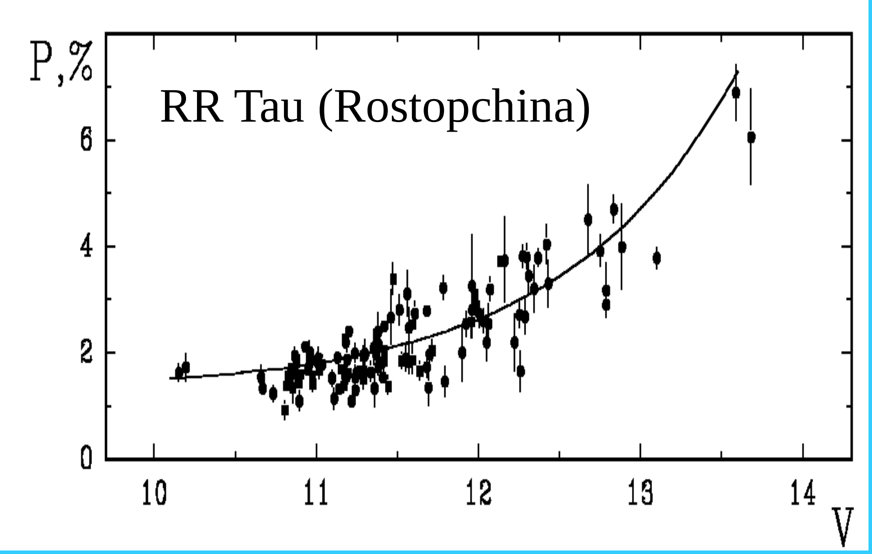


N. Shakhovskoy (1962,1964) discovered variable polarization ($\Delta P \sim 0.5\%$) for the early-type eclipsing binary β Lyr and other close binary systems. This allowed him, for the first time, to estimate the mass of clusters in the gaseous envelopes of these stars at 10^{-9} solar masses.

Polarimetry of variable stars

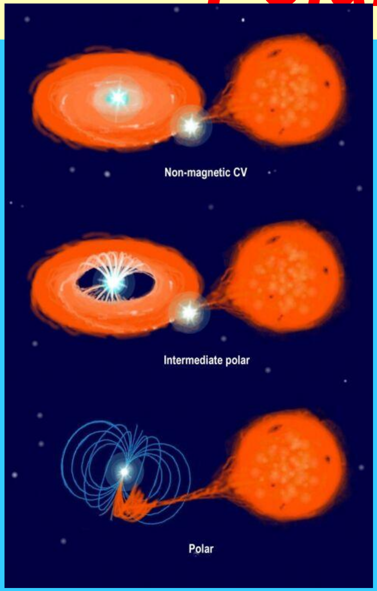


Yu. Efimov carried out observations of 9 deep minima of star R CrB in 1972 – 2003 and revealed a relationship between the brightness and polarization variations. The decrease in brightness of R CrB-type stars is caused by the ejection of a cloud of gas and dust along the line of sight. The expansion of the cloud is accompanied by the growth of dust grains, thereby causing changes in both photometric and polarimetric characteristics of a star.



A high degree of polarization was first discovered for young Ae/Be Herbig stars with circumstellar dust disks (so-called UXORs) during patrol observations (Voshchinnikov et al. 1988; Grinin et al. 1991). The observations fully confirmed the model by Grinin (1988) which implies that during a brightness minimum there should be a significant increase in polarization, a weak blue emission, and other effects caused by the scattering of light by dust grains forming the circumstellar disk.

Polarimetry of cataclysmic variables

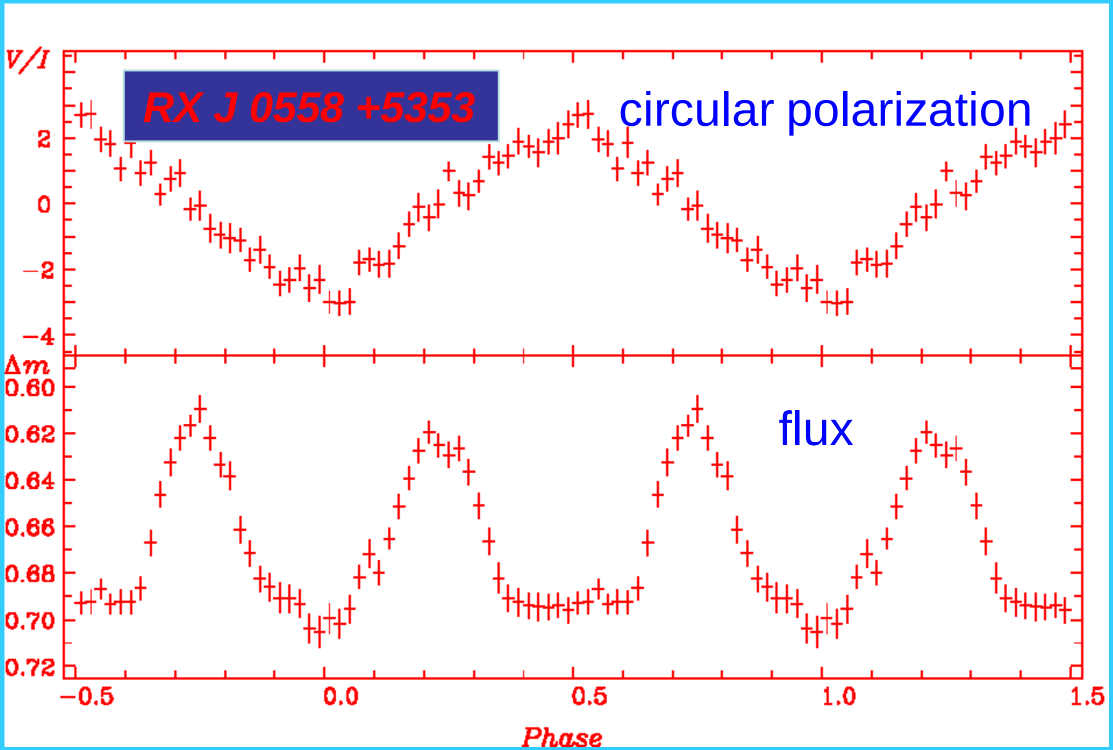


Nova-like binaries

Intermediate polars

Classical and asynchronous polars

Photopolarimetric monitoring of selected cataclysmic variables since 1989 by N. Shakhovskoy (CrAO) and I. Andronov&S.Kolesnikov (Odessa).



Variation of circular polarization with a period of 9 min had been discovered for intermediate polar RX J 0558 +5353 (V405 Aur). Its period = 2*photometric period (Shakovskoy&Kolesnikov, 1997).

Polarimetry at CrAO

•Variable intrinsic polarization was revealed for a number of novae (DQ Her, a new symbiotic PU Vul, N Cyg 1975).

•Variable linear polarization in the visible spectral range was found for several X-ray sources such as Her-X1, Cyg-X1, Cyg-X2, Sco-X1 (Shakhovskoy and Efimov 1976), and Vela X-1 (Beskrovnaya et al.1992).

•From 1994 to 2005, CrAO astrophysicists participated in the large-scale international program focused on the monitoring of a number of blazars and quasars.

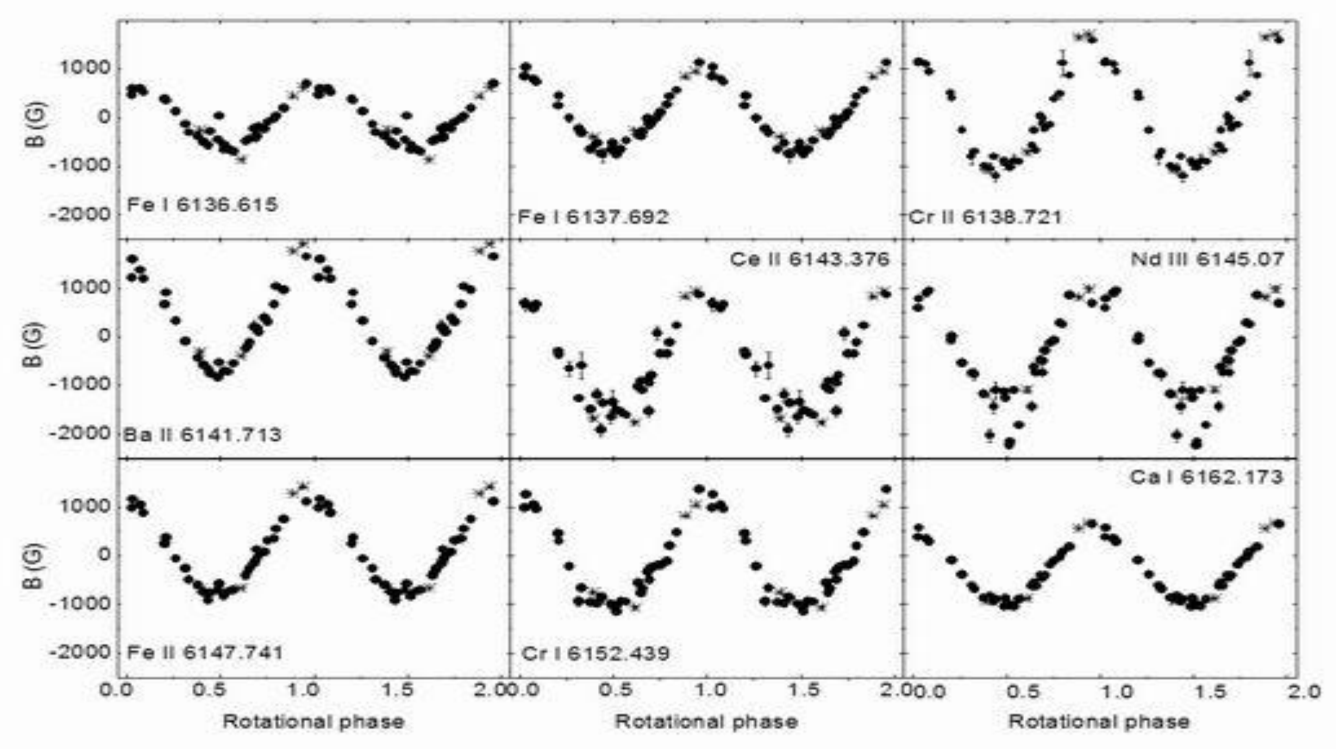
•Among the results of this program was the detection of rapid changes of the spectral dependence of polarization in the quasar 3C 273 and several blazars. The nature of these changes is consistent with the predictions of the model according to which a variable polarized emission is associated with shock waves propagating along relativistic jets.

•An important result of CrAO astrophysicists was the first observational confirmation of the spiral structure of the magnetic field in the inner parts of jets as well as an estimate of the magnetic field and its topology in blazars OJ287 and PKS 0735+178.

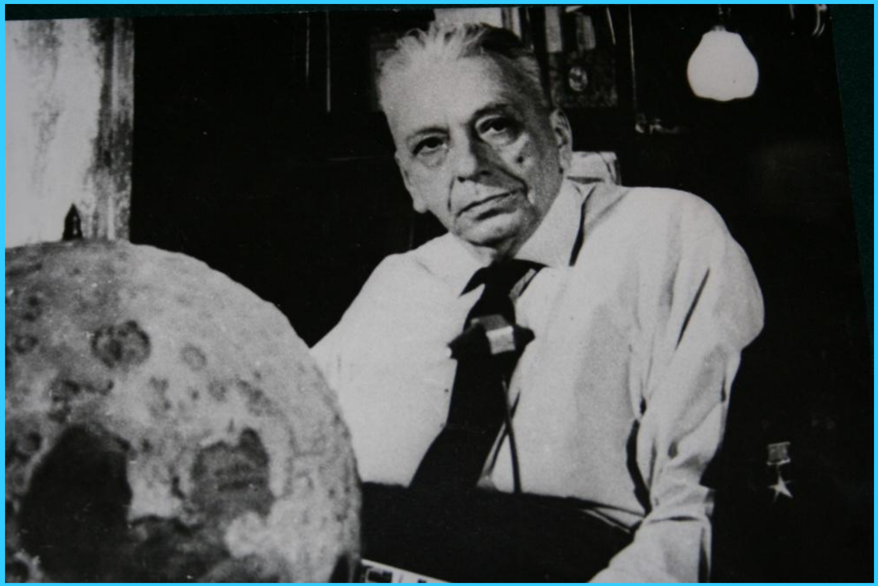
Polarimetric investigations at the Crimean Astrophysical Observatory: Stellar magnetic fields

CrAO began regular measurements of the solar maghetic field in 1960. The technique of the solar magnetograph was applied at the coude spectrograph of the 2.6-m telescope for measurements of stellar magnetic fields (300 gauss) of certain bright stars (A. Severny, 1970); V. Kuvshinov, 1977).

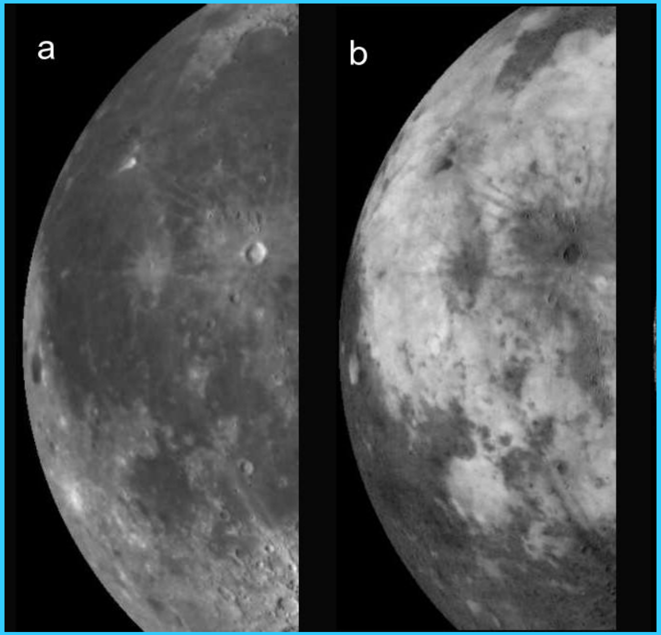
Plachinda (1988) **used the Stokesmeter of the 2.6-m telescope to measure, for the first time, weak (less 100 gauss) magnetic fields for a number of stars and found a correlation between the strength of the magnetic field and the phase of rotation.**



Polarimetry at the Kharkiv Astronomical Observatory



Apparently the first polarimetric observations in Ukraine were carried out by N. Barabashov in 1923 (Barabaschoff, 1926). **He measured polarization for different areas of the Moon with a Cornu polarimeter mounted at a 3-inch refractor and compared his results with laboratory data for different terrestrial powders.**



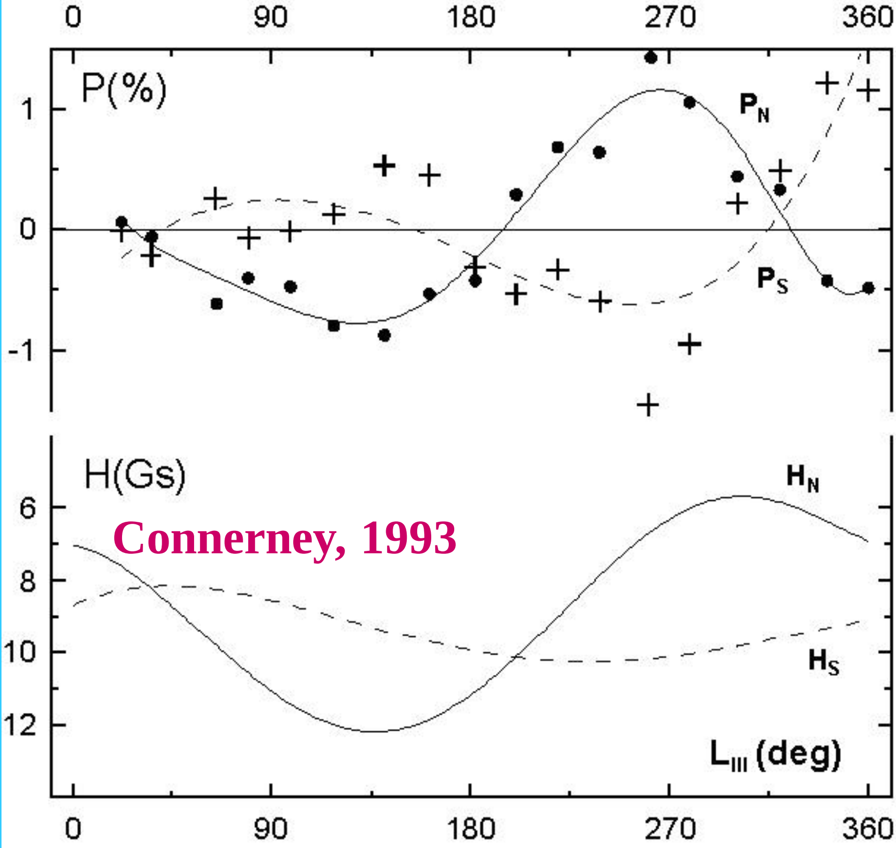
The most important area of lunar research in KhAO over the past several decades has been the synthesis of images or maps of the Moon for different photometric and polarization parameters and analyses of their correlation with properties of the lunar regolith.

Brightness (a) and polarization (b) maps of the Moon. The images anticorrelate owing to the Umov effect. (Opanasenko, 1999).

Polarimetry at the Kharkiv Astronomical Observatory: *Jupiter*

Korokhin et al. (1993, 2000) **have developed methods, instrumentation, and original software packages for polarimetric observations of the Sun, the Moon, and Jupiter using CCD matrices.**

Kharkiv astronomers carried out a 28-year-old cycle of polarization observations of Jupiter, captured two rotations of this planet around the Sun. Longitudinal variations of the degree of linear polarization of Jupiter and its correlatoin with the Jovian magnetic field were found (Starodubtseva et al. 2002).

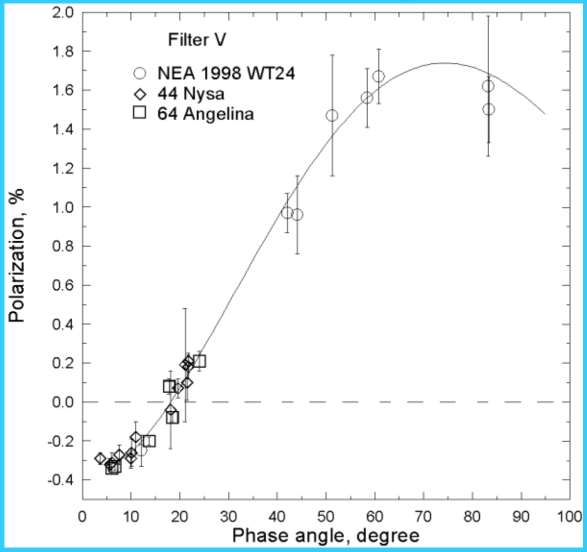


Longitude, deg

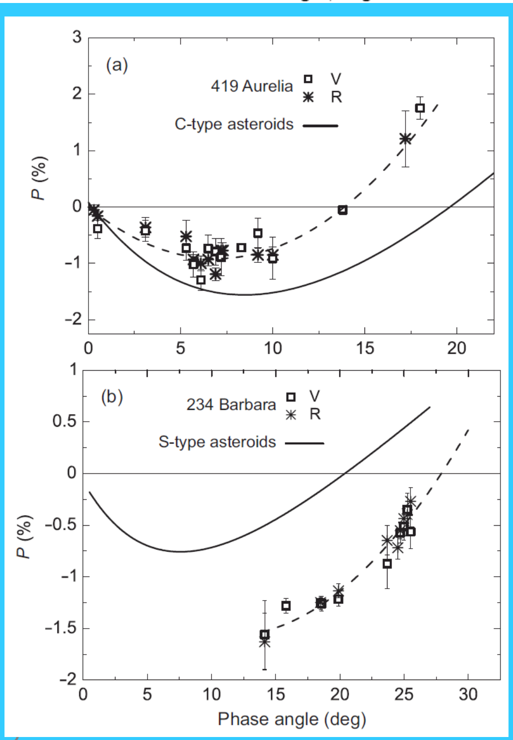
Polarimetry at the Kharkiv Astronomical Observatory

- **The Asteroid Polarimetric Database was created by Lupishko and Vasil’ev (2008).**
- **Yu. Shkuratov (1988) pioneered the application of the theory of CB to the interpretation of the BOE and NPB ubiquitously observed for ASSBs. Theoretical studies, computer modeling, and laboratory simulations of light scattering by regolith surfaces have been carried out by Yu. Shkuratov and his colleagues.**
- **Light scattering by closely packed clusters and the near field effects were studied by V. Tishkovets (2008).**
- **Laboratory photopolarimetric measurements of brightness and polarization at small phase angles 0.1–3.5° were performed by Yu. Shkuratov and A. Ovcharenko (2002).**

Polarimetry at the Kharkiv Astronomical Observatory

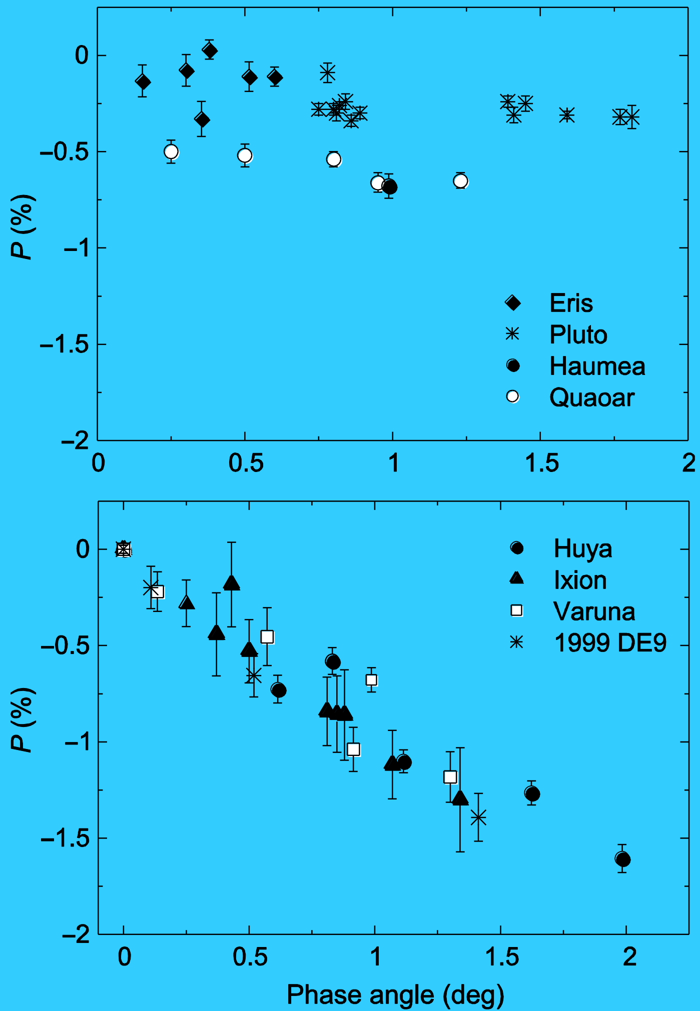


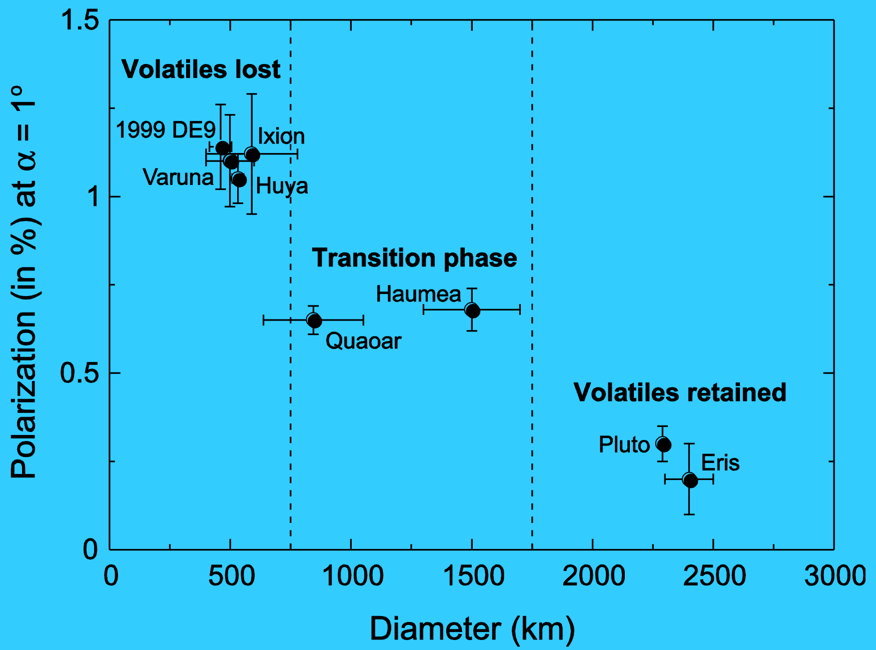
D. Lupishko, I. Belskaya, N. Kiselev, F. Velichko have carried out polarization studies of many MB asteroids as well as the NEA. The totality of NEA observations allows one to conclude that $\boldsymbol{P_{max}}$ in the V filter can reach values 8.5% – 10.5% and ~2% for S- and E-type asteroids, respectively. The angle of maximal positive polarization for the E-type asteroids is unexpectedly small: $\alpha_{max} \approx 80°$ compared to 110° for S-type asteroids. Sizes 420x330 m, and albedo $\boldsymbol{p_V}$ = 0.43 of NEA 1998 WT24 (33342) were obtained (Kiselev et al. 2002).



It has been found that the inversion angles $\boldsymbol{\alpha_{inv}}$ of asteroids cover a wide range of phase angles from uniquely small, ~14° for (419) Aurelia (F-type), to uniquely large, ~ 28° for (234) Barbara (S-type) (Belskaya et al. 2005). Furthermore, it has been shown that the minimal polarization values $\boldsymbol{P_{min}}$ for these asteroids violate significantly the well-known correlation "$\boldsymbol{P_{min}}$ –albedo". The anomalous polarimetric properties of these asteroids could be related to their specific surface compositions.

Polarimetry of TNOs





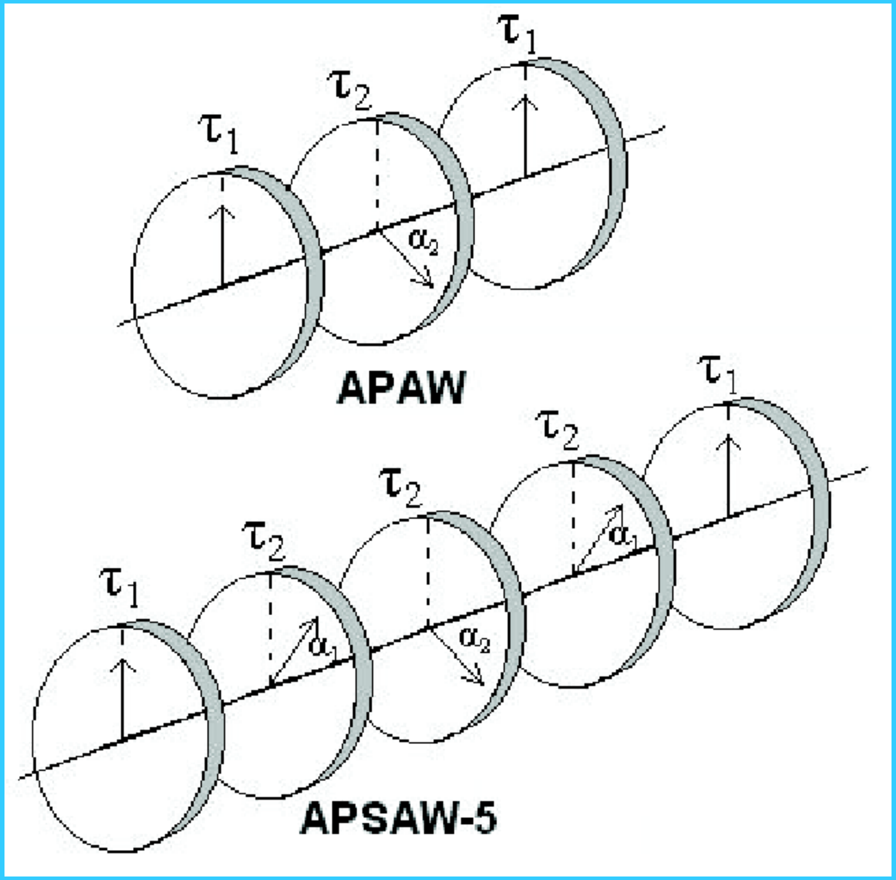
I. Belskaya and her collaborators on the international team using telescopes from the 8 –10-m class have carried out polarimetric studies of Centaurs and TNOs. Two types of polarization phase dependence for TNOs have been found.

Polarimetry at the Maine Astronomical Observatory

Other center of active polarimetric research is MAO. Research programs in MAO have primarily been focused on:

- **development of polarimetric instrumentation and methods of polarization measurements;**
- **polarimetric studies of various solar-system bodies (planets, planetary satellites, asteroids, and comets).**
- **development of fundamental theory of electromagnetic scattering and data interpretation.**

Theory of multicomponent retarders

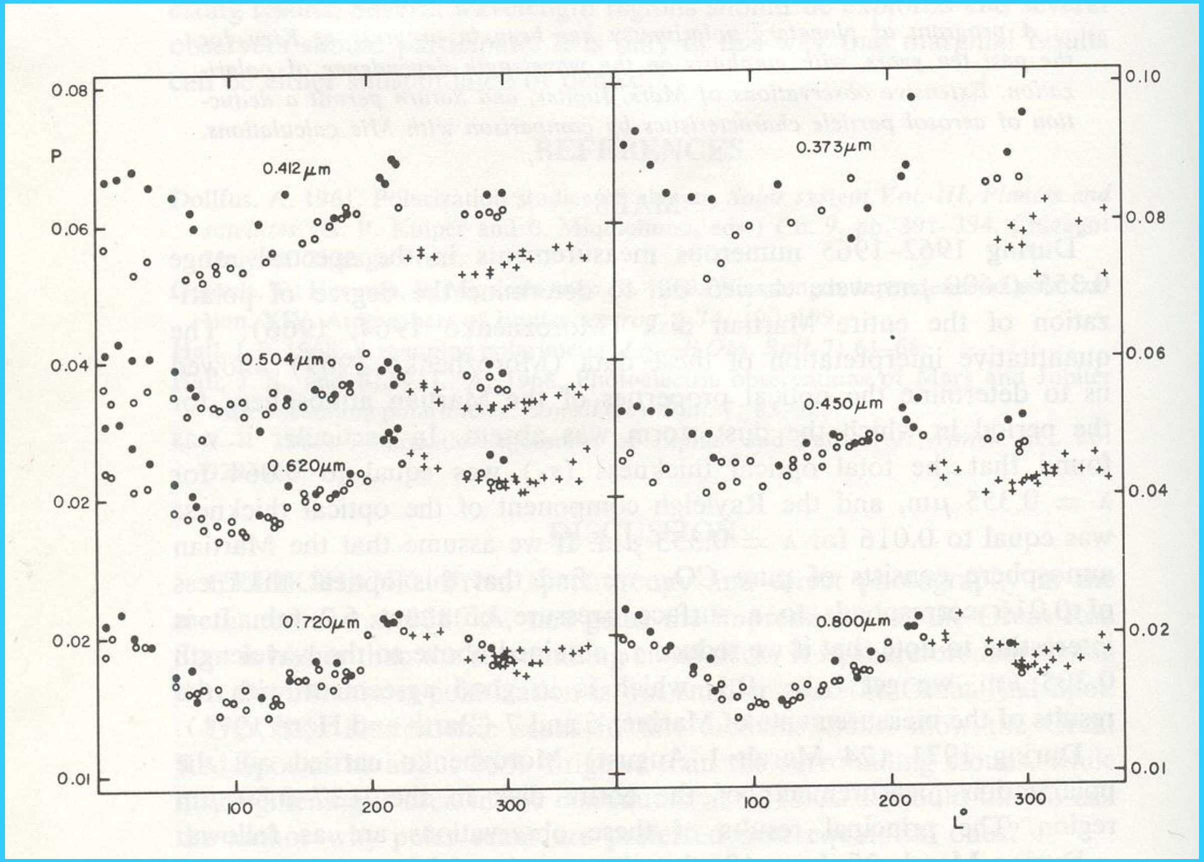


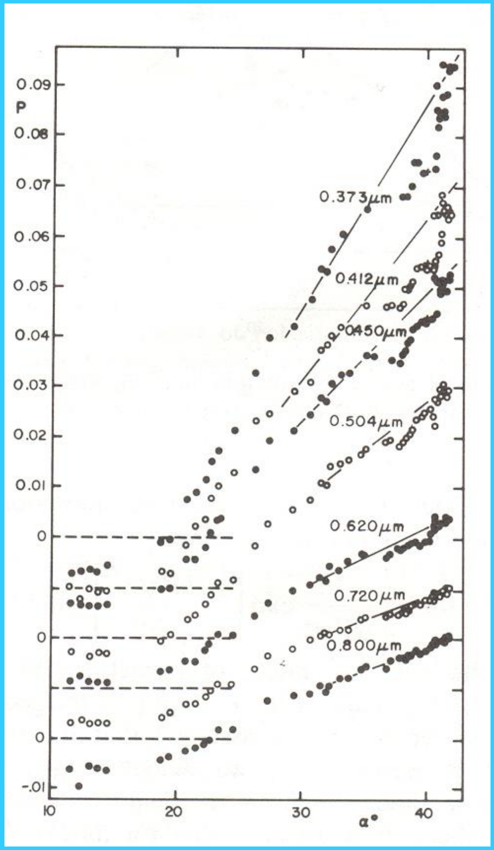
A three-component achromatic phase plate (top panel) and a five-element superachromatic phase plate (bottom panel).

Theory of multicomponent retarders was developed by A. Kucherov in MAO NAN of Ukraine. (Kucherov, 1985, 1986).

As a result, it has become possible to build unique superachromatic retarders. These products are highly valued and have been used in polarimetric observations at many observatories.

Solar system objects: Mars





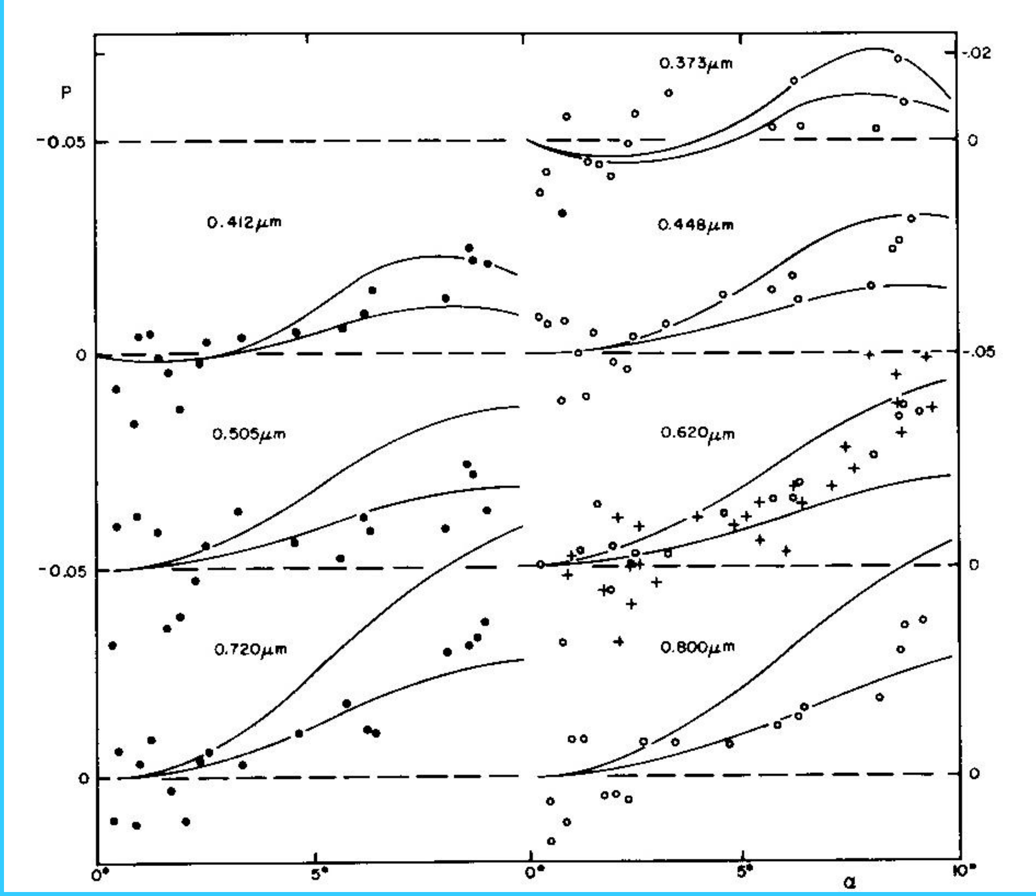
Morozhenko (1973, 1975) carried out polarimetric observations of Mars during the 1971 and 1973 oppositions. He determined the dependence of the degree of linear polarization on the longitude of the Martian central meridian for different wavelength.

Solar system objects : Jupiter

In 1960-s and 1970s – extensive ground-based polarimetric observations of the center of the Jovian disk were carried out by Morozhenko with colleagues.

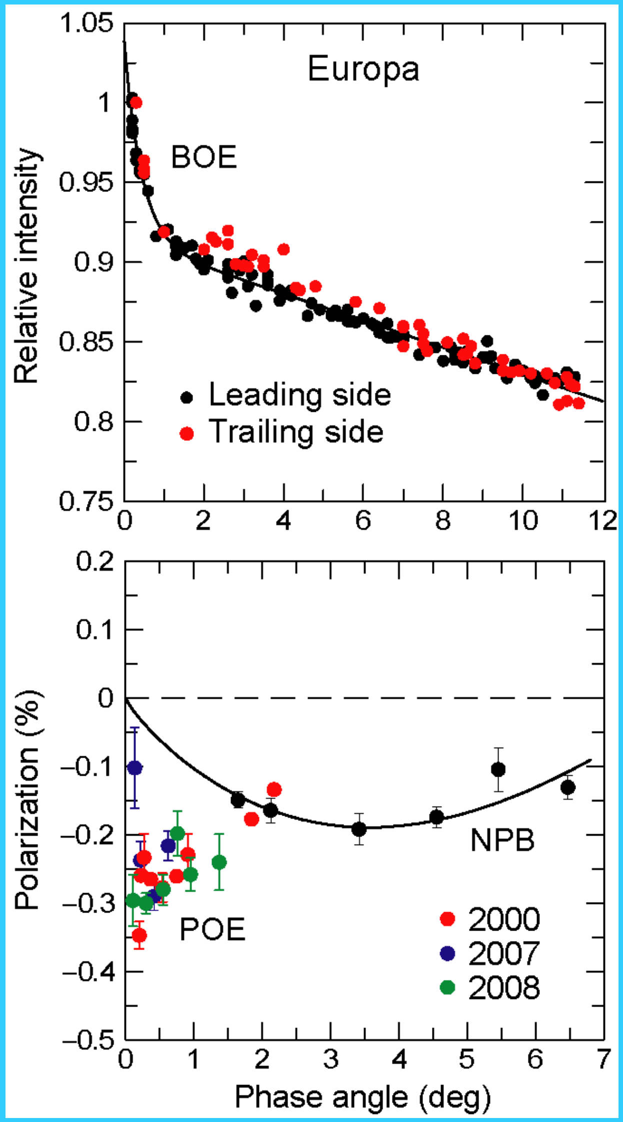
From analysis of ground-based polarimetric observations the next parameters for the atmosphere of Jupiter was found: the refractive index to be n = 1.36 ± 0.01, the mean geometrical radius of particles r_0 = 0.2 μm. This refractive index for the particles agrees well with the ammonia cloud layer hypothesis.

(Morozhenko,Yanovitskii, 1973).

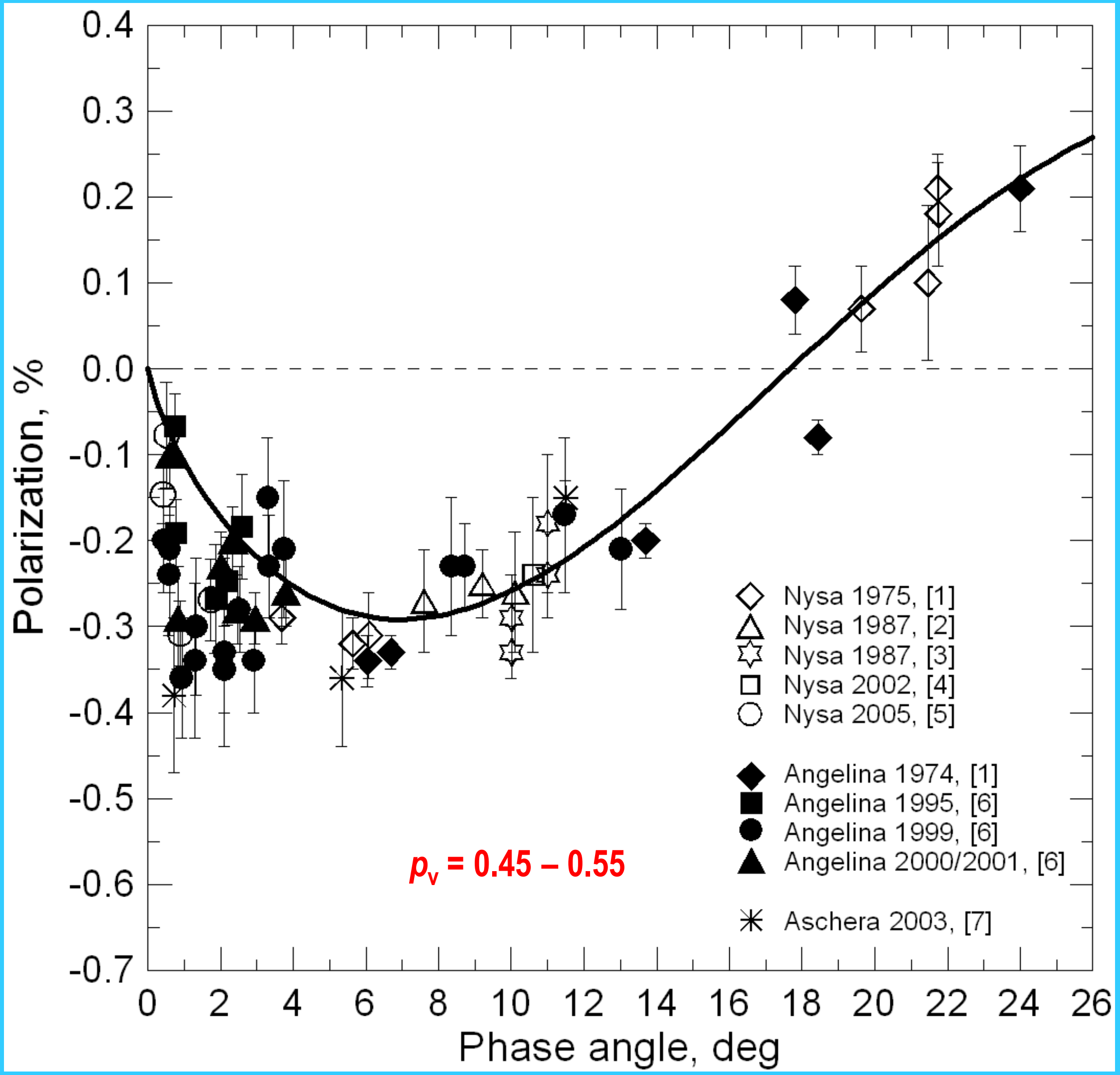


The observed degree of polarization of the center of Jupiter's disk vs phase angle (from Bugaenko et al., 1974).

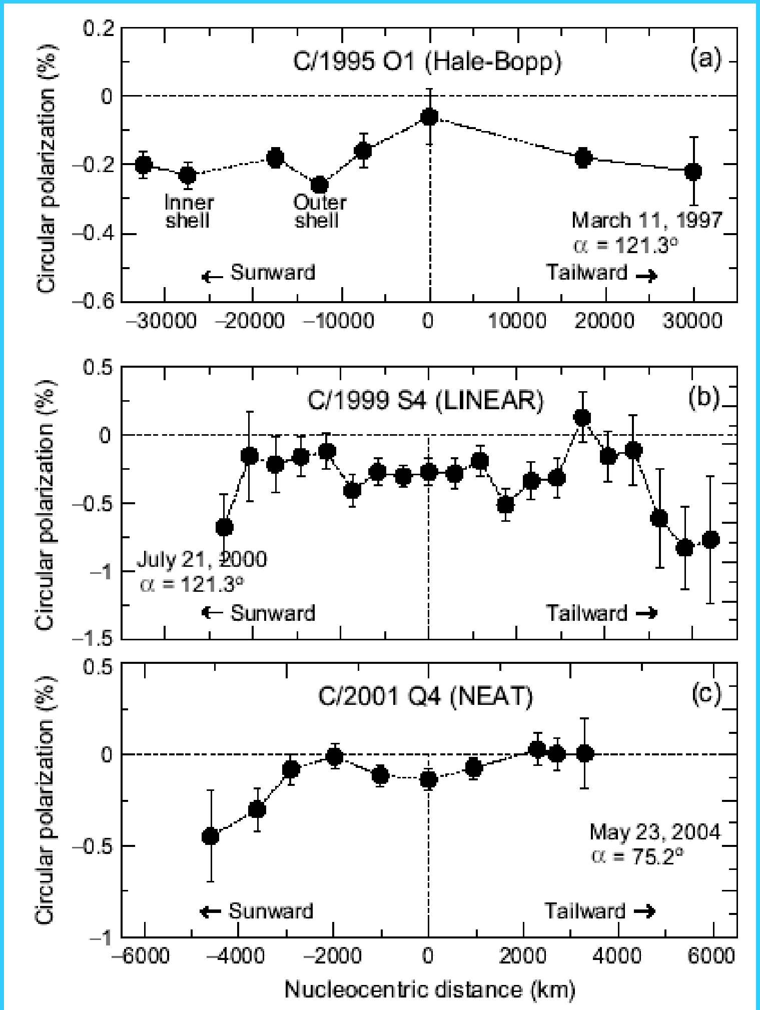
Polarization Opposition Effect

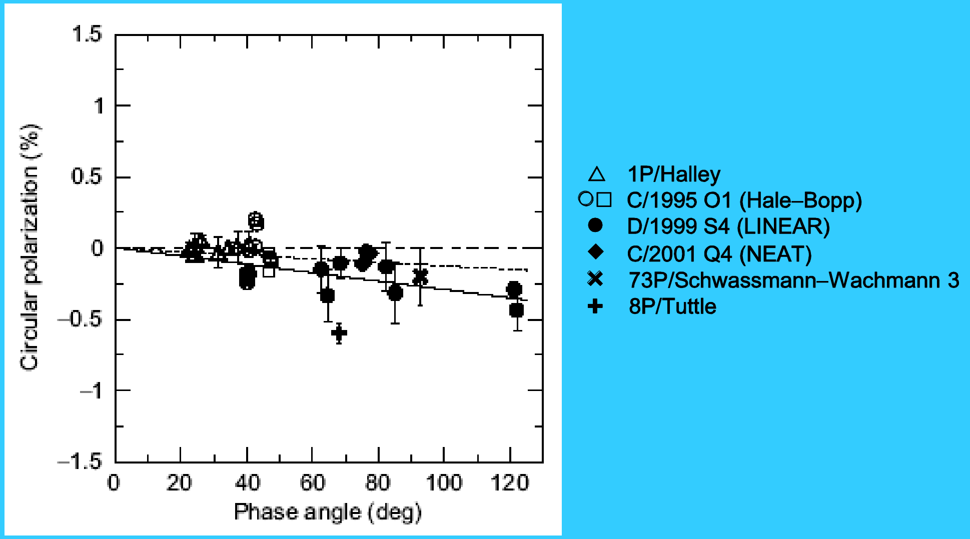


Rosenbush et al. 2005, 2009



Circular polarization in comets





Composite phase-angle dependence of circular polarization for comets

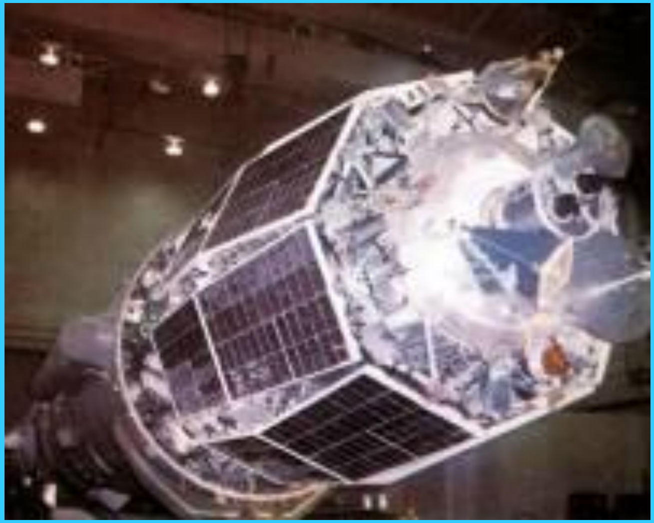
Variations of the degree of circular polarization along the line through the coma and nucleus of comets Hale–Bopp (a), S4 (LINEAR) (b), and Q4 (NEAT) (c).

Theoretical research at MAO

- **Efficient numerical solver of the Ambartsumian nonlinear integral equation for the reflection coefficient and its application to the Jovian atmosphere (analysis of ground-based polarimetric observations) as well as snow and soil surfaces (Yanovitskij, Dlugach, Mishchenko)**
- **Theory of multicomponent superachromatic retarders and its practical implementation (Kucherov)**
- **Efficient analytical orientation-averaging *T*-matrix procedures for nonspherical particles (Mishchenko)**
- **Analytical vector theory of coherent backscattering by particulate media; prediction of the polarization opposition effect (Mishchenko)**

Space-borne polarimeters

CrAO scientists in collaboration with their Swedish colleagues developed a spectrometer–polarimeter intended to record polarization in the 120–150 nm region of the solar spectrum. It was launched onboard the satellite Intercosmos-16 on 27 July 1976. The experiment demonstrated that Lyman- polarization measurements of the solar limb can be a useful diagnostic tool for the study of chromospheric and coronal magnetic fields of the Sun (Stenflo et al. 1980).



Project for the study of aerosols from a satellite

It is currently recognized that terrestrial aerosols have a very strong effect on climate comparable to that of the greenhouse gases. Unfortunately, the uncertainty in existing quantitative estimates of this effect and its anthropogenic component are unacceptably large. Therefore, we are performing a feasibility study of a Ukrainian orbital mini-mission intended for global monitoring of tropospheric and stratospheric aerosols using high-precision multispectral and multi-angle photopolarimetry.

Centers of polarization investigations in Ukraine

CRIMEAN ASTROPHISICAL OBSERVATORY:

1. Different types of variable stars, nebulae and galaxies.
2. Satellites of planets, asteroids, comets (in collaboration with Institute for Astronomy of Kharkiv National University and MAO).
3. Instrumentation and methods of polarization measurements.
4. Developing of theory and interpretation.

MAIN ASTRONOMICAL OBSERVATORY OF NASU:

1. Planets, satellites of planets, asteroids, comets.
2. Instrumentation and methods of polarization measurements.
3. Developing of theory and interpretation.

INSTITUTE FOR ASTRONOMY OF KHARKIV NATIONAL UNIVERSITY:

1. Moon, planets, satellites, asteroids, comets.
2. Instrumentation and laboratory experiments.
3. Developing of theory and interpretation.

ASTRONOMICAL OBSERVATORY OF ODESSA NATIONAL UNIVERSITY:

1. Instrumentation and methods of polarization measurements (in collaboration with CrAO).
2. Cataclysmic variable stars (in collaboration with CrAO).
3. Developing of theory and interpretation.